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Modelling of Creep Property of Base Material for Life Assessment of Mod.9Cr-1Mo Steel Welded Joint

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***Abstract* - In the Mod.9Cr-1Mo steel pipe used for steam piping of a thermal power plant, Type IV damage originating from the fine grained heat affected zone has been concerned. Although it is necessary to evaluate the remaining life evaluation of the piping based on the simulated results of stress and strain distributions acting on piping system, the appropriate creep strain characteristics of each part should be given to the welded joints (base metal, heat affected zone and weld metal) for the high precision analysis model. Therefore, in this paper, first, the Creep strain equation of the base material part is formulated from creep data of NIMS (National Institute for Materials Science) creep tests and used material collected from steam piping used for about 120,000 hours in actual equipment, and the effectiveness of the model is verified.**

Index Terms - Mod.9Cr-1Mo steel, Used material, Creep life equation, Creep strain equation

I. INTRODUCTION

In a high chromium steel pipe (Mod.9Cr-1Mo steel) used for the steam piping thermal power plants under the ultra-supercritical environment with steam pressure of 24.1MPa or more and steam temperature of 593°C or more, it is confirmed that ,by creep deformation, voids are generated in the fine grained heat affected zone (HAZ) and the voids lead to the fracture called by Type IV damage[1]-[3]. The creep damage for the welded joints of the current high chromium steel is evaluated to be too safe based on the creep life equation[4] approximated from the collected creep rupture test data. However, since the test data have large variation and include only the results up to about 50,000 hours, which is shorter than the operating period of the actual equipment, it has been confirmed that the difference between the evaluation by the creep life equation and the damage condition of the actual equipment piping is large[5]. In addition, although the void observation by the replica method is also carried out over the outer surface of the welded joint, in the case of high chromium steel, a creep crack often progresses from within the wall. So, there is a problem that it is not possible to evaluate the seriously damaged point in the material[6].

Therefore, it is necessary to apply an analysis method like FEM based on creep analysis for evaluation of Type IV damage, which can obtain the stress and strain distributions[7]. Type IV damage is caused by the difference in creep strain characteristics among the base metal, the weld metal, the HAZ of the welded joint. Therefore, it is considerably important to give proper creep strain characteristics of each part to the welded joint as a FEM analysis modelling. However, these creep strain characteristics of the welded joints used for the piping equipment have variations due to chemical components of the pipe material, etc. for each plant. In addition, since the weld metal and HAZ are narrow regions, there are problems such as difficulty in collecting specimens required for acquiring creep strain characteristics. In the first research, the creep strain equation of the base material was formulated for the Mod.9Cr-1Mo steel.

II. CREEP DATA

The Creep strain equation of the Mod.9Cr-1Mo steel was constructed from the creep life equation and the minimum creep strain rate equation. The creep data of National Institute for Materials Science (NIMS) was used to construct each equation. The creep data of the used base material sampled from the piping of the actual equipment was used to verify the validity of each equation.

A. NIMS creep data

NIMS creep data used 112 data of test temperature 550-700 °C, test stress 30-240MPa for 5 heat patterns (MgA, MgB, MgC, MgD, MGQ) of plate material and pipe material of Mod.9Cr-1Mo steel (Gr. 91 steel)[8].

B. Creep data of base material of test material

1) Test material and test piece: The test material was sampled from a high temperature reheat steam pipe straight welded joint made of Mod.9Cr-1Mo steel used for about 120,000 hours in an ultra-supercritical pressure thermal power plant with a rated output of 700,000 kW. TABLE Ⅰ shows the specifications and steam conditions of the high temperature reheat steam pipe, and TABLE Ⅱ shows the chemical composition of the base material of the test material and the heat treatment conditions. The chemical composition and heat treatment conditions of the test material satisfied the range of the standard[9]. Fig.1 shows sampling positions and dimensions of the test pieces. The test pieces were collected from the center of the thickness of the test material with a diameter of 6 mm and a length of 30 mm between marks.

2) Creep test: Creep test conditions and rupture times are shown in TABLE III. In the creep test, a single type creep tester with a capacity of 29.4 kN was used, and five test conditions based on JIS (Japanese Industrial Standards) Z 2271-2010. It was carried out in the atmosphere.

III. Modelling of Creep Life Equation

Fig. 2 shows the relationship between the hardness before test and the rupture time of virgin material data of NIMS and used material datum at a temperature of 650°C and a stress of 80MPa. The hardness of the virgin material in each heat was 209 to 226 HV, and the rupture time was 1043.0 h to 5304.9 h, which were very different. Since the used material was used for a long time in the actual equipment, it softened compared with the virgin material and the rupture time was shorter. It is thought that there is a linear relationship between before test hardness and rupture time of virgin and used materials.

Fig.3 shows the relationship between stress and rupture time of virgin and used materials. Under the same conditions of stress and temperature, the rupture time for each heat pattern had a variation of about one digit. Fig. 4 shows the relationship between the stress normalized by hardness(σ/HV) and rupture time of virgin and used materials. Since the relationship between the hardness before the test and the rupture time was recognized, it is considered that the rupture time can be organized by the stress normalized by hardness before the test (σ/HV) to suppress the variation of the rupture time for each heat pattern. An equation of creep life evaluation was constructed from the relationship between σ/HV and the rupture time. The creep life equation which applied σ/HV instead of stress σ for the conventional method is shown in Eq. (1) and Fig.4 shows the estimated value in Eq. (1).

$$t_r = 10^{\{LMP/T_{abs} - C\}} = 10^{\left\{ \left\{ \begin{matrix} 26928.8 - 10018.5\log(\sigma/HV) \\ -5193.6\log(\sigma/HV)^2 - \\ 666.9\log(\sigma/HV)^3 \end{matrix} \right\} / T_{abs} - 29.51 \right\}} \quad (1)$$

Where t_r is the rupture time, *LMP* is Larson-Miller Parameter, T_{abs} is an absolute temperature, C is a constant, σ is a stress, and HV is a hardness before test.

The conventional creep life equation is based on the time-temperature parameter (TTP) method, and formulates a typical TTP, Larson-Miller Parameter (*LMP*), as a polynomial function of stress. Therefore, it has a tendency to return in the low stress region, and it is worried to evaluate the life to be excessively short.

Therefore, in order to further improve the tendency to return on the low stress side, improvement of the creep life equation was tried. Since the sharp decrease of creep strength was observed only in the long-term region, the creep life equation was divided into the long-term region equation and the short-term region equation.

The relationship between σ/HV and LMP/T_{abs} is shown in Fig.5. The measured values can be estimated high accurately by a linear equation for short-term region data in LMP/T_{abs} and σ/HV relation shown in Eq. (2).

TABLE I Piping Specification and Steam Condition of High Temperature Reheat Pipe

Piping Specification	Material	KA-SCMV28 NT SR
	Outer diameter	711.2mm
	Thickness	39mm
Steam condition	Pressure	4.52MPa
	Temperature	596℃
Usage time		about 120000hours

TABLE II Chemical Composition and Heat Treatment Condition of Base Metal

	Chemical composition (wt%)							
	C	Si	Mn	P	S	Ni	V	Nb
Test material	0.09	0.35	0.44	0.006	0.001	0.14	0.2	0.08
Specification	0.08〜0.12	0.20〜0.50	0.30〜0.60	≦0.020	≦0.010	≦0.40	0.18〜0.25	0.06〜0.10
	Chemical composition (wt%)				Heat treatment condition			
	Cr	Mo	N	Al	Normalizing		Tempering	
Test material	8.44	0.98	0.047	0.01	1050°C×30min		780°C×30min	
Specification	8.00〜9.50	0.85〜1.05	0.030〜0.070	≦0.04	1040°C〜1095°C		≧730°C	

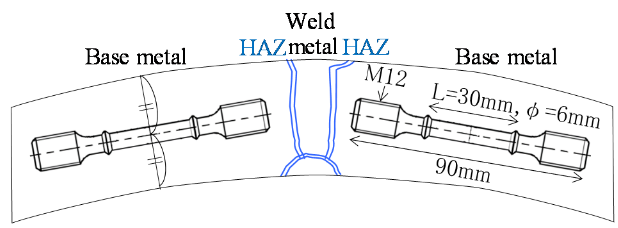


Fig.1 Position of specimen cut from welded joint and size of specimen

TABLE III Creep Test Condition of Used Material

Temperature(°C)	Stress(MPa)	Rupture time t_r (h)
600	160	60.0
	140	244.0
650	100	184.2
	80	975.1
	70	1725.1

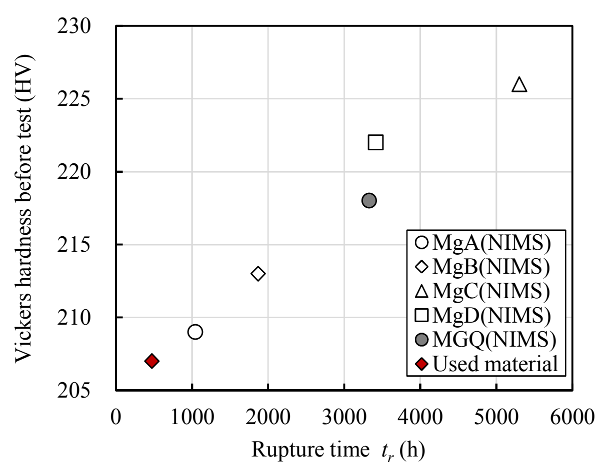


Fig.2 Relationship between vickers hardness before test and rupture time at 650°C and 80MPa conditions

$$\sigma/HV = (0.000268T_{abs} - 0.370)\,LMP/T_{abs} + (-0.0120T_{abs} + 14.3) \quad (2)$$

Usually, LMP is expressed as a polynomial function of stress, but Eq. (2) expresses LMP as a normalized stress-temperature function. The creep life equation in the short-term region constructed from the Eq. (2) is shown in the Eq. (3).

$$t_r = \min\left[\overbrace{10^{(-0.0316T_{abs}+35.4)+(-0.0159T_{abs}+6.84)\sigma/HV}}^{\text{Short-term region equation}},\ \underbrace{0.00743(\sigma/HV)^{-1}\exp(13117.9/T_{abs})}_{\text{Long-term region equation}}\right] \quad (3)$$

In order to avoid the tendency to return in the low stress region, the creep life equation for the short-term region was constructed as a linear equation of σ/HV.

On the other hand, in the long-term region equation, it was constructed from the Arrhenius-type temperature-dependent equation shown in Eq. (4).

$$t_r = A(\sigma/HV)^{-n}\exp(Q/RT_{abs}) \quad (4)$$

Where A is a constant, n is a stress index, Q is an activation energy of creep, and R is a gas constant. The long-term region is considered as the diffusion creep region and n = 1. Fig. 6 shows the comparison between the measured values and the estimated values based on the long-term region equation in Eq. (3) in the relationship between σ/HV and the rupture time. The estimated values were able to estimate the decrease of creep strength in the long-term region accurately. The creep life equation (Eq. (3)) was constructed as the minimum value of the long and short-term region equations for the rupture time. Fig.7 shows the comparison between the measured values and the estimated values in the relationship between σ/HV and the rupture time. The estimated rupture time tended to be overestimated in the 600 °C data of used materials, but was able to be expressed almost accurately with no tendency to return in the low stress region.

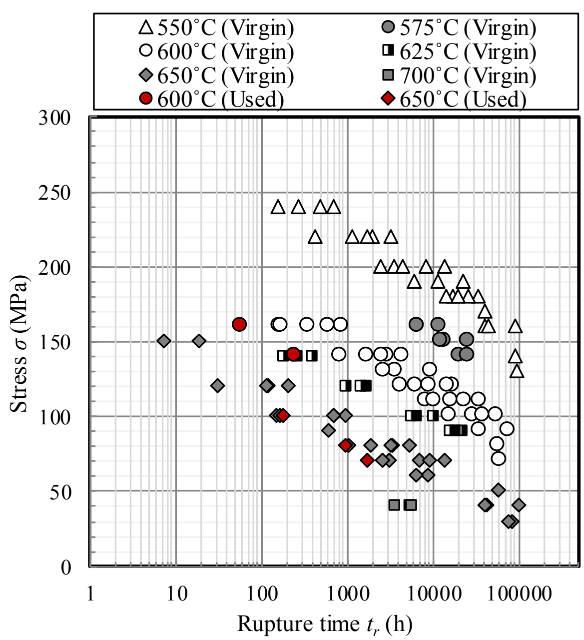


Fig.3 Relationship between stress and rupture time

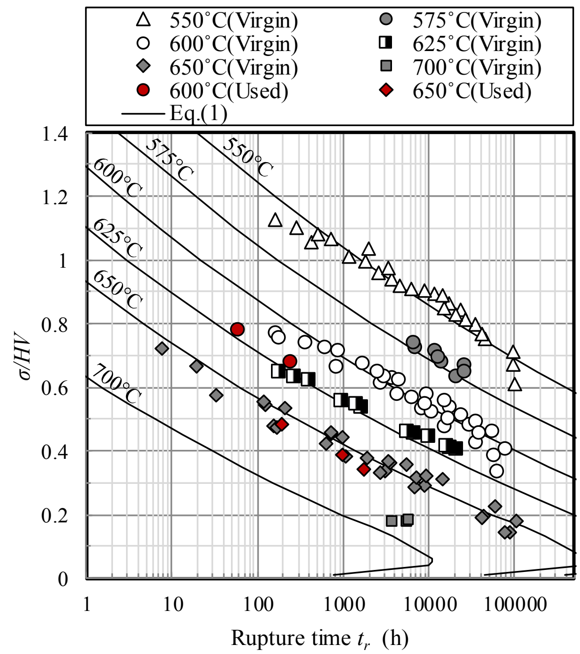


Fig.4 Relationship between σ/HV and rupture time before creep life equation correction

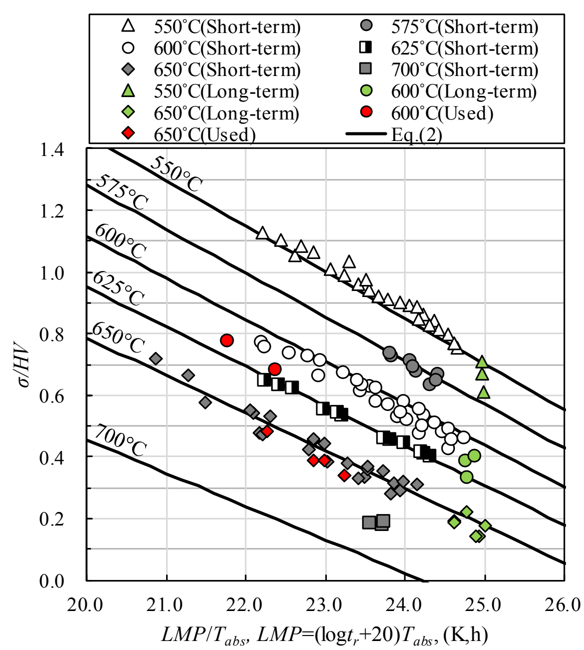


Fig.5 Relationship between σ/HV and LMP/T_{abs}

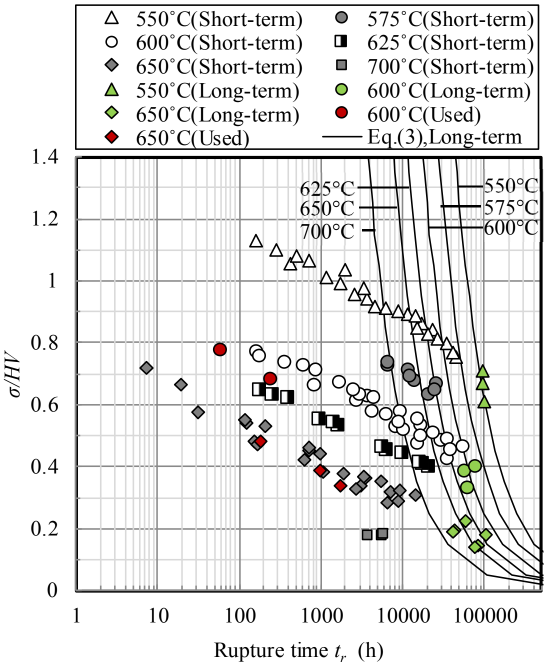


Fig.6 Relationship between *σ / HV* and rupture time after correction of creep life equation for long-term region.

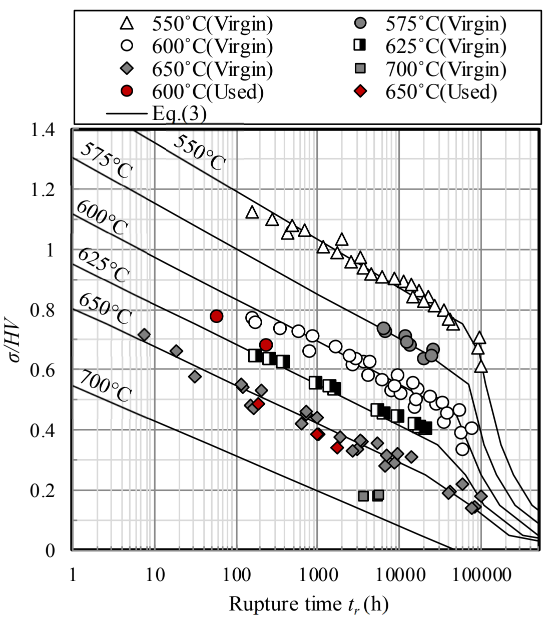


Fig.7 Relationship between *σ/HV* and rupture time after creep life equation correction

IV. Modelling of Minimum Creep Strain Rate Equation

Fig. 8 shows the relationship between the minimum creep strain rate and the rupture time, and the figure shows the estimated value of Eq. (5) called by Monkman-Grant law, and it has been confirmed that this relationship holds for many materials.

$$\dot{\varepsilon}_m = 0.121 t_r^{-1.17} \qquad (5)$$

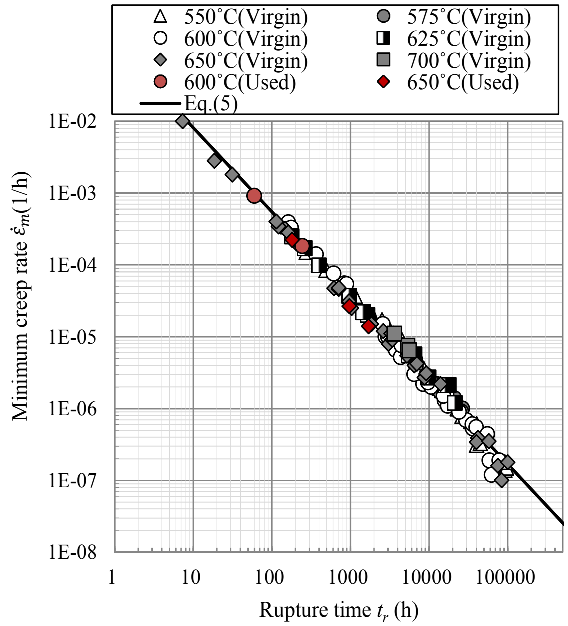


Fig.8 Relationship between minimum creep strain rate and rupture time

Eq. (5) was able to estimate the measured values with high accuracy, and confirmed that the Monkman-Grant law can applies for virgin and used Mod.9Cr-1Mo steels together.

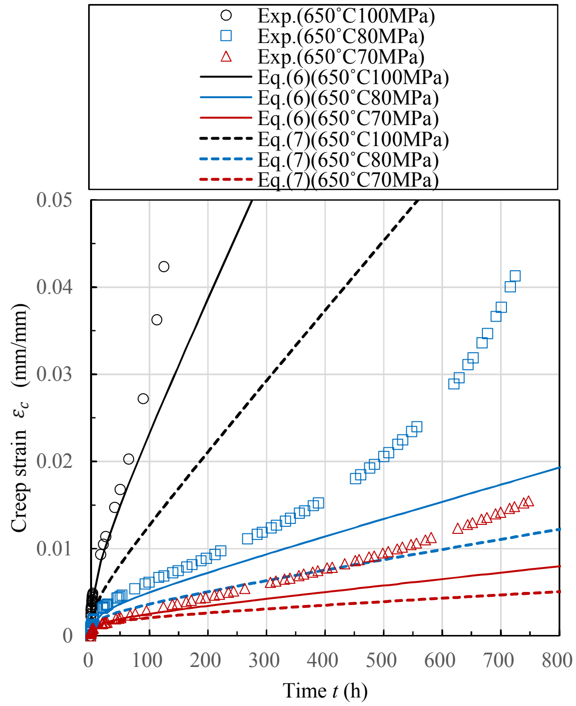
V. Modelling of Creep Strain Equation

Eq. (6) shows the Creep strain equation for primary and secondary creep, which was constructed referring to the Creep strain equation of Takahashi[10]. When the creep rupture occurs at the HAZ region of the welded joint test piece, the creep strain in the base material region seems to be the early stage of the third creep deformation. Therefore, in this study for the purpose of FEM analysis of welded joints, it is considered that the base metal is sufficient to predict by the secondary creep deformation.

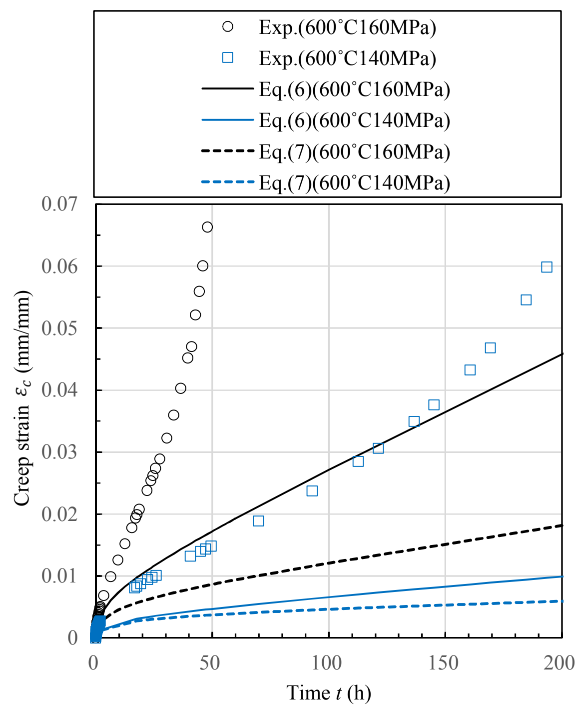
Fig. 9 shows the comparison between the measured and estimated values of creep strain. The creep strain estimated value tended to be underestimated in the 600°C data of the used material, but was roughly expressed with high accuracy in the 650°C data of the used material. Also, the broken line in the figure shows the estimated value of creep strain characteristics of Takahashi excluding third-order creep (Eq. (7)). The estimated value by Eq. (6) was considered to express the measured value more accurately than Takahashi's equation (Eq. (7)).

$$\varepsilon_c = 74.1/\exp(7.92 \times 10^{-3} T_{abs})\, t_r^{-0.595} \times \ln(2.95 t_r^{-0.0392} t + 1) + \dot{\varepsilon}_m t \qquad (6)$$

$$\varepsilon_c = 72.55/\exp(9.9 \times 10^{-3} T_{abs})\, t_r^{-0.356} \times \ln(2.95 t_r^{-0.041} t + 1) + \dot{\varepsilon}_m t \qquad (7)$$



(a) Used material at 600°C condition



(b) Used material at 650°C condition

Fig.9 Comparison of measured and estimated creep strain

VI. Conclusion

For the Mod.9Cr-1Mo steel, since the result of rupture time was organized by the stress normalized by the initial hardness before test (σ/HV), it was possible to suppress the variation of rupture time for each heat pattern. In the LMP/T_{abs} - σ/HV relationship in the short-term region, the measured values can be accurately estimated by the linear equation. From this relationship, the short-term region equation of creep life equation was constructed. The long-term region equation is an Arrhenius-type temperature-dependent equation. The constructed creep life equation has no tendency to return in the low stress region, and the evaluation accuracy is improved by organizing on the hardness. Although it was confirmed that this creep life equation tends to overestimate the data for used material 600 °C, it was considered that it can be estimated with considerably high accuracy.

The Creep strain equation up to the secondary creep depending on hardness was constructed from the constructed creep life equation etc. The creep strain estimated value tended to be underestimated for the used material 600 °C data, however it was considered that the used material 650 °C data was estimated with high accuracy. In the future, in addition to the creep strain equation of the Mod.9Cr-1Mo steel, the creep strain equation of weld metal and HAZ will be constructed, and the remaining life evaluation method of the welded joint will be completed.

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