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Microstructural Degradation in Power Plant Steels and Life Assessment of Power Plant Components

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Abstract

Extensive creep testing was carried out on 1Cr1Mo¼V low alloy forging and casing steels in as received (normalized and tempered) and aged condition. Both the steels exhibited considerable secondary and tertiary stages in the creep tests conducted in the temperature range between 813 and 873 K (540℃ and 600℃). The primary stage, though present, was rather negligible in higher temperature ranges. Casting steel showed wedge type cavities which grew as cracks along the grain boundaries. In the case of forged steel, the voids were elliptical and flat which developed during the tertiary stage of creep deformation. Tertiary creep deformation and creep ductility of the two steels investigated have been analyzed based on the type of voids developed during the tertiary stage. Based on detailed microstructural investigations using scanning and transmission electron microscope, prevailing damage mechanisms such as structural transformation, particle coarsening, grain boundary thickening have been identified and applied for remaining life assessment of the two steels. Hardness and other mechanical properties were observed to decrease slightly on aging; both for rotor forging and casing casting steel. The softening occurred due to dissolution of M_3C and Mo_2C carbides and coagulation of others resulting in reduced creep strength. Gradual fall of creep strength at intermediate aging times was due to recovery in ferrite, gradual depletion of solid solution carbides from the ferrite matrix, metastability and transitional character of precipitated carbides. Creep crack growth studies have also been carried out on both the steels. Life assessment calculations have also been carried out using creep crack growth methodology.

Keywords: Creep; ductility; low alloy steels; aging; microstructure; minimum creep rate

1. Introduction

Most components of a steam turbine are made of steels containing various amounts of principal alloying elements nickel, chromium, molybdenum and vanadium [1]. With the exception of some of the high temperature rotors, bolting, blades and valve stems, which are made of 12% Cr steels, all components are made of low alloy steels. Low alloy steels find wide application in high temperature power plant components such as steam turbine rotors and casings. The basic strengthening mechanisms in these alloys are solid solution

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strengthening and precipitation strengthening. These steels derive their strength mainly by solid solution strengthening and are widely used in steam turbine components. Molybdenum and vanadium present in these steels, improve the creep resistance as compared to the plain carbon steels with the creep ductility retained at around 20-25%. Solid solution strengthening reduces the stacking fault energy, thus impeding cross slip at elevated temperature. Chromium improves the oxidation-corrosion resistance [2,3]. This investigation was undertaken to analyze the damage evolution in these solid solution strengthened steels.

2. Experimental procedure

Materials used in the present investigation are 1Cr1Mo¼V steam turbine rotor forging and casing casting steels. Grain size of the rotor forging steel was ASTM No.6-7 and that of the casing steel was ASTM No.4-5.

Creep is a microstructure sensitive property of the material. Therefore, to study the creep behaviour of these steels in service exposed condition equivalent to 2,00,000 hours at 813 K (540^oC), these steels were subjected to an equivalent aging treatment at 873 K for 3648 hours. The idea behind this aging heat treatment is to study the creep behaviour also in the material condition equivalent to the service exposed steels.

Creep experiments on round specimens were carried out at temperatures of 773, 813, 848 and 873 K (500, 540, 575 and 600°C) with a temperature stability of ±2°C. The rupture time ranged from 40 h to 4000h. The details of experimental set up and test procedure are given elsewhere [3,4].

3. Results and discussion

3.1. Creep data correlations

A typical relation between creep strain, e and time, t, for rotor forging steel at 873 K (600°C) is shown in Fig. 1. The creep curves in general, show the three stages, - primary, secondary and tertiary. However, the first stage primary creep strain, e, is very small as compared to the overall rupture strain, e_f, which is contributed mainly by the secondary and tertiary strains, e_2 and e_3, respectively. Creep strain, e_{23}, where the transition from secondary to tertiary stage occurs and the corresponding time, t_{23}, are indicated in the figure. Various plots for rotor forging steel are given in Figs.1 to 6.

The relation between minimum (steady state) creep rate, e_s, and the applied stress σ for aged rotor steel is shown in Fig. 2. The log-log plot for the two alloys yields a linear relation over the experimental stress range studied thus follows the power law equation given by

$$\dot{e}s = \dot{e}o \ [\sigma / \sigma o \ ] \ n \tag{1}$$

where $\dot{e}_o$ and σ_o are temperature dependent constants. Values of creep stress exponent, 'n' are around 7.6 and 6.6 for as received and aged rotor forging steel and 6.8 and 5.8 for as received and aged casing casting steel, respectively at 873 K (600^oC). Monkman and Grant [5] have noted that the minimum creep rate, $\dot{e}_s$, can be related to the rupture time, t_r, by the relation

$$\dot{e}_s . \ t_r = C_{MG} \tag{2}$$

where C_{MG} is a constant. The relation between the minimum creep rate, ε_s, and the rupture time, t_r, is shown in Fig. 3 on the log-log plot. The value of 'n' for as-received rotor steel varies from 7.75 to 12.13 in the temperature range of 773 to 873 K. For aged steel the values of 'n' vary from 6.67 to 10.64 in the same temperature range. Values of stress exponent 'n' are found to decrease with increase in temperature, as the creep processes at higher temperature become more diffusion controlled. At higher stresses, creep rate is determined by the deformation processes associated with larger 'n' values. Conversely, in the lower stress regime, the contribution made by the process with larger 'n' values decreases rapidly with decreasing stress so the over all creep rate is governed by the process having lower 'n' value such as diffusion creep. Also the values of 'n' are found decreasing with aging indicating the prominent occurrence of diffusion controlled creep

processes in aged material. Values of 'n' ranging from 1 at low stresses and 14 at high stresses have been reported [6]. Low 'n' values are associated with lower stress, grain boundary sliding, diffusion creep and dislocation climb whereas high 'n' values are associated with higher stress, matrix deformation and dislocation bowing between the particles. The cavity formation in rotor and casing casting steels can be seen in Figs.7 and 8, respectively.
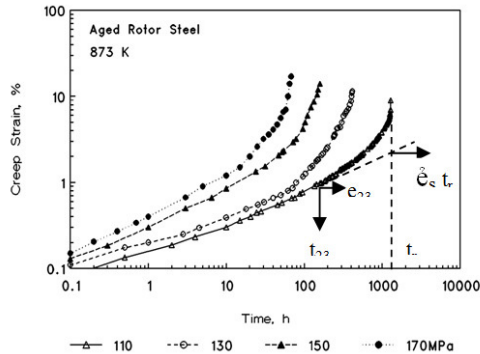

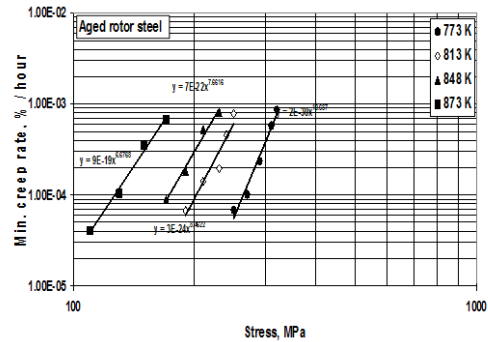Fig.1. Creep strain vs time plots of aged 1Cr1Mo¼V rotor steel tested at 873 K.

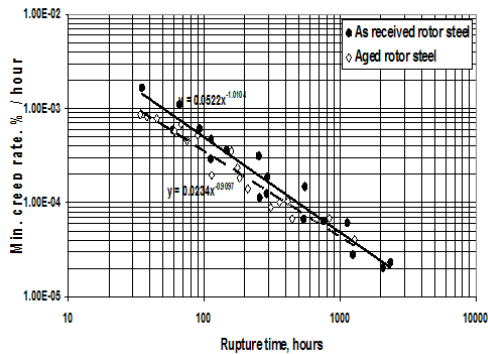Fig. 2. Stress vs minimum creep rate plot for aged rotor steel.

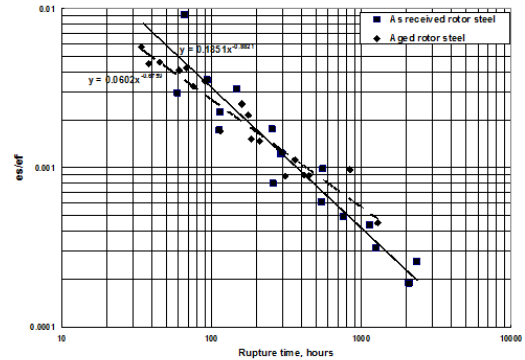Fig. 3. Minimum creep rate vs rupture time plot for rotor steel.

Fig. 4. $\dot{e}_s / e_f$ vs rupture time plot for rotor steel.

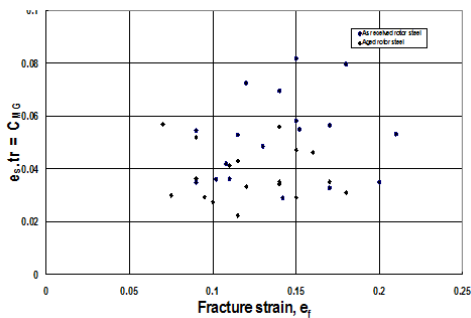

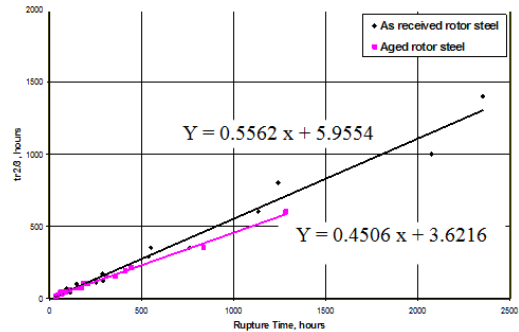Fig. 5. Creep fracture strain vs $e_s.t_r$ plots for rotor steel.

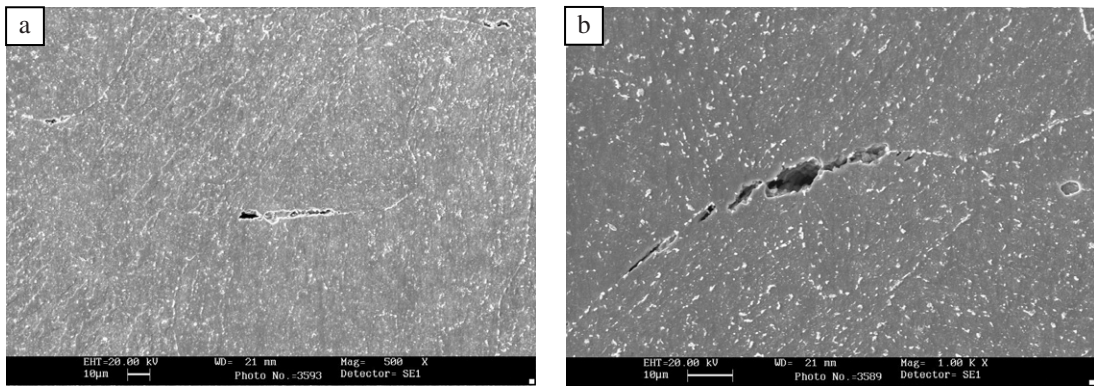Fig. 6. $t_{r2/3}$ vs rupture time plot for rotor steel.

Fig. 7.(a). Wedge type creep cavities in as received casing steel away from the fracture tip tested at 873K, 110 MPa, (b) Grain boundary cavities in aged casing steel along with coarse carbides.
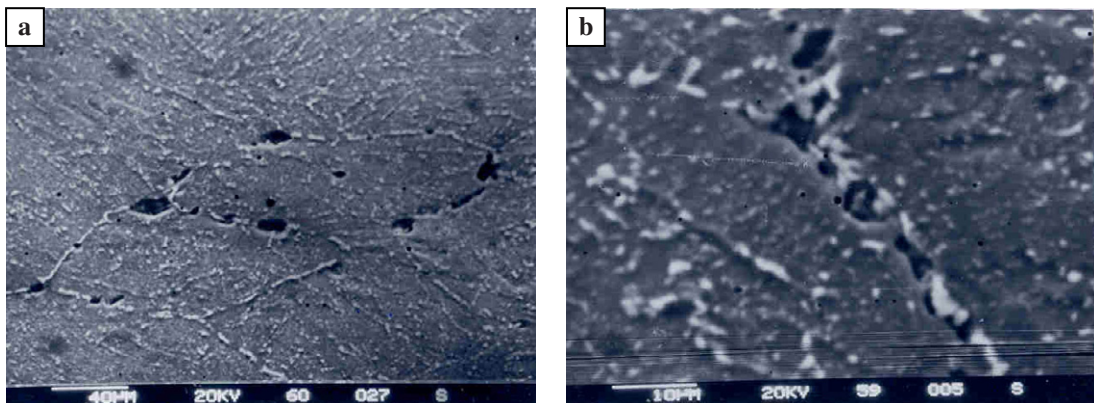

Fig. 8. Microstructure of as received rotor forging steel specimen creep tested at 873 K, 110 MPa showing elliptical creep cavities.
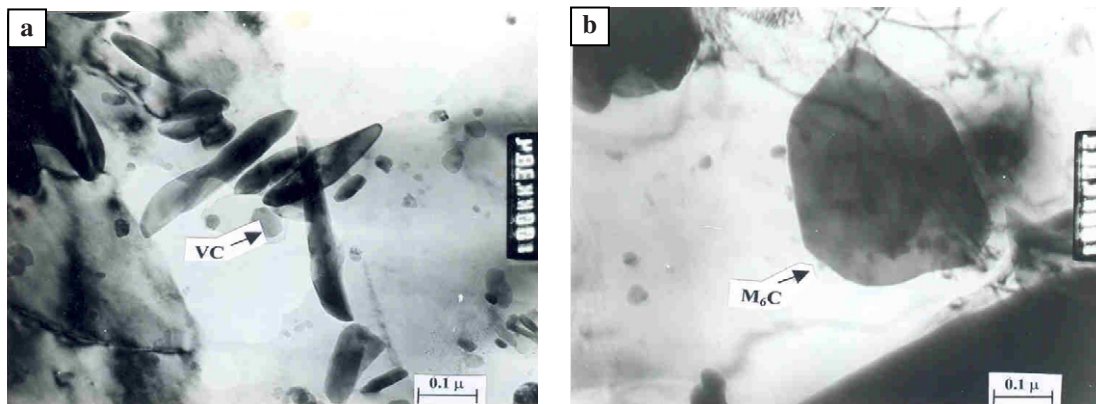

Fig. 9.Transmission electron micrographs of aged rotor forging steel specimen creep tested at 813K, 250 MPa.

The as-received rotor forging steel contains mostly Fe_3C, VC and Mo_2C carbides. Fe_3C plate like particles are of approximately 0.4μ diameter. The VC particles are in the form of 0.1μ wide and 0.5μ long needles. The carbides in the aged steel have transformed into $M_{23}C_6$, M_6C and VC (Fig.9). M_6C and VC are mostly matrix carbides. As revealed by EDX analysis, these are rich in Cr, Mo and V. Grain boundaries mostly contain

$M_{23}C_6$ as also corroborated by EDX analysis, which indicated presence of Cr and Mo. The size of $M_{23}C_6$ and M_6C particles is around 0.5μ. M_6C particle is also surrounded by a few dislocations as shown in Fig.9b.

As discussed above, microstructural damage in rotor forging and casing casting occurs due to structural softening, microstructural changes with respect to change in carbide chemistry, void formation etc.

4. Effect of corrosion on life prediction of boiler tubes

In thermal power plants, the efficiency of power plant depends on the outlet steam temperature. The steam temperature should be maintained for efficient output of power plant. In order to maintain a constant outlet steam temperature, heat energy is transferred to steam through boiler tube walls from flue gas produced in combustion of coal. In these harsh conditions boiler tubes undergo different degradation processes like creep, fireside corrosion/erosion on outer wall of tubes and steamside oxidation on inner wall of boiler tubes. Therefore, remaining life assessment of boiler tubes is necessary at regular time intervals for better functionality of power plant. In laboratory scale, the creep life is estimated using accelerated stress rupture test on service exposed boiler tube. Accelerated stress rupture tests are carried out at higher temperatures under the nominal steam load and remaining life is estimated by extrapolating the results to service temperature.

Crucial parameter in estimating creep life is operating temperature of the metal. But, this temperature varies during long run of power plant because of the insulating effect of oxide layer. The mid wall metal temperature at a particular time is calculated using following equations. For a particular time step, mid wall temperature can be calculated using equations 3-10 which can be used in estimating rupture life from accelerated stress rupture testing.

4.1. Governing Equations

$$\frac{1}{\propto_1}\frac{\partial T_1}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right) \quad r_1 \leq r \leq r_2 \tag{3}$$

$$\frac{1}{\propto_2}\frac{\partial T_2}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right) \quad r_2 \leq r \leq r_3 \tag{4}$$

4.2. Boundary Conditions

$$T_1(r_1, t) = T_s \tag{5}$$
$$T_1(r_2, t) = T_2(r_2, t) \tag{6}$$
$$K_1 \frac{\partial T_1(r_2, t)}{\partial r} = K_2 \frac{\partial T_2(r_2, t)}{\partial r} \tag{7}$$
$$h[T_g - T_2(r_3, t)] = -K_2 \frac{\partial T_2(r_3, t)}{\partial r} \tag{8}$$

4.3. Initial Conditions

$$T_1(r, 0) = T_s (Steam\ temperature) \tag{9}$$
$$T_2(r, 0) = T_s (Steam\ temperature) \tag{10}$$

r_1	=	inner radius of oxide scale
r_2	=	outer radius of oxide scale
r_3	=	outer radius of metal tube
T_1	=	Temperature of oxide-scale at a particular radius and time

T_2	=	Temperature of metal at a particular radius and time
α_1	=	Thermal diffusivity of oxide layer
α_2	=	Thermal diffusivity of metal tube
K_1	=	Thermal conductivity of oxide scale
K_2	=	Thermal conductivity of Metal tube
h	=	convective heat transfer co-efficient of flue gas
T_s	=	steam temperature
T_g	=	Flue gas temperature

4.4. Assumptions

- Hoop stress value is assumed to be constant, though there is a thinning effect of the boiler tubes because of fireside corrosion, erosion on outer wall and steamside oxidation on inner wall of boiler tube.
- No exfoliation of the steam oxidation scale in the continuous operation of boiler tube.
- Oxide scale growth rate and thinning rate of the boiler tubes are constant.
- Steam temperature is maintained constant throughout the process and inner surface temperature of oxide scale is assumed to be equal to steam temperature at any time step.
- The average metal temperature is used in estimating the residual life of boiler tubes.
- Thermal properties are assumed to remain constant in the operational temperature range.
- Creep rupture occurs when it satisfies the Robinson's rule.

4.5. Robinson's rule

$$\sum_{i=1}^{n}\left(\frac{t}{t_r}\right)_i = 1 \tag{11}$$

$$\left(\frac{t}{t_r}\right)_1 + \left(\frac{t}{t_r}\right)_2 + \left(\frac{t}{t_r}\right)_3 \cdots\cdots\cdots + \left(\frac{t}{t_r}\right)_n = 1 \tag{12}$$

4.6. Algorithm for computing residual life of service exposed tubes

The following parameters are required for estimating the residual life

(a) Thermal properties of oxide scale and steel should be obtained.
(b) Initial and final tube diameter and thickness should be measured.
(c) Oxide scale thickness is measured using ultrasonic non-destructive equipment.
(d) Linear growth rate of oxide is calculated using equation13.
   Linear growth rate = (oxide scale thickness/service exposure time) (13)
(e) Thinning rate of the tube is calculated using equation14
   Thinning rate = (initial thickness-final thickness)/service exposure time (14)
(f) At a particular time interval, oxide scale thickness and average temperature are obtained using equations 3&14, respectively.
(g) Average temperature is used in equation 15 to obtain the rupture life.
   T = a*log tr+b (15)
(h) Life fraction is calculated using equation 11.
(i) Total residual life can be estimated using Robinson's rule 12.

Several T22 tubes from various sections of Platen Superheater, Final Superheater and Reheater are subjected to accelerated stress rupture tests. Creep life is calculated by extrapolating the results to service exposure

temperature. After incorporating the effect of oxide scale, the creep life is recalculated using above algorithm. The results are plotted in the Fig.10. The remaining life of boiler tubes obtained from incorporating the effect of oxide layer is one order less than the life estimated from accelerated stress rupture test, which is much closer to realistic values.
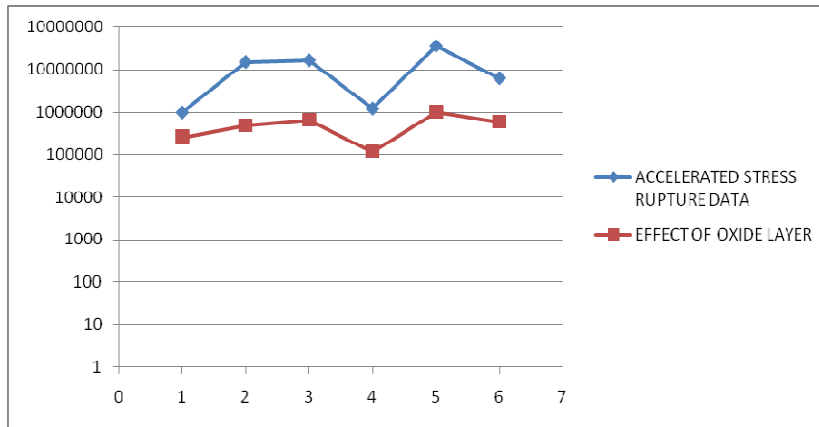

Fig. 10. Accelerated stress rupture data Vs effect of oxide layer on accelerated stress rupture data.

5. Conclusions

From the experimental investigations carried out to study the creep behaviour of 1Cr1Mo¼V low alloy forging and casing steels, the following conclusions are arrived,

- Creep deformation for both as received and aged materials shows three stages of creep. However, the primary and tertiary stages are rather short and the total strain is contributed mainly by the secondary and tertiary stages. The creep fracture strain decreases, in general, with increasing exposure time. Aging has been found to increase creep deformation rates and decrease rupture time as compared to as received specimens.
- Stress versus minimum creep rate bears a power law relation in the form $\dot{e}_s = A\sigma^n$ with creep stress exponent around 7.6 and 6.6 for as received and aged rotor forging steel and 6.8 & 5.8 for as received and aged casing casting steel, respectively at 873 K (600°C).
- Time at the beginning of the tertiary stage, t_{23}, appears to bear a relation with the rupture time, t_r, in the form $t_{23} = 0.5\ t_r$.
- In the case of rotor steel, failure is contributed by spherical and elongated voids along the grain boundaries. In casing steel, flat, elliptical and wedge type of voids, nucleating at triple points, develop as cracks, causing failure.
- In aged steels, rupture life is slightly less but is comparable to as-received steel. It is higher than that for the steels aged at intermediate stages. Evolution of more stable microstructure such as coarsened MC, precipitation of $M_{23}C_6$, formation of 'H' carbides in the ferritic matrix containing low density dislocation sub-structure together with freshly formed Mo_2C and VC, are responsible for improvement in creep-rupture life.
- SEM and TEM micrographs of as-received and aged materials exhibit the shape, size and distribution of carbides. The predominant carbides identified in as-received rotor forging material are Fe_3C, VC, Mo_2C and $M_{23}C_6$ and aged forging steel are $M_{23}C_6$, M_6C and VC.
- The carbides in as-received casing steel are Fe_3C, VC, Mo_2C and $M_{23}C_6$ whereas in aged steel, they are $M_{23}C_6$, M_6C, VC and 'H' carbides. On aging, the precipitates have coarsened and coagulated. Cr and Mo have reverted to matrix in aged casing steel resulting in improvement in creep life.

- Remaining life of boiler tubes obtained from incorporating the effect of oxide layer is one order less than the life estimated from accelerated stress rupture test, which is much closer to realistic values.

Acknowledgement

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