RECENT TECHNIQUES FOR RESIDUAL LIFE ASSESSMENT OF MATERIALS SERVING FOSSIL FUEL FIRING AGED POWER PLANTS

Isamu NONAKA and Masaki KITAGAWA
Research Institute, Ishikawajima-Harima Heavy Industries Co., Ltd.,
3-1-15 Toyosu, Koto-ku, Tokyo, Japan

ABSTRACT

Some of the Japanese fossil fuel firing power plants have been operating for more than two hundred thousand hours, and several different kinds of damage have been observed, so that the assessment of residual service life of these aged components has become an important issue. This paper discusses, of a number of assessment techniques being developed at IHI, three major ones. They are:
1. Creep-fatigue damage assessment based on the behavior of microcracks;
2. Creep damage assessment in the early stage based on changes in the chemical composition of carbides; and
3. Nondestructive assessment of creep residual life for heating tubes and linepipes based on creep strain and strain rate, called the omega (Ω) method.

INTRODUCTION

Since the residual life assessment became mandatory for the plant diagnosis of aged thermal power stations in 1987 as a formal requisite for extending the regular inspection intervals, several such assessments have been conducted for each of the pertinent plants. Although no serious damages have actually been found by those inspection works, it is true that several kinds of damages that hitherto remained unobserved have begun to make appearances in those plants that are kept operating beyond two hundred thousand hours[1]. We consider this to be sufficient warning to continue the rational residual life assessment even though the mandated assessment has been alleviated in 1995.

In short, the current R&D on the residual life assessment can be stated as directed three ways: one, to develop novel measurement technologies to evaluate the new kind of damage that has escaped quantitative detection; second, to improve the accuracy and precision of the current practices; and third, to cut down the cost of assessment work by devising means of labor-saving and automation. Table 1 presents, as an example, the activities we are undertaking at IHI for furthering our own capabilities of the residual life assessment for components of power plants.

This paper describes the first three items in the table, i.e., first, the method of quantitatively assessing the creep fatigue damage by the propagation behavior of microcracks; then, the second, the method of quantitatively evaluating the early stage creep damage from the composition changes in precipitated carbides; and the third, the method of predicting the residual service life from the creep deformation, which we call the Omega (Ω) method.

THE METHOD OF QUANTITATIVELY ASSESSING THE CREEP FATIGUE DAMAGE BY THE PROPAGATION BEHAVIOR OF MICROCRACKS[(2),(3)]

Background

It is inevitable that the boiler components should suffer from various sorts of damage in their service lives: typically, the fatigue damage by the thermal stresses that occur on the start-and-stopping of the plant and the creep damage during the steady operation. The damage is such that, while the creep damage dominates in the heating tubes, linepipes, and headers, i.e., those members where the stress concentration can be safely disregarded, it is the creep fatigue damage that must be evaluated for the weldments of header stubs, Y-piece branches of the main steam pipes, and nozzle stubs of linepipes, i.e., those where comparatively large bending stresses occur due to stress concentration. We note here that although a number of nondestructive methods of assessment have been developed for the creep damage and the fatigue damage in their pure forms, no such means are available for the creep fatigue damage, which has to be evaluated by conducting separately the stress analysis, then by combining by the linear cumulative damage law.

For this, we offer an interesting observation. Figure 1 compares for a Type 304 stainless steel the creep breakage (top) to the creep fatigue breakage (bottom). It will be seen that, in the case of straight creep, numerous voids are created by the creep damage, and that they are mutually linked together and grown into a major crack, whereas, in the case of creep fatigue, even though voids are formed likewise, they do not connect each other, but act as a site to initiate microcracks, which grow into the major crack. This shows how it is important to know the behavior of microcrack growth in evaluating the creep fatigue damage.

Principles

The initiation and propagation of microcracks under creep fatigue was studied empirically with a 2.25Cr-1Mo steel. The specimens were heat treated to simulate the weld heat affected zone (HAZ), and were subjected to strain-controlled fatigue with trapezoidal waveform at 570°C. The strain range ($\Delta\epsilon_t$) was 0.3 to 0.7% and the strain holding time (t_H) was 1 to 180 min. The test was interrupted several times to examine the specimen surface by the replica metallography for microcracking.

Figure 2 shows microcracks as induced in simple fatigue (top) and those as produced in creep fatigue (bottom). We note that while the crack propagation is through grains, i.e., transgranular, under fatigue, it is along the grain boundary, i.e., intergranular, when creep-fatigued. We also find in the latter case that cracks are initiated in multitude early in the creep-fatigue life, and grow only by linking each other so that in the end one of those coagulated cracks becomes the main crack which leads to final fracture.

This observation was tested for verification by defining each examination time as the relative creep fatigue life through dividing the fatigue cycle of that time, N, by the final fracture cycle, N_f, and by plotting the length of the longest crack found on each examination against N/N_f. The result is shown in Fig. 3(b), where it will be noted that all the data fall nicely on a single correlation line despite large difference in the testing condition. Another aspect of creep fatigue as distinguished from straight fatigue is shown in Fig. 3(a) for HAZ simulating 2.25Cr-1Mo steel and for Mod.9Cr-1Mo steel: it is evident that N/N_f cannot be related solely to the largest crack length, but depends on the strain range also.

Application to Actual Boiler Components

We have examined several components of a certain operating power boiler for their states of creep fatigue damage. Figure 4 presents three pieces as an example together with the points of examination. In the figure, (a) is a header stub, where the toes of the fillet welding between the heating tube and the header were examined. As the heating tube is less rigid compared to the header proper, the HAZ along the weld toe is liable to produce damage as stress tends to concentrate there. In (b) is shown a Y piece of the main steam pipe, which comprises three linepipes circumferentially welded to the central Y-shaped forged steel piece. Here, each HAZ is damage-prone because of the bending stresses that are given rise to by the reaction forces of the linepipes and are concentrated there. Finally, (c) is a linepipe nozzle stub where two linepipes are mutually fillet welded so that the HAZ's at the weld toes are liable to damage because of concentration of bending stress.

Results of metallography conducted on these specimens are illustrated in Fig. 5. In (a), which is the header stub's weld toe, small cracks of 1mm or so long are seen along the grain boundaries in the HAZ grain-coarsened region. In (b), which was taken of the main steam pipe Y piece, there are numerous voids seen existing together with microcracks. SEM inspection showed, confirming the observation stated regarding Fig. 1, that these cracks were not of voids as they were linked together but were those that were initiated at the voids. Finally, in (c), which shows a HAZ part of linepipe nozzle stub, there are microcracks in the grain-coarsened region, and voids in the grain-refined region.

Now, the progress of creep fatigue damage occurring in the linepipe nozzle stub was analyzed with the regression line of Fig. 3(b) as a working curve. The result is presented in Fig. 6. In the figure, Cracks A. B, and C denotes the cracks that are seen in Fig. 5(c). As the Crack C is the longest of all, we read off the working curve for the relative creep fatigue life N/N_f to be 0.8, and conclude that 80% of the life of this structural piece has been expended.

THE METHOD OF QUANTITATIVELY EVALUATING THE EARLY STAGE CREEP DAMAGE FROM THE COMPOSITION CHANGES IN PRECIPITATED CARBIDES

Background

As illustrated in Fig. 7, there have been two ways to evaluate the creep damage occurring in 2.25Cr-1Mo steel: because deterioration of HAZ is mainly by forming voids, the current practice is to take the void area as a damage parameter, whereas the damage parameter for the base metal, which deforms plastically, is the granular elongation. The trouble with these methods that rely on the detection of mechanical damage is that their capacity of detecting damage is limited only to the latter half of material's useful life, i.e., over 0.4 and over 0.5 respectively in Fig. 7 in the cumulative creep damage rate. Even though we would concur to the opinion that, for the members with a designed service life over 200,000h, it should be sufficient if the damage is assessed in the latter half of the intended lifetime, we take exception to this view here because neither method is precise enough to warrant safety.

For this purpose, we have found that metallurgical damage, as against the mechanical damage discussed above, can be detected in terms of microstructural changes early in the creep life. Particularly, we have found that carbides alter their form and composition with accumulation of damage, ultimately affording a site to initiate void. Here, we intend to discuss the changes in the composition changes.

Principles

Figure 8 shows how the progress of early stage creep can be followed by the changes taking place in the carbide composition in the HAZ part of 2.25Cr-1Mo steel. The creep test was conducted at 630°C with the applied stress as the parameter, and small specimens of 3 by 3 by 1 (thickness) mm were taken successively in each run interrupting the test appropriately. These specimens were electrolyzed to extract only carbides as residue, and the residues were spectro-analyzed for their components, particularly Mo and Cr. Though simple, this method has proved to give highly reproducible results, and, perhaps more importantly, the specimens are small enough to allow direct sampling from operating components without harming them.

It will be seen in Fig. 8(a) that both the Cr/residue ratio, which is the content of Cr in the carbide as expressed as the mass ratio of Cr to that of the whole residue, and the Mo/residue ratio can be arranged nicely as a function of the Larson-Miller Parameter (LMP). Here, the Cr/residue ratio decreases, while the Mo/residue ratio increases, both monotonically with increasing LMP. These features have been further reduced to a simpler function of LMP by taking the Mo/Cr ratio as shown in Fig. 8(b), where the whole data fall tightly on a single trend line despite varying testing conditions and with or without weld post heat treatment.

From Fig. 8(b), working curves of Fig. 8(c) have been derived to determine the creep life rate directly from the Mo/Cr ratio as a function of the applied stress. It will be appreciated here that, for stresses of actual operation conditions, i.e., 30 MPa or thereabout, the Mo/Cr ratio reflects sensitively the expenditure of the life in the early stage of creep life.

Application to Actual Boiler Components

This method has been tried on several components of an operating power boiler, of which we intend to report the case of the circumferential weldment of a reheater outlet header here. Samples were taken from HAZ and base metal, yielding Mo/Cr ratios of 2.55 and 1.77, respectively. Then, a working curve was derived from Fig. 8(c) for the design stress of 31.4 MPa as shown in Fig. 10. Entering Fig. 10 with the given Mo/Cr ratios, we read that 37% of the creep life has been expended for HAZ, but only 6% for the base metal. These conclusions were verified by the creep tests conducted with undersize specimens.

THE METHOD OF PREDICTING THE RESIDUAL SERVICE LIFE FROM THE CREEP DEFORMATION: THE Ω METHOD[6,7]

Background

In the case of heating tubes, the current practice of predicting the residual service life is to extract sample tubes from an operating boiler, and assess the results of creep tests conducted on the sample tubes by the time-and-temperature parameter method. Highly reliable though this method certainly is, the trouble is that it must be practiced at the expenses of a great deal of time, labor, and cost because the sampled out tubes have to be replaced with new ones involving the on-site welding work and because the creep test consumes about 3,000 hours of time. To alleviate this trouble, we have developed the replica metallography method, in which we assess the creep damage from the microstructure of specimen tube's surface in

terms of the granular deformation for the base metal part and the void area rate for the HAZ.

The omega (Ω) method of residual life prediction we are going to propose in this section is to improve the granular deformation method.

Principles

It is well known that the theta (θ) method and the omega (Ω) method are available to express the creep deformation rationally. We have found that either method can be modified to evaluate the remaining life, and that the Ω method, whose principle is presented in Fig. 11, is simpler than the θ method.

Namely, a creep curve, which is perceived customarily as consisting of three parts of the primary, the secondary, and the tertiary creep parts, as shown in the upper diagram of Fig. 11, can be replotted in terms of the logarithm of the creep strain rate (ln $\dot{\varepsilon}$) and creep strain (ε) to reveal the importance of the tertiary creep stage, as shown in the lower diagram. The Ω value is simply the gradient of the tertiary creep stage as represented by equation (1) in the figure. It can be shown that eq. (1) can further be transformed into eq. (4), which allows one to calculate the remaining life by determining the actual $\dot{\varepsilon}$, provided that the Ω value is known for the prevailing temperature and stress.

The verification of this theory was done by conducting creep tests on Mod.9Cr-1Mo steel at 500, 550, and 600°C. Figure 12 presents the 600°C test results in terms of the ln $\dot{\varepsilon}$ vs ε plots with the applied stress as the parameter. The presence of long enough linear tertiary creep stage is evident. The Ω values determined from these plots are shown in Fig. 13 together with 500°C and 550°C test data. As might be expected, the Ω value depends on both the stress and temperature, such that it tends to be the higher, the lower the stress and temperature.

Figure 14 shows the remaining life as calculated on eq. (4) for the remaining life rates t/t_r of 0.1, 0.5, and 0.8, and as plotted against the actual rupture time. It will be noted here that the predictions done at remaining life rates of 0.5 and 0.8 are accurate enough. Inasmuch as the life expectancies of the components of actual boilers are generally over 200,000h, the ability of making reliable predictions at a remaining life rate of 0.5 should be considered quite satisfactory.

Proposition of Application to Operating Components

The Ω method of remaining life prediction can be applied to the continuous nondestructive surveillance in a number of ways. Figure 15 shows some examples. For example, by establishing a pair of gauge points on a heating tube or a linepipe, and by measuring its outer diameter at regular intervals, the creep rate can be determined accurately and with ease.

In the meantime, however, the Ω value must be acquired empirically. An important point of accumulating Ω values may be that, as inter- or extrapolation of pertinent Ω value for the operating temperature and stress will be inevitable, the factors that exert major influences on the Ω value should be quantitatively determined. Also, it may be necessary that the heat-by-heat variation even for the same grade of steel should be accounted for as is often the case.

CONCLUSIONS

Various components of the power boiler have been examined for their natures of sustaining damage so as to develop a reliable method of remaining service life assessment for each.

(1) For the header stub, Y-piece of the main steam pipe, and the linepipe nozzle stub, which are liable to creep fatigue damage, there has been no practical way of assessing the damage nondestructively. We have found that the creep fatigue in these components is controlled by the initiation of microcracks and their growth up to several millimeters, a process which can be followed precisely and readily by replica metallography, and that the damage as expressed by the relative creep life, N/N_f, can be correlated uniquely to the length of the longest microcrack found on each inspection. This method has duly been verified with actual components of a certain operating power boiler.

(2) For the early stage creep damage, which remained unmeasurable for long because mechanical damages, such as granular elongation and void formation, are not apparent yet, we have found the carbide composition changes sensitively following the accumulation of damage, such that Mo/Cr mass ratio in the carbide composition can be uniquely correlated to the Larson-Miller parameter. Owing to the smallness of the sample required (no more than 3 by 3 by 1mm), this method can be used for the inspection of live components, the efficacy of which has been verified by applying to a certain power boiler.

(3) As for the heating tube, whose remaining service life is being assessed by extracting several tubes and running creep tests on them at a great cost and time, we have developed a nondestructive creep life prediction. Called the omega (Ω) method, it works on the fact that, when plotted on the basis of logarithm of creep strain rate ($\ln \dot{\varepsilon}$) vs creep strain (ε), the first half of the tertiary creep stage emerges as a prominent linear part, yielding the Ω value as its gradient, and that the expended life can be calculated from the Ω value so determined beforehand for the material concerned and for the operating stress, temperature, and ε and $\dot{\varepsilon}$. Several practical methods of measuring and ε and $\dot{\varepsilon}$, continuously and on site, have been proposed together with cautions to be taken in accumulating the Ω empirically.

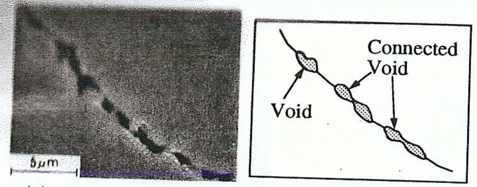
REFERENCES

(1) I. Nonaka, et al., "Evaluation of the ligament crack life for boiler header," *Preprints, 33rd High Temperature Strength Symposium*, JSME (1995), pp. 129-133.
(2) I. Nonaka and M. Kitagawa, "On the possibility of determining the high temperature fatigue damage of 2.25Cr-1Mo steel from the state of microcrack formation," *Preprints, 40eth Annual Convention*, JSME (1991), pp. 237-239.
(3) I. Nonaka, et al., "Fundamental study of assessing the creep damage occurring in the boiler header stub," *Zairyo*, 41/471, 1749-1753 (1992).
(4) The Power Reactor and Nuclear Fuel Development Corp., *Present Status of R&D of Fast Breeder Nuclear Reactors*, PNC-TN 141092-011 (1991), pp. 55.
(5) I. Nonaka, et al., "Development of a method of assessing the early stage creep occurring in 2.25Cr-1Mo steel by the carbide composition change," *Preprints, 42nd Annual Convention*, JSME (1993), pp. 13-15.
(6) I. Nonaka, et al., "Assessment of residual creep life for HAZ simulating 2.25Cr-1Mo steel by the Ω method," *Research Papers on Material Mechanics*, JSME B/95-2, (1995), pp. 379-380.
(7) I. Nonaka, et al., "Assessment of residual creep life for Mod.9Cr-1Mo steel by the Ω method," *Preprints, 33rd High Temperature Strength Symposium*, JSME, (1995), pp. 184-188.

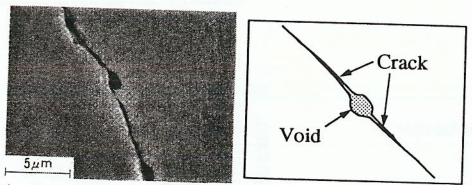
Table 1 Recent activities at IHI for the assessment of residual service life

Purposes	Research Themes	Components	Materials[1]	Damage	Features
To develop a method for newly discovered damage	"Determination of creep fatigue damage on the characteristics of the microcrack formation"	Header stubs, Linepipe nozzle stubs, Main steam pipe Y-pieces, etc.	STBA 24 (H)	Creep fatigue	Of the voids and the microcracks (<1mm), the maximum crack length can be related to the creep fatigue life expenditure.
	"Determination of early stage creep damage on the changes in the carbide composition"	Headers, Linepipes	STBA 24 (H, M)	Early stage creep	The Mo/Cr mass ratio of carbide changes sensitively following early stage creep strain.
To improve the current practices of residual life assessment for the heating tubes	"Prediction of the residual creep life by the Ω method, and method of on site measurement of creep."	Heating tubes	STBA 24 (H, M) STBA 28 (M)	Creep	The residual life can be accurately assessed from the Ω value, which is the gradient of the tertiary creep stage in $\ln \dot{\varepsilon}$ vs ε plot.
	"Determination of creep damage on the intragranular strains."		STBA 24 (M)		Quasi-nondestructive method in which a small sample is used for TEM examination.
	"Improvement of the TTP2 method in appraising the results of creep test of extracted tubes."		STBA 24 (M) SUS 304HTB, etc.		Saving of cost and time as well as improvement of the TTP method of evaluating the creep test results for residual life.
To meet the urgent needs of providing a method of residual life assessment	"Evaluation of residual life for components subjected to the corrosion fatigue damage."	Radiant heat water wall tubes	STS 480 STBA 22	Corrosion fatigue	The corrosion taking place during steady operation and fatigue on start/stopping of the plant are satisfactorily simulated.
	"Life prediction on the thermal fatigue crack propagating in header's ligament."	Headers	STBA 24 (H, M)	Creep fatigue	Development of fracture mechanics method of life prediction for propagating thermal fatigue cracks. (in progress)
	"Residual life assessment for the Type IV crack in the longitudinal welded joint of linepipes."	Linepipes	STBA 24 (H, M)	Creep	Analysis of actual damage, and development fracture mechanics method of assessing the residual life. (in progress)

[1]H: weld heat affected zone (HAZ); M: base metal.
[2]Time-and-temperature parameter method of analysis.

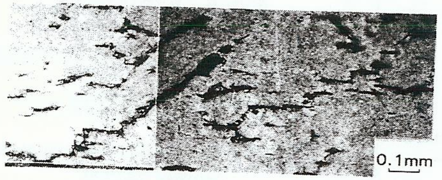


(a) Creep (550℃, σ =176MPa,t_r=20362h)

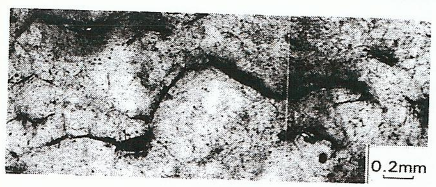


(b) Creep-fatigue (550℃, Δ ε_t=1%, t_H=10h, N_f=315)

Fig.1 Comparison of creep-fatigue fracture mechanism with creep fracture mechanism for 304 stainless steel.

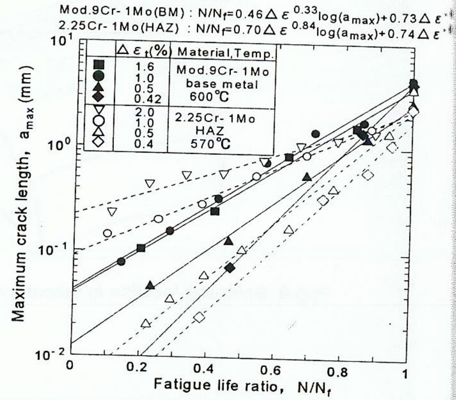


(570℃, Δ ε_t=1%)
(a) Fatigue

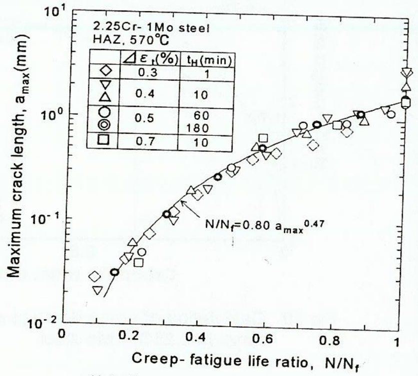


(570℃, Δ ε_t=0.4% t_H=10min)
(b) Creep-fatigue

Fig.2 Comparison of small cracks under creep-fatigue with those under fatigue for 2.25Cr-1Mo HAZ.



(a) Fatigue damage



(b) Creep-fatigue damage

Fig.3 Calibration curves of creep-fatigue damage for 2.25Cr-1Mo HAZ and Modified 9Cr-1Mo steel.

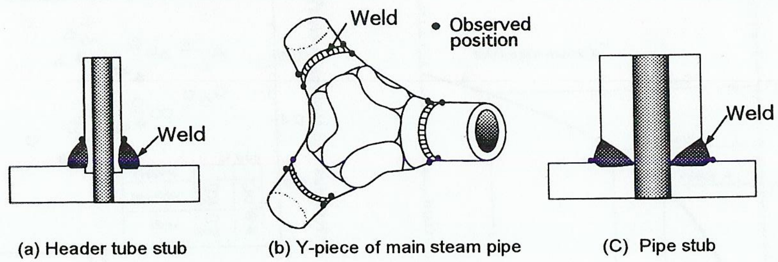
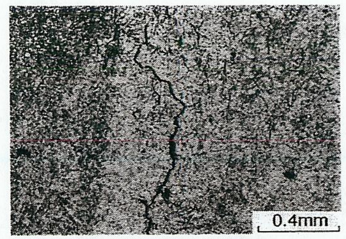
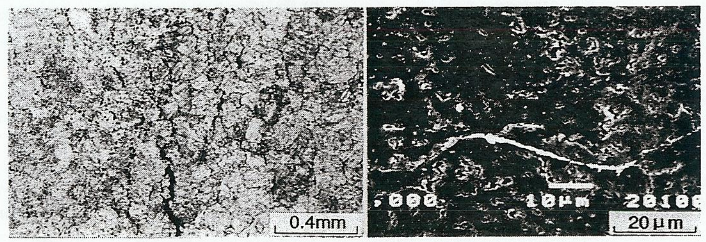


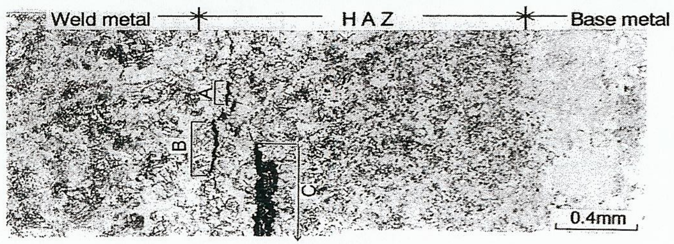
Fig.4 Evaluated components and observed positions.



(a) Header tube stub



(b) Y-piece of main steam pipe



(C) Pipe stub

Fig.5 Optical and SEM micrographs showing small cracks and voids.

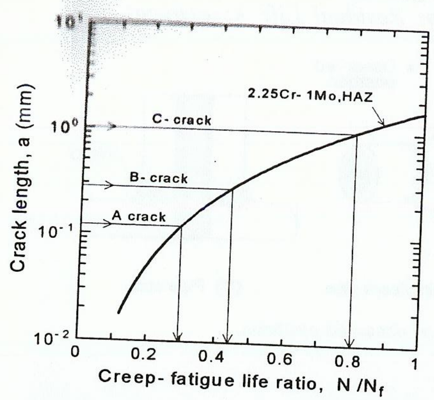


Fig.6 Calculation of creep-fatigue damage using calibration curves.

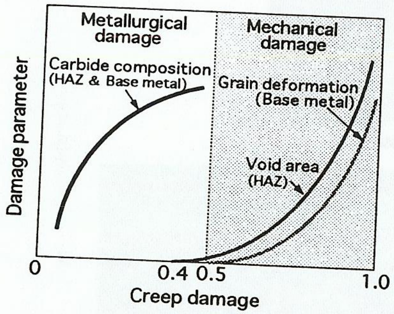
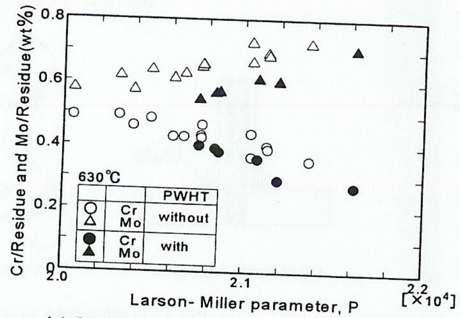
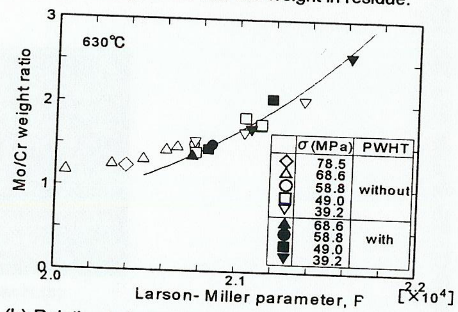


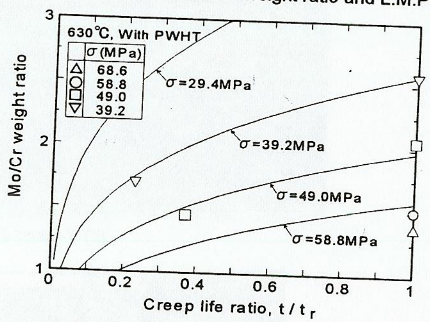
Fig.7 Meaurement of small amount of creep damage for 2.25Cr-1Mo steel.



(a) Change of Cr and Mo weight in residue.

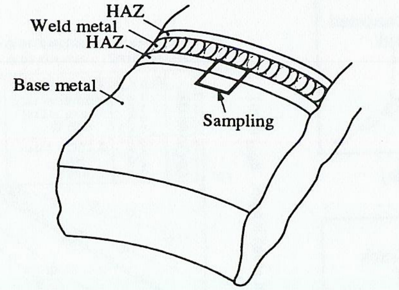


(b) Relation between Mo/Cr weight ratio and L.M.P..



(c) Calibration curves of creep damage.

Fig.8 Meaurement of creep damage based on the change of carbide compositions in 2.25Cr-1Mo HAZ.



Fug.9 Sampling location in reheater outlet header.

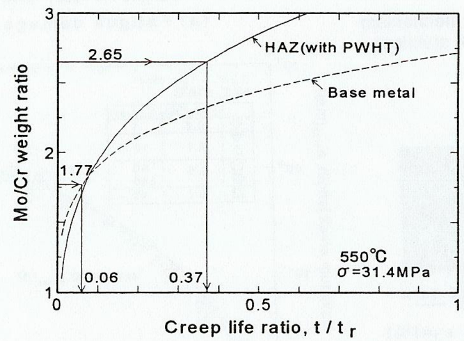
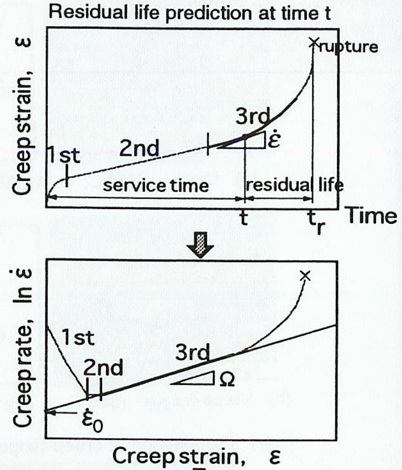


Fig.10 Calculation of creep damage using calibration curve in 2.25Cr-1Mo steel.



$$\ln\dot{\varepsilon} = \Omega\varepsilon + \ln\dot{\varepsilon}_0 \qquad (1)$$

$$\Downarrow$$

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp(\Omega\varepsilon) \qquad (2)$$

$$\Downarrow$$

$$\varepsilon = -(1/\Omega)\ln(1-\dot{\varepsilon}_0\Omega t) \qquad (3)$$

$$\Downarrow$$

$$t_r - t = 1/(\dot{\varepsilon}\,\Omega) \qquad (4)$$

Fig.11 Calculation of residual life based on Omega method.

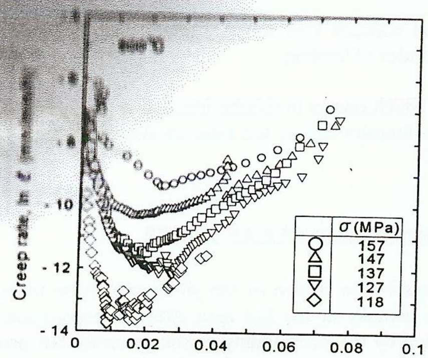


Fig.12 Relation between creep rate and strain in Modified 9Cr-1Mo steel.

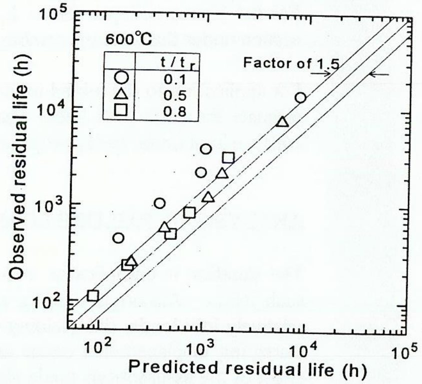


Fig.14 Prediction of residual life based on Omega method in Modified 9Cr-1Mo steel.

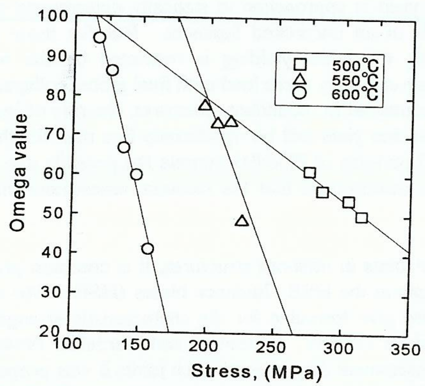


Fig.13 Effect of stress and temperature on Omega values in Modified 9Cr-1Mo steel.

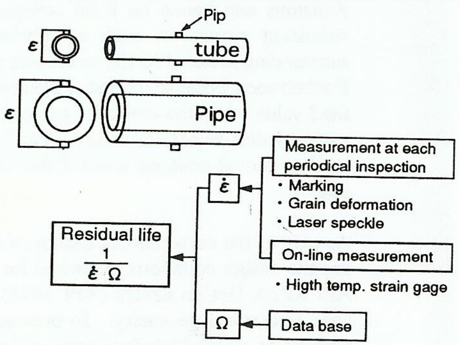


Fig.15 Evaluation procedure of residual life using Omega method.