Evaluation of Creep Damage Progress by Metallurgical Examination in Aged Power Boiler Pressure Parts

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In order to confirm the reliability of non-destructive plant life assessment method by metallurgical examination, creep damage was evaluated in aged power boiler pressure parts operated more than 100 000 h. Then the evaluated creep damage was compared with destructive tests, namely creep rupture test and creep fatigue test, of samples removed from the same positions of components inspected by the metallurgical method.

In the metallurgical method, metallurgical degradation was quantified by variation of type and shape of carbide, variation of distribution of alloying elements and nucleation of creep voids. All quantified values but shape of carbide varied systematically during the further operation for 1 or 2 years at all of inspected components. Comparing the quantified metallurgical degradations, with consumed life fraction assessed by destructive tests, relative fraction of M_6C carbide, which was quantified type of carbide, and characteristics of Cr and Mo composition spectra, which was quantified distribution of alloying elements, were found to suit the life assessment during first half of life. The creep void density, which was quantified nucleation of creep voids, was found to suit during the latter half.

Consequently residual life of aged power boiler pressure parts can be assessed by the metallurgical method.

KEY WORDS: power boiler; life assessment; metallurgical degradation; creep damage; non-destructive evaluation; replication; creep; creep-fatigue.

1. Introduction

Many fossil power plants in Japan were constructed in 1950s and 1960s. Such aged plants are more than half of all fossil power plants and have been operated for more than 20 years. They are going to be forced into further operation after appropriate repair or partial replacement because of economical reason.¹⁾ In order to extend the plant life by systematic maintenance, there is no doubt that reliable life assessment technology has to be established.

The life of fossil power plant has been assessed by analytical and/or destructive methods. In the former, the accuracy of assessment depends on material property data and appropriateness of load condition. In the latter, sampling of test piece is very expensive especially on thick wall component and it takes time to carry out creep tests. Thus, development of non-destructive life evaluation (NDE) methods has been recognized worldwide as the growing importance in recent years.²⁾

For NDE, correlation diagram between the non-destructive factors related to damage and consumed life must be established. Generally the correlation diagram for creep damage is obtained by accelerated creep test at higher temperatures and/or stress than

operating conditions of actual plants. So the accuracy of the correlation diagram must be ascertained before applying the NDE methods to actual plant life evaluation.

The principal objective of this study is to examine the metallurgical NDE methods, which have been developed through laboratorial tests.^{3,4)} The metallurgical methods are applied to elevated temperature components in aged power boiler operated more than 100 000 h and it will be discussed whether they can detect the creep damage progress during the further operation for 1 or 2 years. The consumed life evaluated by the NDE methods will be compared with that by destructive tests of samples removed from the same components.

2. Experimental Procedure

2.1. Boiler Investigated

Specification and operating records of the boiler investigated are given in Table 1. Field inspections and sampling of test pieces were carried out three times, in August 1986, August 1987, and January 1989. The boiler has been forced into the severe middle load operation, with frequent start and stop and load swings, in recent years.

Table 1. Specification and operating record of the boiler investigated.

Type	Controlled circulation boiler
Evaporation rate	1 225 t/h
Steam temperature (°C)	Superheater outlet: 571.0 Reheater outlet: 540.6
Maximum operating pressure (kg/m ² g)	Superheater outlet: 200.4 Reheater outlet: 42.2
Operating time (h)	1st: 123 786 (August, 1986) 2nd: 130 294 (August, 1987) 3rd: 136 564 (January, 1989)
Number of start and stop	1st: 645 (August, 1986) 2nd: 688 (August, 1987) 3rd: 763 (January, 1989)

Location of inspected components, their metal temperatures and number of inspected positions in each component are listed in Table 2. The location of the components are indicated in Fig. 1, where they are indicated with their marks listed in Table 2. Field inspection was carried out twice at the same position of each component and progress of damage during the two inspections was examined. First inspection of all components and second inspection except the pendant front superheater outlet header stub tube, marked with FSO, were carried out in August 1986 and January 1989, respectively. Second inspection at FSO was carried out in August 1987.

In addition to the field inspection, samples were removed from each component near the field inspection positions. These samples were subjected to de-

Table 2. Inspected components, their metal temperatures and number of inspected positions.

Component	Mark	Material	Metal temp. (°C)	Number of inspected positions			
				Field inspection		Removed tube	
				1st	2nd	1st	2nd
Pendant front superheater inlet header stub tube	FSI	1Cr- $\frac{1}{2}$ Mo	497	8	8	6*	—
Pendant front superheater outlet header stub tube	FSO	2 $\frac{1}{4}$ Cr-1Mo	543	8	8*	6	—
Pendant rear superheater outlet header stub tube	RSO	2 $\frac{1}{4}$ Cr-1Mo	571	12	6	6	6
Pendant rear superheater dissimilar metal welded joint	RSW	2 $\frac{1}{4}$ Cr-1Mo	571	12	6	6	6
Pendant reheater outlet header stub tube	RO	2 $\frac{1}{4}$ Cr-1Mo	540	15	8	6*	6
Pendant reheater dissimilar metal welded joint	RW	2 $\frac{1}{4}$ Cr-1Mo	540	14	8	6	6

1st inspection was executed in August 1986.

2nd inspection was executed in January 1989.

* 1st removing of tubes of FSI and RO and 2nd field inspection on FSO were executed in August 1987

Fig. 1. Location of inspected components in boiler.

Fig. 2. Illustrating indicating thermal stress induced at header stub tube (1) and dissimilar metal welded joint (2).

structive tests and cross-sectional structure examination in order to confirm accuracy of the life evaluated by the field inspection.

As shown in Table 2, all inspected components are header stub tube and dissimilar metal welded joint. Fig. 2 illustrates thermal stress induced at header stub tube and dissimilar metal welded joint. In header stub tube, the temperature difference between tubes in a panel or between header and roof causes thermal stress during unsteady state, and creep damage is accumulated during stress relaxation. In dissimilar metal welded joint, creep damage progresses due to thermal stress, caused by the difference in thermal expansion coefficient between the ferritic tube and the austenitic weld metal.⁵⁾ The highest thermal stress is always induced at the weldment heat affected zone (HAZ) in each component.

2.2. Metallurgical Life Assessment

Metallurgical life assessment methods employed in this investigation are listed in Table 3. These methods have been developed based on accelerated creep test and structural examination in laboratory.^{3,4)} Though the creep void density, spheroidizing rate of carbide and relative fraction of M_6C carbide can be evaluated non-destructively by replication method, a minute sample ($\sim 1 \text{ mm}^3$) is needed to obtain composition spectrum of Cr and Mo.

The creep void density was defined as the number of creep voids per unit area, measured with more than 10 scanning electron micrographs taken at a magnification of 500. The spheroidizing rate of carbide was defined as the mean aspect ratio of more than 50 carbides, measured with transmission electron micrographs of carbon extraction replica. Relative fraction of M_6C carbide was defined as the number fraction of M_6C carbides. Carbides were identified with energy dispersive X-ray spectrometer (EDS) attached to scanning transmission electron microscope (STEM). As M_6C is mainly composed of Mo and Fe, and other types of carbides observed in HAZ, namely, M_7C_3 and $M_{23}C_6$ are mainly composed of Cr and Fe, M_6C carbide can be distinguished by analyzing compositions with EDS.

The characteristics of composition spectrum of Cr and Mo were measured with computer aided X-ray

microanalyzer (CMA). Fig. 3 indicates quantitative structural analysis method with CMA.⁶⁾ In this study, X-ray intensity data of 90 000 points were analyzed on a specimen. Based on above measurement, area rate, *i.e.*, frequencies of a composition from C to $C+0.1 \text{ wt}\%$ were plotted as a function of composition, C , as shown in Fig. 3(2). The composition spectrum indicates degree of uniformity in microscopic distribution of composition. The composition spectrum is sharp for a sample with uniform composition distribution, namely when there is no precipitate or when precipitates are much finer than the area of an analyzed point. The composition spectrum becomes broad as the precipitates have grown and coarsened. In this study, composition spectrum was measured for Cr and Mo, and characterized by its peak height, half-width and attenuation constant. The spectrum was assumed as Gaussian distribution around the peak and logarithmic distribution in high composition region.

All the structure quantities were measured in HAZ of 2 1/4Cr-1Mo steel weldment crept up to various life fractions. They are related to creep rupture life fraction as shown in Figs. 4 and 5.

Replica, carbon extraction replica and minute sample were taken to measure the structure quantities. Replication area in header stub tube and dissimilar metal welded joint are illustrated in Fig. 6. Carbon extraction replica was taken from the re-polished and re-etched area where replica had been taken.

2.3. Destructive Test

2.3.1. Creep Rupture Test

Specimens for creep rupture tests were taken from removed tubes of each component as the HAZ lays at the middle of the gauge. Specimens from header stub tube were taken from the same position as replication area and its opposite side of the tube because the thermal stress was considered to be highest at these positions on the circumference of tube. Creep rupture test was carried out at 873 and 923 K. The applied stresses were chosen so that specimens would rupture at about 300, 1 000 and 3 000 h.

2.3.2. Creep Fatigue Test

Creep fatigue test was designed to create creep damage during stress relaxation, according to what happens in actual plant components.⁷⁾ The specimen is shown in Fig. 7. The HAZ lays in the middle of the specimen and stress concentrates at the HAZ. When the specimen welded to austenitic steel is heated, thermal stress is induced due to the difference in thermal expansion coefficient between austenitic and ferritic steels. The stress relaxation takes place due to creep deformation when the specimen is held at high temperature. In this study, the holding temperature and time were set to 873 K and 3.6 ks, respectively. Thermal stress has been estimated to be 155 MPa immediately after heating up and 128 MPa after the holding at 873 K for 3.6 ks based on non-elastic stress analysis.

In this study, nucleation and growth processes of

Table 3. Metallurgical life assessment methods.

Method	Sample	Structural analyzer*
Creep void density	Replica	SEM
Spheroidizing rate of carbide	Carbon extraction replica	STEM
Relative fraction of M_6C carbide	Carbon extraction replica	STEM with EDS
Characteristic of composition spectrum of Cr and Mo	Removed sample	CMA

* SEM : Scanning Electron Microscope

STEM : Scanning Transmission Electron Microscope

EDS : Energy Dispersive X-ray Spectroscopy

CMA : Computer Aided X-ray Microanalyzer

Fig. 3. Quantitative structural analysis method with CMA.

Fig. 5. Relation between characteristics of Cr and Mo composition spectra and life fraction based on accelerated creep test at laboratory.

Fig. 4. Relation between non-destructive structure quantities and life fraction based on accelerated creep test at laboratory.

creep voids were observed on polished and etched specimen surface every 30 heat cycles. The creep-fatigue life fraction was estimated from the compari-

son of the number of heat cycles to the first appearance of creep voids or cracks between the removed tube and unused material.

3. Results

3.1. Structure Evaluation

The measurement of creep void density was made with scanning electron micrographs of replicas at the two inspections. The creep void densities at the two inspections are plotted on Fig. 8. No creep void was observed at both inspections in pendant front superheater outlet header stub tube, marked with FSO, but creep void density in all other components was found to increase during the operation. Intergranular macrocracks were observed in component FSI at the second inspection, in the position where no creep void was observed at the first inspection. This damage progress of FSI is considered to be caused by the fatigue because the operating temperature of FSI is too low to accumulate creep damage during the operation for 1 or 2 years.

Fig. 9 shows scanning electron micrographs of replicas stripped from the same positions at the first

Fig. 6. Relation area in each component.

Fig. 7. Creep fatigue test specimen.

and the second field inspection on pendant rear superheater outlet header stub tube, marked with RSO, and pendant rear superheater dissimilar metal welded joint, marked with RSW. Though no creep void was detected in the replica from RSO at the first inspection, a number of creep voids, which appeared as white dots, were detected on grain boundaries at the second inspection. Only several isolated creep voids were observed at the first inspection, but microcracks, which appeared as white line along grain boundary, were observed at the second inspection in RSW.

Transmission electron micrographs of carbon extraction replicas stripped from the same positions at the two field inspections on RSO and RSW are shown

Fig. 8. Variation of area density of creep void by further operation in each component.

in Fig. 10. The observation was made at the same position as that in Fig. 9. Chromium carbides, M_7C_3 and M_{23}C_6 , which precipitated in the HAZ before exposure were transformed into molybdenum carbides, M_6C , as shown in Fig. 4. Chromium carbides

Fig. 9. Scanning electron micrographs of replicas stripped from same positions at the two field examinations on components marked RSO and RSW.

Fig. 10. Transmission electron micrographs of carbon extraction replicas stripped from the same positions at the two field examination on components marked with RSO and RSW.

usually precipitate on the martensitic lath boundary and have rod-like or plate-like shape. Molybdenum carbides, on the other hand, tend to precipitate on sub-grain boundary made by the recovery of martensitic lath and have a granular shape. As shown in Fig. 10, the shape of most carbides in RSO changed from the rod-like or plate-like shape at the first inspection to the granular shape at the second inspection.

Relative fraction of M_6C carbide was measured with EDS analysis. More than 50 carbides were analyzed in each carbon extraction replica. The result are shown in Fig. 11. Though the variation of relative amount of M_6C carbide is less remarkable than that of creep void density, it should be noted that creep voids are formed only when the relative fraction of M_6C has exceeded 60 % except in FSI.

In FSI where the temperature is low, however, creep voids were observed at the position where the relative fraction of M_6C carbide is about 20 %. This suggests that fatigue is responsible for the progress of mechanical damage in FSI.

There was no significant difference in spheroidizing rate of carbide between the two inspections. The spheroidizing rate of carbide is less sensitive to life fraction as shown in Fig. 4.

Fig. 12 shows an example of composition spectra for Cr and Mo at the first inspection. The measurement was made with CMA just beneath the outer surface at the HAZ on the longitudinal section of removed tubes. The peak of the Cr composition spectrum was the highest for RW and lowers in the following order: RSW>RSO>FSO. This order corresponded to the order of the relative fraction of

M_6C carbide. High peaks of Cr spectra in RW and RSW signify that Cr dissolved from Cr carbides, $M_{23}C_6$ and M_7C_3 into matrix. Lower peaks of Cr in FSW and RSW showed that Cr carbide remained and relative fraction of M_6C is lower. On the contrary, the peak of Mo composition spectrum in RW was highest, though the relative fraction of M_6C carbide was unity, namely, all carbides were M_6C in RW. Carbon concentration in the HAZ of RW, the dissimilar metal welded joint, is lower due to the diffusion of carbon toward austenitic weld metal owing to the difference in carbon activity between the CrMo steel and the austenitic weld metal. Then, the M_6C carbides precipitated in RW were smaller as shown in Fig. 10 and the Mo composition spectrum was considered to remain sharp.

Fig. 13 shows the variation of Cr and Mo composition spectra of RSO and RO during the two inspections.

Fig. 11. Variation of relative fraction of M_6C carbide by further operation.

tions, where peak height; ' K_1 ' and half-width; ' b ' were evaluated with Gaussian approximation around the peak of composition spectrum and Mo attenuation constant ' λ ' was evaluated with logarithmic approximation in the high composition region. Since the composition spectra were measured on the removed tubes, the second inspection was not made at the same tube but at a tube close to the tube inspected first. The peak heights of Cr of both components increased and correspondingly the half-widths decreased as the result of the further operation. Though the half-width of Mo increased with increasing creep life fraction in creep rupture tests, it decreases slightly in RO during the operation. This disagreement may have been caused because the measurement was made on the different tubes between the first and the second investigations.

3.2. Destructive Tests

3.2.1. Creep Rupture Test

Examples of creep rupture test results of first removed tubes are given in Fig. 14. The shaded band is the creep rupture data of unused 2 1/4Cr-1Mo steel, JIS STBA24, reported by National Research Institute for Metals, the Science and Technology

Fig. 12. Composition spectra for Cr and Mo of first removed tubes from each component.

Fig. 13. Variation of characteristics of Cr and Mo composition spectra by further operation.

Fig. 14. Creep rupture properties of first removed tubes from each component.

Agency, Japan.⁸⁾ The creep rupture strength of the tube removed from each component was found to be lower than the data band of unused material, suggesting that creep damage was accumulated during the long term operation. The creep rupture life fractions of each removed tube were estimated from the difference in Larson-Miller parameter between removed tubes and unused tube at 40, 50 and 60 MPa. Fig. 15 shows the life fraction assessed with this procedure. Since the creep rupture strength of the unused material of the present tubes was unknown, lower limit of the data band were used for the strength of unused material.

The life fraction of FSO and RSO decreased with the decreasing stress, as often reported on creep ductile material such as base metal of CrMo steel, with ferrite-pearlite or ferrite-bainite structure.⁹⁾ Specimens of FSO and RSO ruptured transgranularly at base metal with high ductility of 30–80 %, especially at higher stresses. On the other hand, creep rupture life fraction of RSW, RO and RW were nearly constant independently of the stresses. These specimens showed the intergranular fracture at the HAZ with low rupture ductility below 20 %.

The difference in creep rupture behavior between the components is considered to be related to the relative amount of the HAZ in a cross section of creep rupture test specimen. For the dissimilar metal welded joint, made by butt welding, the rupture occurred at the HAZ existing over the cross section. For the header stub tube, attached to the header by seal welding, the creep rupture strength and its fracture properties were thought to be affected by the base metal occupying majority of the cross section.

3.2.2. Creep Fatigue Test

The life fraction determined by creep fatigue test is also plotted in Fig. 15. The life fraction was assessed by comparison of the numbers of cycles at the first appearance of creep voids or microcracks between

Fig. 15. Life fraction assessed by creep rupture test of first removed tubes from each component.

the removed tube and unused material of the same specification. Nucleation and coalescence of creep voids was observed during creep fatigue tests at the HAZ of all specimens, though some specimens fractured transgranularly in creep rupture test. The life fraction by creep fatigue test corresponded to that by creep rupture test within the error of 20 % for RO and RW, in which the fracture occurred at the HAZ with brittle fracture even in the creep rupture test. For RSW, which also showed brittle creep fracture for creep rupture test, the life fraction was different between creep fatigue test, 100 %, and creep rupture test, 75–82 %. Life fraction by creep fatigue test was assessed at the outer surface of removed tube and the life fraction of 100 % means that macrocracks had already been formed before creep fatigue test. On the other hand, the macrocracks were removed when the creep rupture test specimen were prepared. The difference in assessed life fraction mostly came from the difference in specimen preparation. For FSO and RSO, in which the life fraction varied with the assessed stress, life fraction of creep fatigue test is closed to that of creep rupture test at 60 MPa.

4. Discussion

Among non-destructive creep damage assessment methods, the method based on creep voids has been studied extensively.¹⁰⁾ The assessed life, however, is considered to be less accurate during early half of creep life because of the life fraction of nucleation of creep void depends on impurity contents, test conditions and so on in the HAZ in CrMo steels.¹¹⁾ During the creep in the HAZ of CrMo steel, Cr carbides, $M_{23}C_6$ and M_7C_3 transforms into Mo carbide, M_6C . Through the accelerated creep test and the structure analysis, the presence of segregation of sulfur to interface between M_6C on grain boundary and matrix has been reported.¹²⁾ The segregation is considered to lower the interfacial energy and the interface acts as the nucleation site for creep void. Then the precipitation of M_6C during creep is judged to be related directly to nucleation of creep voids.

Fig. 16 shows the relation between non-destructive structure quantities and life fraction. The symbols and the corresponding bands were evaluated with removed tubes and the lines were obtained from unused material (see Fig. 4). As shown in Fig. 16, the data band of relative fraction of M_6C carbide is narrow enough and agrees with the laboratory data (dashed line) up to life fraction of 50 %. Above 50 %, the data band is too wide to assess the creep life. Since the upper side of the data band corresponds to the data from components of dissimilar metal welded joint and the lower side from component of header stub tube. The difference during the latter half of the life is considered to be related to the kind of components. That is, the relative fraction of M_6C carbide is considered to increase faster with life fraction in components of the dissimilar metal welded joint due to the decarbonization in the dissimilar metal welded joint. The spheroidizing rate of carbide is not so

Fig. 16. Relation between non-destructive structure quantity and life fraction evaluated by creep rupture test of removed tubes.

sensitive to the life fraction. This method is not helpful for life assessment in any stage of life.

The creep void density varies remarkably with the life fraction above 50 % and the data band agrees with result of laboratory test (solid line). Then this method is useful when life fraction is greater than 50 %. Creep life fraction must be assessed by creep void density when creep voids are observed in each scanning electron micrograph with the magnification of 500. It should be assessed by relative fraction of M_6C when creep voids are hardly observed.

Several quantifying methods of morphology of creep voids have been proposed. Creep void density is measured merely by counting the number of creep voids in certain area of replica with scanning electron microscope without distinguishing grain boundary which is necessary to assess the life fraction by 'A' parameter proposed at ERA.¹⁰⁾ In addition, as the grain size is almost constant at the HAZ adjacent to the fusion line, where creep voids are apt to form during creep damage, creep void density must be well corresponding to the 'A' parameter.

Fig. 17 shows the relation between peak height of Cr and Mo composition spectra and creep life fraction evaluated by creep rupture test of removed tubes. Peak height of Cr composition spectrum increases and that of Mo composition spectrum decreases with increasing life fraction, and the values agree with the lines determined by the laboratory test. The widths of both data bands are narrow enough to assess life fraction at the early half of the life, while the data bands become wider in the latter half of life especially for Cr composition spectrum. This behavior will be also explained by the decarbonization in dissimilar metal welded joint. The peak height of Cr composition spectrum may increase faster because of the uniform distribution of Cr dissolved from Cr carbides in the component of dissimilar metal welded joint remarkably due to the lower carbon content.

Fig. 17. Relation between peak height of Cr and Mo composition spectrum and life fraction evaluated by creep rupture test of removed tubes.

5. Conclusion

In order to develop non-destructive life assessment method for aged power boiler pressure parts, progress of damage in actual aged power components was examined twice at same positions by means of metallurgical methods. The results are summarized as follows.

(1) Among several non-destructive methods based on metallurgical examination, creep void density and relative fraction of M_6C carbide are most effective when quantifying structural change during a few years of operation.

(2) Characteristics of Cr and Mo composition spectra, also varied systematically with life fraction.

(3) In the early half of the life, the relative fraction of M_6C carbide and the characteristics of the composition spectrum, namely the methods quantifying the metallurgical damage, are useful for life assessment, while creep void density is more relevant in the latter half.

(4) Relation between the above structural quantities and life fraction measured with samples removed from inspected components corresponds to that evaluated by accelerated creep tests of unused material.

(5) Residual life of actual component can be assessed by the above non-destructive methods.

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