Chapter

The Quantitative Estimation of Mechanical Performance on the Creep Strength and Prediction of Creep Fracture Life for Creep Ductile Materials Based on *QL** Parameter

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Abstract

Previously, we have proposed creep deformation law estimated by non-dimensional time representation to predict creep fracture and remnant life. Furthermore, using steady state creep rate coupled with crack growth rate law based on Q^* parameter, QL^* parameter was derived and it was found to enable us to discriminate creep ductility and predict creep fracture life. In this study, a quantitative estimation and a prediction methods of mechanical performance on creep strength (MPCS) and creep fracture life of the creep ductile materials including a weld joint notched specimen was noticed and the following studies were conducted. 1) The similarity law of creep deformation, 2) QL^*map, which discriminates creep ductility and predicts creep fracture life, 3) Derivation method of mechanical indicators, "Converted stress", and ΔQL^*, which quantify MPCS, 4) Example of the quantitative estimation by these parameters using P91 steel and its weld joint notched specimens. From these results, the concept of the converted stress and the ΔQL^*were found to enable us to conduct quantitative estimation of MPCS and prediction of creep fracture life, with the short experimental period, the small number of specimens, the reasonable accuracy and an economic efficiency, which is an engineering significance.

Keywords: QL^*, MPCS, converted stress, creep ductility, weld joint, creep fracture life, ΔQL^*

1. Introduction

Concerning the estimation of mechanical performance on creep and creep-fatigue interaction, the law on the relationship between applied stress and fracture life [1], the

Larson-Miller parameter [2], the Manson-Coffin law [3, 4] and the Ω method [5] were proposed for a smooth specimen. Furthermore, from the point of the application to actual engineering structure, the prediction of the crack growth life originated from a site of stress concentration is important and the establishment of the law of creep crack growth rate to predict creep crack growth life has been conducted [6, 7]. Especially, the establishment of the quantitative estimation method on the mechanical performance for a weld joint specimen under creep condition is important, because the effect of the morphology of heat affected zone (HAZ) line and the difference of material structure, between the weld metal, HAZ and the base metal, on the creep fracture life are significant factors to predict the creep fracture life [8].

Furthermore, from the point of actual application under recent social demand, such as the short experimental period and economical situation, it is necessary to establish the predicting method of creep fracture life by using small number of specimens and by conducting the short life creep test.

In this study, under these social demands mentioned above, by using a notched specimen of creep ductile material, the methods of estimating the quantitative mechanical performance on creep strength (MPCS) and of predicting creep fracture life of the weld joint by using small number of specimens and by conducting the short life creep test were proposed.

2. Theoretical foundation and background

2.1 Similarity law of creep deformation

For creep ductile materials, the time sequential characteristic of creep deformation plotted against non-dimensional time controlled by each fracture life, t_f was found to be independent of applied stress and temperature, that is, similarity law of creep deformation [9]. This behavior was illustrated as shown in **Figure 1a** and **b**. For such case, fracture life is possible to be predicted by the value of *RNOD* at the current

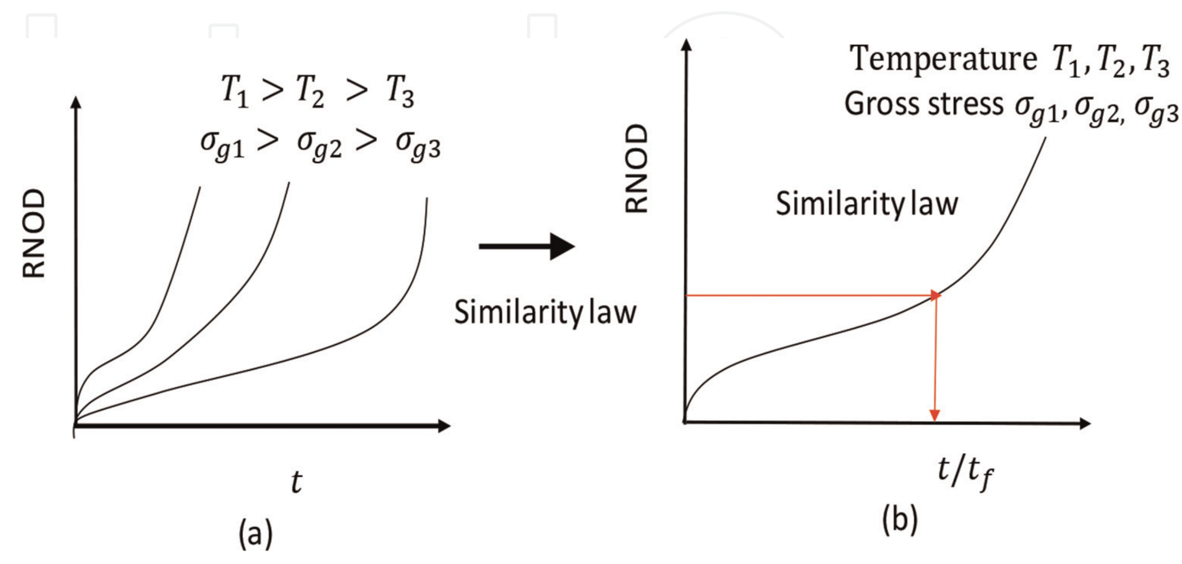

Figure 1.
Similarity law of creep deformation for a notched specimen. (a) The relationship between RNOD and loading time, (b) The relationship between RNOD and non-dimensional loading time controlled by each creep fracture life [9].

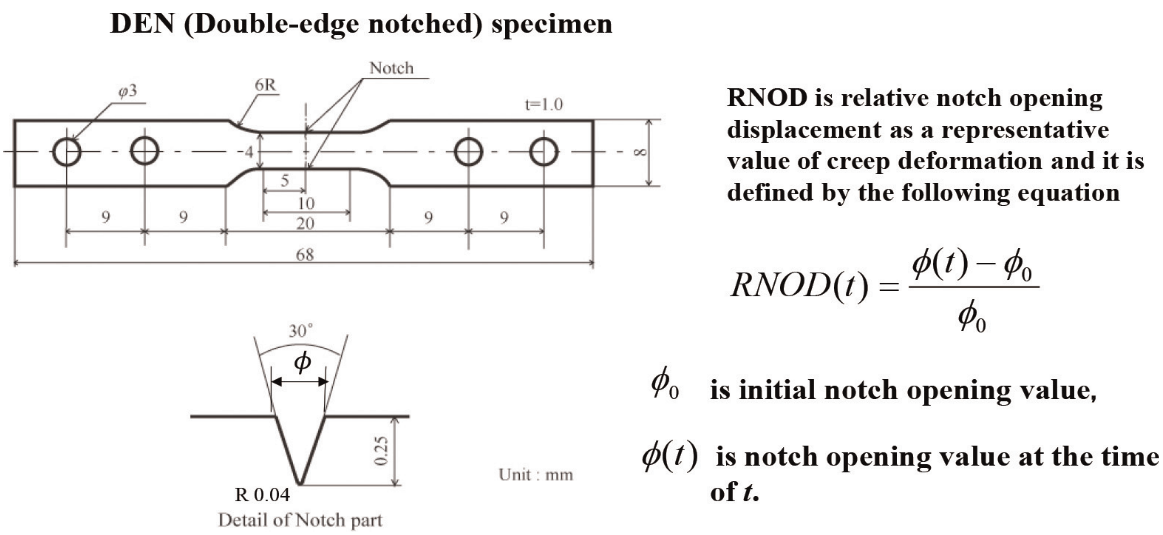

Figure 2.
Definition of relative notch opening displacement (RNOD) [10].

loading time, t as shown in **Figure 1b**. Where, as a measure of deformation for a notched specimen, the concept of the Relative Notch Opening Displacement (RNOD, a representative value of deformation of a DEN specimen) [10] given by Eq. (1) was used.

$$RNOD(t) = \frac{\phi(t) - \phi_0}{\phi_0} \tag{1}$$

where $\phi(t)$ is the notch opening value at the time of t and ϕ_0 is the initial notch opening value as shown in **Figure 2**.

2.2 Evaluation method of creep ductility (QL^* parameter)

The creep crack growth rate (CCGR) is written by Q^* parameter as shown in the Eq. (2) and (3) [6, 7].

$$\frac{da}{dt} = A^* \, exp\,(Q^*) = A^* \sigma_g^{m_g} \, exp\left(-\frac{\Delta H_g}{RT}\right) \tag{2}$$

$$Q^* = -\frac{\Delta H_g - m_g \, ln\, \sigma_g}{RT} \tag{3}$$

By integrating Eq. (2) and (3), the life of creep crack growth is written by Eqns. (4) and (5),

$$t_f = \int_0^{t_f} \frac{da}{A^* \sigma_g^{m_g} \, exp\left(-\frac{\Delta H_g}{RT}\right)} = \frac{a_f - a_i}{A^* \sigma_g^{m_g} \, exp\left(-\frac{\Delta H_g}{RT}\right)} = \frac{C}{A^* \sigma_g^{m_g} \, exp\left(-\frac{\Delta H_g}{RT}\right)} \tag{4}$$

$$\frac{1}{t_f} = A_g \sigma_g^{m_g} \, exp\left(-\frac{\Delta H_g}{RT}\right) \tag{5}$$

where t_f is the life of crack growth and $A_g = \frac{A^*}{C}$.

The steady state creep strain rate is given by the Eq. (6).

$$\dot{\varepsilon}_s = A_c \sigma_g^{m_c} exp\left(-\frac{\Delta H_c}{RT}\right) \tag{6}$$

Dividing Eq. (6) by Eq. (5), QL^* parameter is given by Eq. (7) [11, 12].

$$QL^* = \dot{\varepsilon}_s{}^{\alpha} \bullet t_f = M\sigma_g^m exp\left(-\frac{\Delta H}{RT}\right) \tag{7}$$

Where A^*, A_g and A_c are constants. σ_g is gross stress (MPa), m_g and m_c are exponent of gross stress and ΔH_g, ΔH_c is activation energy of crack growth and creep strain (J/mol), respectively. R is gas constant (J/K · mol), T is absolute temperature (K). $m = m_c - m_g$, $\Delta H = \Delta H_c - \Delta H_g$, M is creep ductility. α is constant and it nearly equal to unity.

For creep ductile materials, since steady state creep rate well correlates with the inverse value of fracture life, values of m and ΔH almost equals to zero, respectively, that is, $m_c = m_g$ and $\Delta H_c = \Delta H_g$. For such case, Eq. (7) is written by Eq. (8), that is, the relationship between logarithmic values of $\dot{\varepsilon}_s$ and t_f is independent of gross stress and temperature.

$$QL^* = \dot{\varepsilon}_s{}^{\alpha} \bullet t_f = M \tag{8}$$

Based on the QL^* concept, the relationship between logarithmic values of $\dot{\varepsilon}_s$ and t_f for various materials are obtained as shown in **Figure 3** [11], that is, the QL^* map. The data band for each material shows the creep ductility as the value of $QL^*(= M)$.

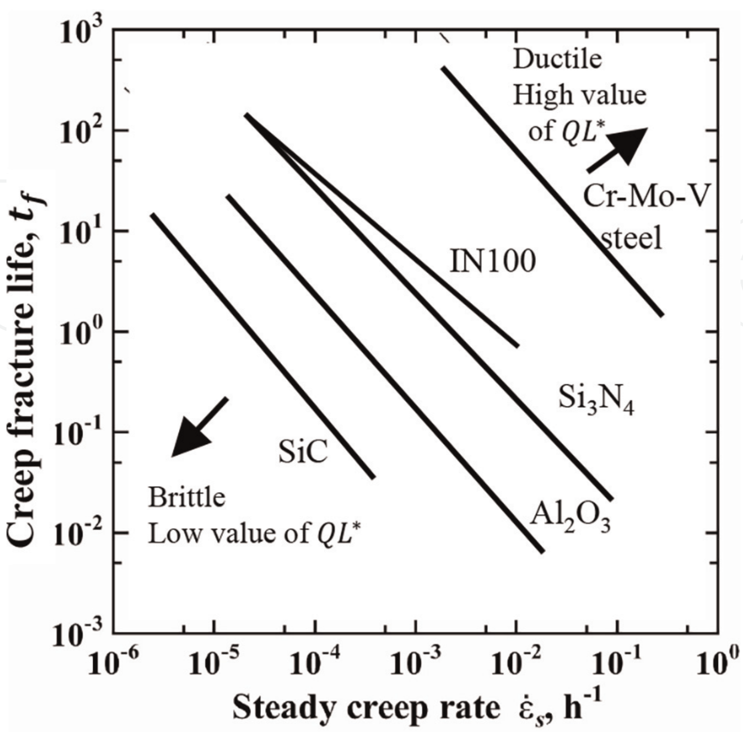

Figure 3.
QL^* map for creep ductile and brittle materials. The relationship between creep fracture life and steady state creep rate.

2.3 Derivation method of the converted stress and ΔQL^*

For the case of creep ductile materials such as Cr-Mo-V steel, the similarity law of creep deformation and Eq. (8) described in the Section 2.1 and 2.2 are valid [11, 12]. For such case, the concept of the converted stress is defined and valid to conduct a quantitative estimation of the MPCS and the prediction of creep fracture life.

This section shows the derivation method of the converted stress. When the same similarity law of creep deformation is valid both for A and B materials, the relationship between $ln\, t_f$ and $ln\, \dot{\varepsilon}_s$ in the QL^* map is unique as shown in **Figure 4** [12], where A material is a control material to make the QL^* line and B material is a target material to estimate MPCS.

The flow chart of the derivation method of the converted stress is shown in **Figure 5**.

When the similarity law of creep deformation is valid, Eq. (8) is unique both for A and B materials and it was written by Eq. (9),

$$t_f = M_1 \dot{\varepsilon}_s^{-\alpha}, \tag{9}$$

where M_1 is creep ductility for A and B materials.

Steady state creep rate for the A material is experimentally given by Eq. (10).

$$\dot{\varepsilon_{SA}} = K_A \sigma_A^{m_A} \tag{10}$$

Using Eqns. (9) and (10), t_{fA} is given by Eq. (11),

$$t_{fA} = M_1 {K_A}^{-\alpha} \sigma_A^{-\alpha m_A} \tag{11}$$

where t_{fA}, $\dot{\varepsilon_{SA}}$, K_A, σ_A and m_A is the creep fracture life, the steady state creep strain rate, the material constant, the applied stress and power coefficient value of σ_A, obtained by creep tests for the A material, respectively.

When the steady state creep rate, $\dot{\varepsilon_{SB}}$ for the B material is experimentally obtained by non-fracture test, substituting $\dot{\varepsilon_{SB}}$ in to Eq. (9), the predictive creep fracture life, t_{fB} for the B material is given by Eq. (12), because Eq. (9) is unique both for A and B materials.

$$t_{fB} = M_1 \dot{\varepsilon_{SB}}^{-\alpha} \tag{12}$$

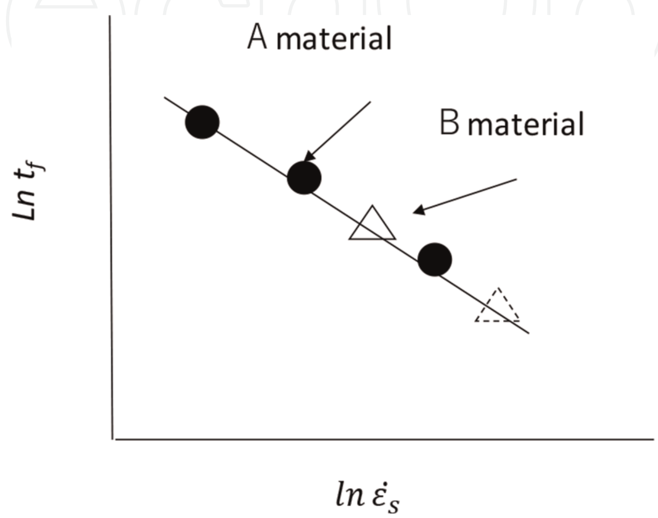

Figure 4.
QL line for A and B materials when the similarity law of creep deformation is valid both for A and B materials.*

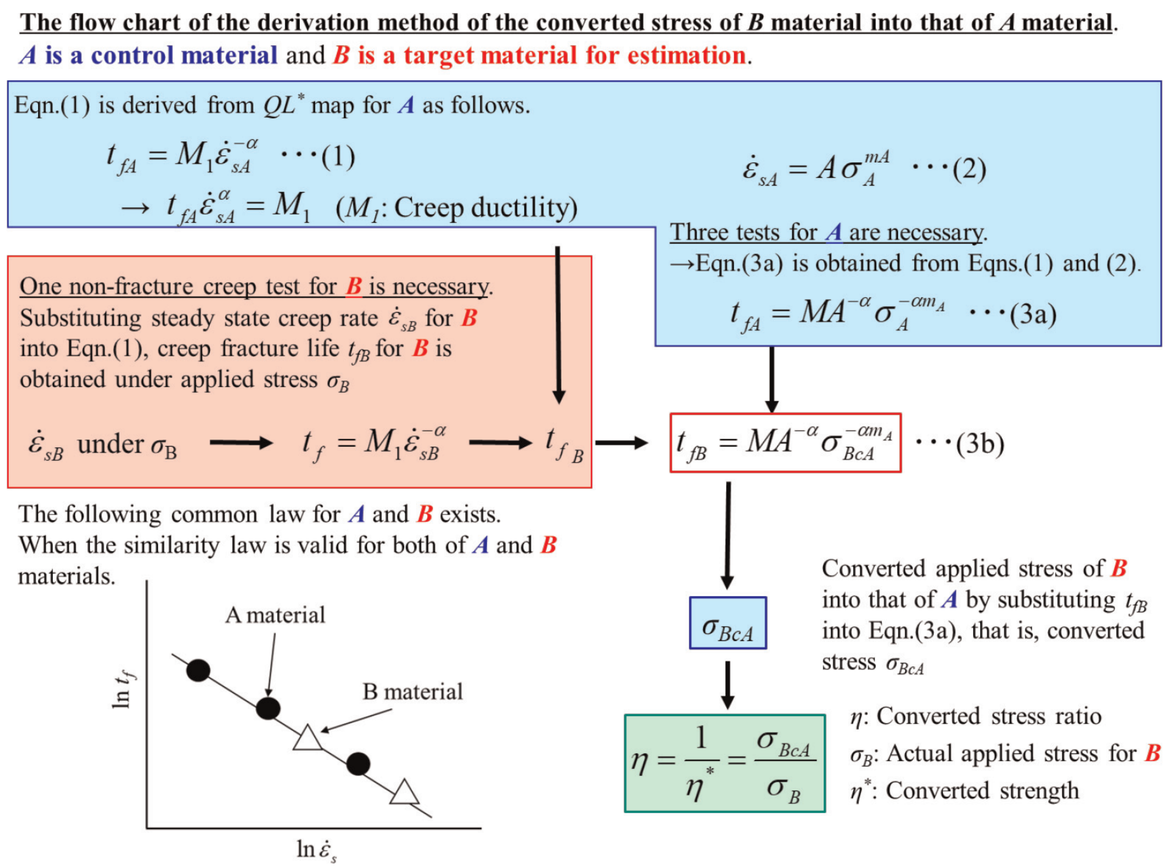

Figure 5.
Flow chart of derivation method of the converted stress.

Substituting t_{fB} given by Eq. (12) into t_{fA} in Eq. (11), the converted stress of the B material into that of the A material, σ_{BCA} is given by Eq. (13).

$$t_{fB} = M_1 A^{-\alpha} \sigma_{BCA}^{-\alpha m_A} \tag{13}$$

where σ_{BCA} is the converted stress of the B material into that of the A material.

The converted stress of the B material into that of the A material, σ_{BCA} means applied stress which causes the equivalent steady state creep rate, $\dot{\varepsilon_{SB}}$ for the A material given by Eq. (10).

Furthermore, the converted stress ratio, η is defined and it is written by Eq. (14).

$$\eta = \frac{1}{\eta^*} = \frac{\sigma_{BCA}}{\sigma_B} \tag{14}$$

where σ_B is actual applied stress for the B material, η^* is the converted strength, which is the inverse value of the converted stress ratio, η. η is a quantitative indicator of the MPCS.

For the case of $\eta > 1.0$, $\sigma_B < \sigma_{BCA}$ being valid, it means creep strength of the B material is lower than that of the A material.

For the case of $\eta < 1.0$, $\sigma_B > \sigma_{BCA}$ being valid, it means creep strength of the B material is higher than that of the A material. The detailed derivation method is shown in **Figure 5**.

In addition, the concept of ΔQL^* is useful to discriminate the difference of the creep ductility caused by different materials or different local stress multi-axiality

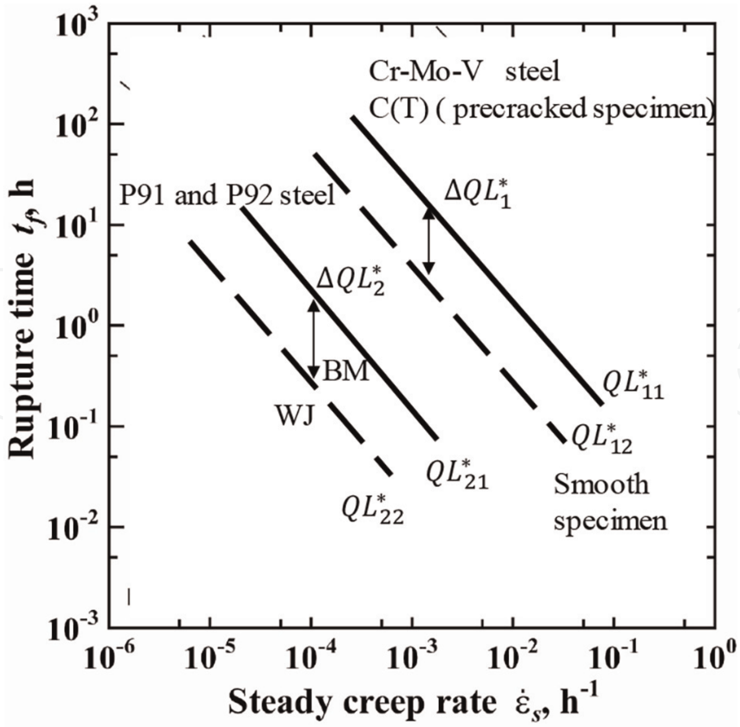

Figure 6.
The schematic illustration of the comparison of QL* *line between a notched specimen (C (T) specimen) and smooth specimen for Cr-Mo-v steel [12] and that between base metal and weld joint of C (T) specimen for P91 and P92 steels [14].*

characterized by $TF = \frac{3(\sigma_x+\sigma_y+\sigma_z)}{\sigma_{eq}} = \frac{3\sigma_P}{\sigma_{eq}}$ such as weld joint, that is, the structural brittleness [13]. σ_P is hydrostatic stress. σ_{eq} is equivalent stress.

Schematic illustration of experimental characteristics of ΔQL^* between a C (T) and a smooth specimens for Cr-Mo-V steel and a base metal and a weld joint of a notched specimen for P91 and P92 steels is shown in **Figure 6** [12, 14]. The difference in ΔQL^* between a C (T) and a smooth specimens is considered to be caused by the difference in compliance between a cracked specimen and a smooth specimen [12]. The difference in ΔQL^* between a base metal and a weld joint with a different weld metal will be caused by different local stress multi-axiality at the HAZ [8, 14]. For both cases, however, ΔQL^*, that is different creep ductility, exists, a parallel QL^* line appears [12, 14].

Using the concept of the converted stress and ΔQL^*, a quantitative estimation of MPCS and prediction of creep fracture can be conducted as shown in **Figures 5** and **6** mentioned in the Section 4.

3. The prediction of creep fracture life and the derivation of the converted stress to estimate the mechanical performance of creep strength of a double edge notched weld joint specimen for P91 steel based on the QL^* concept

3.1 Material and specimen

The material used for this study is P91 steel and matching weld metal of US-9Nb, which is a similar material as P91 steel. The chemical composition and mechanical properties are shown in **Tables 1** and **2**.

C	Si	Mn	P	S	Ni
0.08–0.12	0.2–0.5	0.3–0.6	<0.02	<0.01	<0.40
Cr	Mo	V	Nb	Al	N
8.0–9.5	0.85–1.05	0.18–0.25	0.06–0.10	<0.04	0.03–0.07

Table 1.
Chemical compositions of P91 steel (wt%).

Tensile stress (MPa)	0.2% proof stress (MPa)
590	410

Table 2.
Mechanical properties of P91 steel.

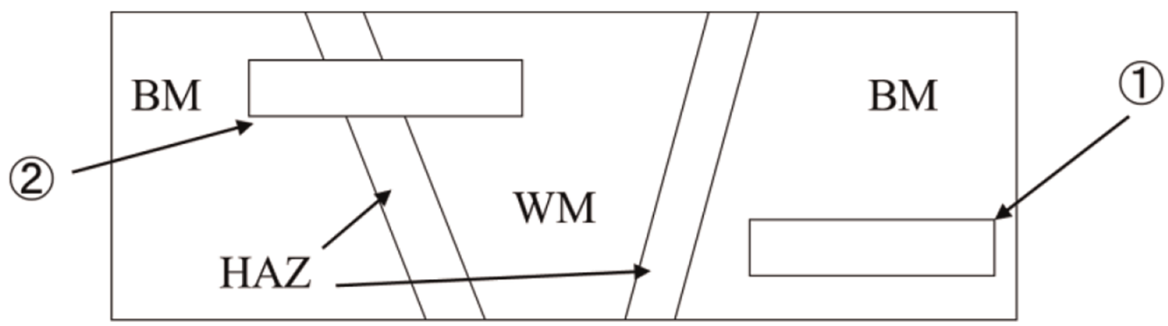

Figure 7.
Sampling site of specimen of base metal and weld joint. ① Base metal ② Weld joint.

The specimen used is a double-edge notched specimen (DEN) as shown in **Figure 2**. Sampling sites of specimen of base metal and weld joint are shown in **Figure 7**.

3.2 Experimental method

The machine system was designed and developed to enable automatic real-time observational experiments using a CCD microscope [15]. Now, CCD microscope was replaced to digital microscope manufactured by KEYENCE corporation. Using this apparatus, in situ observation of creep damage progression was conducted and the images of the damage region were quantified using a PC. The tests were conducted under high temperature vacuum conditions of 10^{-4} Pa. The creep damage region around the notch tip was found to be a dark region, composed of voids and micro-cracks originating along grain boundaries, as shown in previous results for SUS304 stainless steel [10, 15]. The dark region is defined as a creep damage region owing to the following reasons.

The specimens were heated using infrared rays (IR) under vacuum conditions, as shown in **Figure 8**. Creep damage is caused by micro-cracking along a grain boundary, which is composed of voids at the grain boundary [10, 15] that are considered to be caused by vacancy diffusion [16, 17]. In the damage region, a specimen surface becomes irregular due to micro-cracking along a grain boundary. In this region, diffused reflection of light by the lamp of IR was caused and it shows as the dark region.

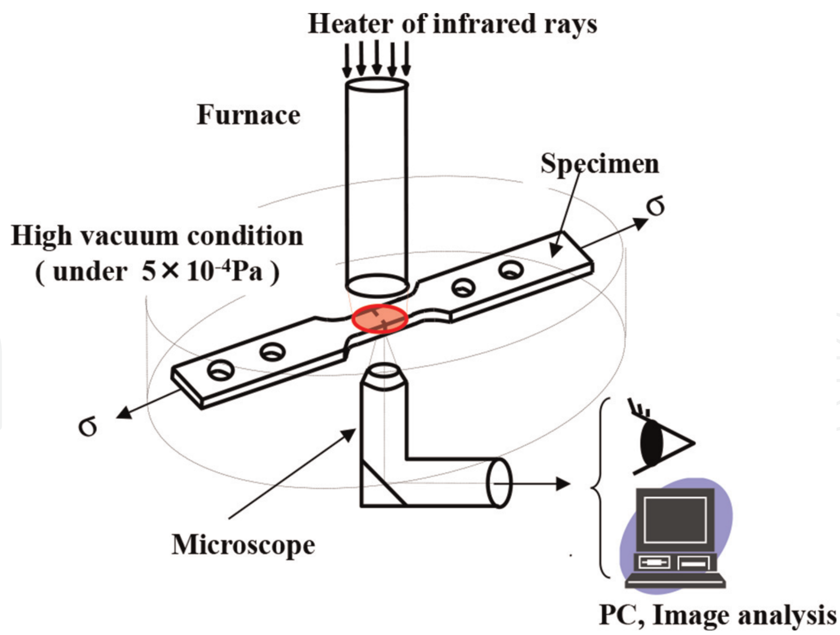

Figure 8.
Schematic illustration of in-situ observational creep-fatigue testing machine [15].

3.3 Experimental conditions and results

Previously, experimental results were published in Japanese [19], however, more detailed analyses are needed by more accurate analyses. In this section, updated results are written.

3.3.1 Similarity law of creep deformation

Experimental conditions, their results of steady state RNOD rate and creep fracture life are shown in **Table 3**. These results show that the fracture life of weld joint takes 3.5 ∼ 5% of that for the base metal.

	No.	Temp. (°C)	Stress (MPa)	Steady state RNOD rate (1/hr)	Creep fracture Life t_f, (hr)
Weld joint	W-1	650	135	5.65×10^{-2}	9.5
	W-2		113	9.00×10^{-3}	55.1
	W-3		113	2.00×10^{-2}	23.0 (predicted)
Base metal	B-1	650	200	1.13×10^{-1}	4.0 (predicted)
	B-2		135	1.62×10^{-3}	183.6
	B-3		113	1.44×10^{-4}	*1550.0

"Predicted" means that creep test was interrupted at the accelerated creep region and its final creep fracture was predicted from this point.
"" means that it almost covers total fracture life, however it is interrupt test.*

Table 3.
Experimental conditions, results of steady state RNOD rate and creep fracture life of DEN specimen (Base metal and weld joint for P91 steel).

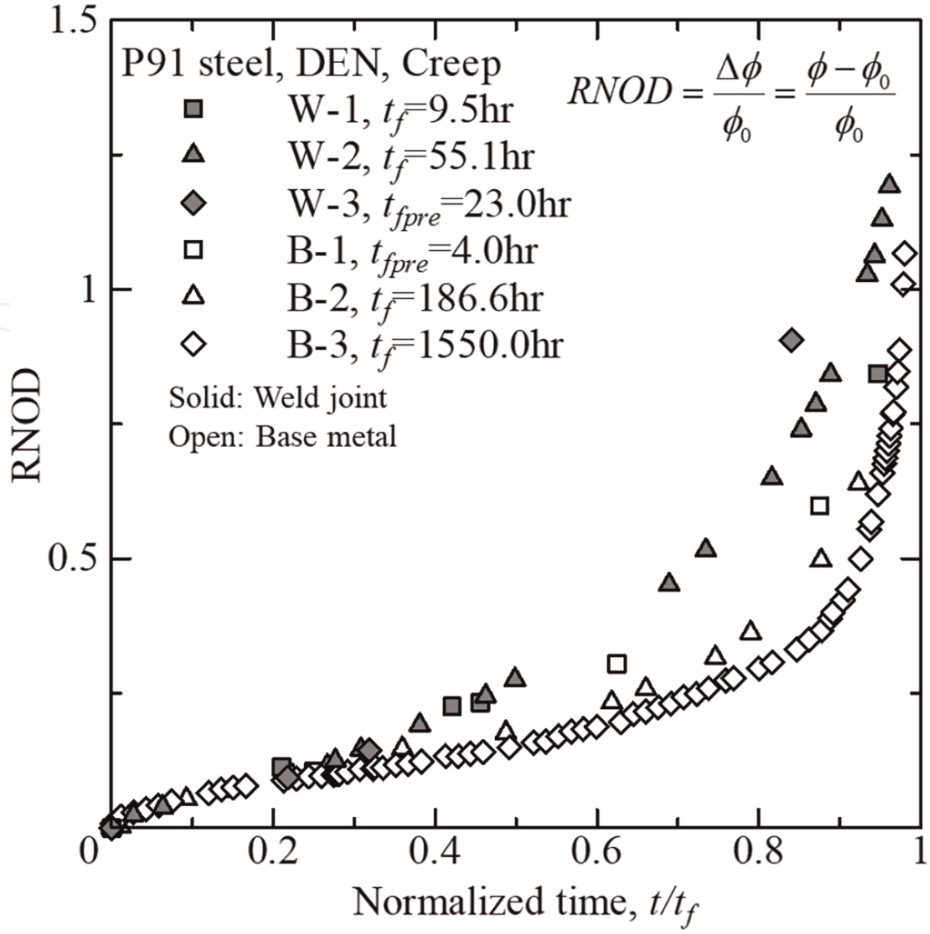

Figure 9.
Non-dimensional time sequential behavior of RNOD of the base metal and weld joint for P91 steel. t/t_f: non-dimensional creep fracture life of each specimen.

Non-dimensional time sequential characteristics of the RNOD curve (creep deformation) controlled by each fracture life are shown in **Figure 9**. For the base metal, the similarity law of RNOD curve caused, which is independent of applied stress. For the weld joint, the similarity law also caused for the case of $t/t_f < 0.5$.

3.3.2 Damage progression behavior of the notched specimen of the weld joint and the base metal

The time sequential behavior of damage progression around a notch tip of the weld joint specimen for P91 steel observed by the in situ observational testing machine under creep condition with a temperature of 650°C is shown in **Figure 10**. These results show that the creep damage preferentially originated at the HAZ of the base metal side, however this damage was not a dominant damage of final fracture. After that, another creep damage newly originated from both of the upper and the lower notch tips. When this damage area spread over the whole ligament from the upper notch tip to the lower notch tip, final fracture occurred, that is, creep fracture of a weld joint notched specimen is not creep crack growth dominant but it is creep damage dominant, which related to the similarity law of creep deformation as is mentioned in the Section 3.3.1.

The time sequential behavior of damage progression around a notch tip of the base metal observed by the in situ observational testing machine under creep condition with a temperature of 650°C for P91 steel is shown in **Figure 11**.

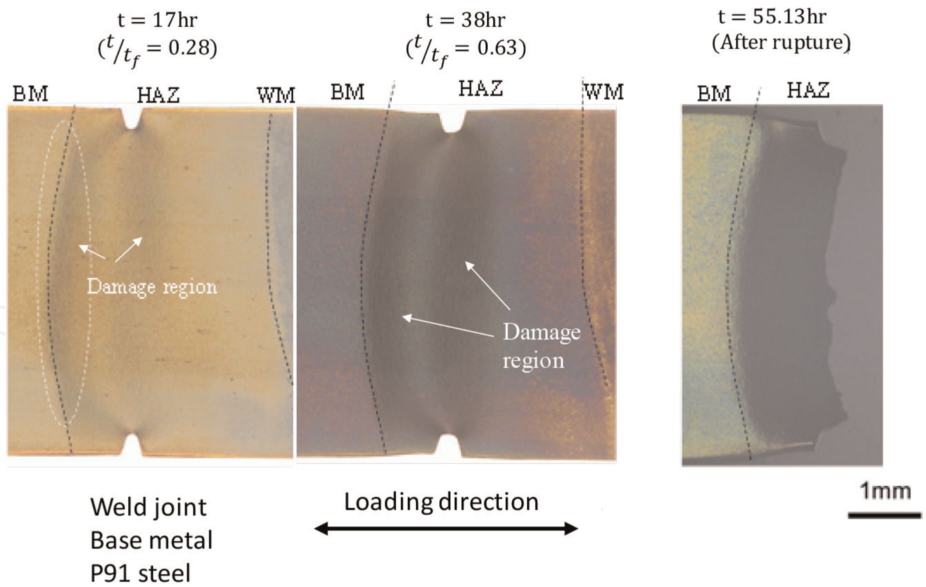

Figure 10.
The time sequential behavior of damage formation around a notch tip of the weld joint specimen under creep condition with a temperature of 650°C and 113 MPa for P91 steel.

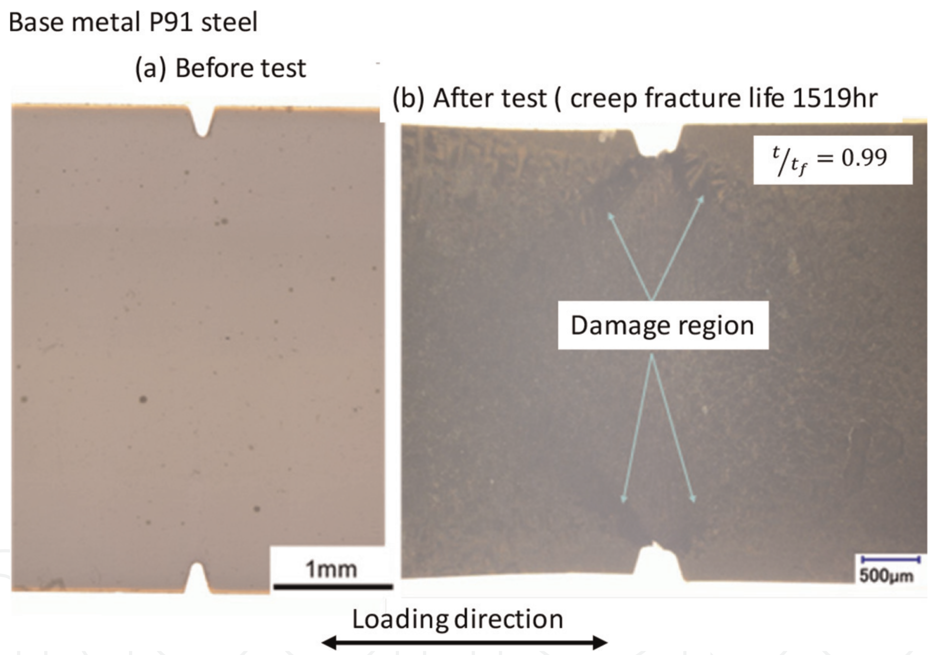

Figure 11.
The time sequential behavior of damage formation around a notch tip of the base metal under creep condition with a temperature of 650°C and 113 MPa for P91 steel.

For the base metal, creep damage originated from a notch tip in the direction of shearing stress. When the damage area spread over the specimen width, final fracture occurred. However, damage progression behavior is different from that of the weld joint, creep fracture mechanism is also creep damage dominant, which also related to the similarity law of creep deformation as is mentioned in the Section 3.3.1.

3.3.3 Experimental law of creep fracture life and creep strain rate

As shown in **Figure 12**, a unique linear logarithmic relationship between creep fracture life and steady state creep strain rate, that is, the unique QL^* relationship was

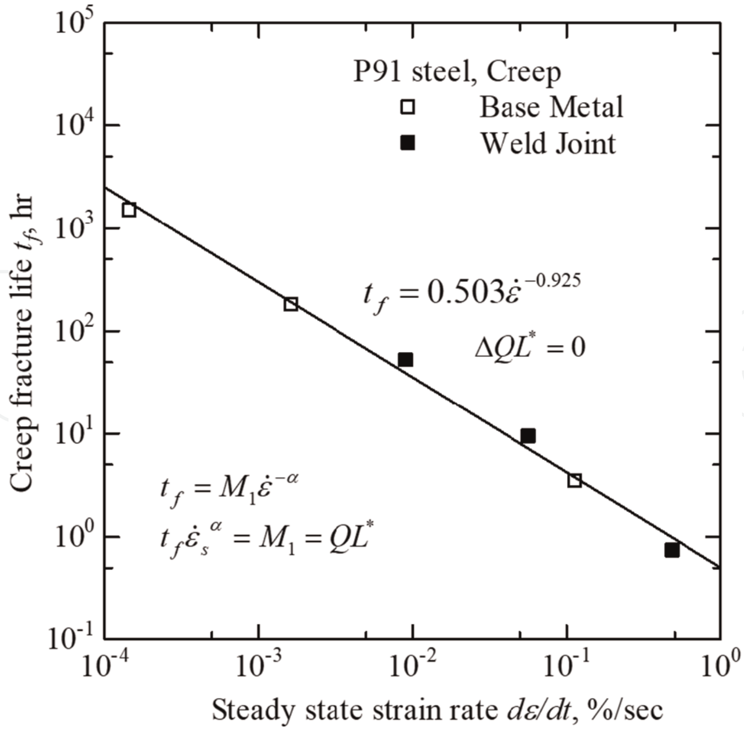

Figure 12.
The relationship between logarithmic value of t_f and $d\varepsilon/dt$.

found out both in base metal and weld joint, which means the weld joint is considered to have a similar property as that of base metal, that is, $\Delta QL^* = 0$.

As shown in **Figure 13**, the linear logarithmic relationship between the steady state creep strain rate and the applied stress was found out both for the base metal and the weld joint respectively.

From these experimental results, the following equations are obtained.

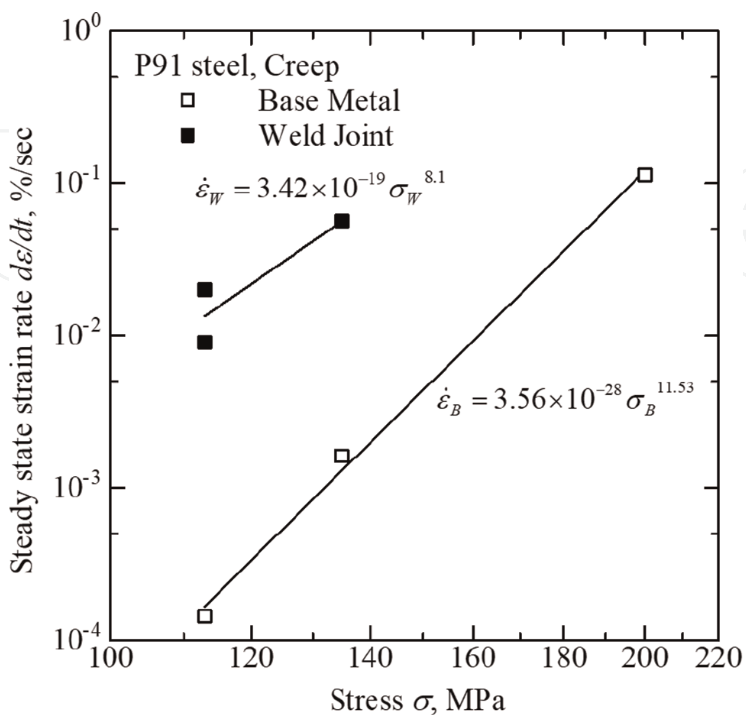

Figure 13.
The relationship between logarithmic value of $d\varepsilon/dt$ and applied stress, σ.

$$t_f = 0.503\dot{\varepsilon}^{-0.925} \tag{15}$$

$$\dot{\varepsilon}_B = 3.56 \times 10^{-28}{\sigma_B}^{11.53} \text{ (Base metal)}, \tag{16}$$

$$\dot{\varepsilon_W} = 3.42 \times 10^{-19}{\sigma_W}^{8.1} \text{ (Weld joint)}, \tag{17}$$

where t_f, $\dot{\varepsilon}_B$, σ_B, $\dot{\varepsilon_W}$ and σ_W is creep fracture life, steady state creep strain rate and applied stress for the base metal and weld metal respectively.

3.3.4 The derivation of the converted stress and the converted stress ratio

As shown in **Figure 12**, the QL^* relationship is written by Eq. (15) both of the base metal and the weld joint.

As shown in **Figure 13**, the linear logarithmic relationship between the steady state creep strain rate and the applied stress is given by Eq. (16) for the base metal.

Substituting Eq. (16) into Eq. (15), Eq. (18) is obtained for the base metal.

$$t_{fB} = 1.234 \times 10^{25}\sigma_B^{-10.67}, \tag{18}$$

where t_{fB} is the creep fracture life under applied stress, σ_B, for the base metal.

Using the experimental results of steady state creep strain rate, $\dot{\varepsilon}_W$ of the weld joint and substituting it into $\dot{\varepsilon}$ in Eq. (15), the fracture life, t_{fweld} of the weld joint specimen corresponding with $\dot{\varepsilon}_W$ is obtained.

Substituting t_{fweld} into t_{fB} in Eq. (18), the converted stress of the weld joint into that of the base metal, σ_{WCB}, with the same fracture life as t_{fweld} is obtained by Eq. (19).

$$\sigma_{WCB} = t_{fweld}^{-1/10.67} \times \left(1.234 \times 10^{25}\right)^{1/10.67} \tag{19}$$

The converted stress ratio, η, is defined by Eq. (20).

$$\eta = \frac{\sigma_{WCB}}{\sigma_W} \tag{20}$$

The accuracy of predictive creep fracture life of the weld joint derived from the QL^* line is about 71% ~ 76% accuracy to the actual life as shown in **Table 4**.

The value of the converted stress ratio of the weld joint into that of the base metal, $\eta = \sigma_{WCB}/\sigma_W$ is 1.39 and 1.41 for the case of 135 MPa and 113 MPa of σ_W respectively as shown in **Table 4**. These results mean that the creep strength of the weld joint is lower than that of base metal of 39% and 41%, respectively. The scattering of the converted stress ratio is 0.7%. On the other hand, the value of the ratio of creep fracture life of the weld joint to that of the base metal is 0.052 and 0.035 respectively. The scattering of the creep fracture ratio is 20%.

From these results, the converted stress ratio is more accurate indicator of estimating the MPCS than the fracture life ratio from the point of the data scattering.

For creep ductile materials, the prediction of the creep fracture life of the target materials and the quantitative comparative estimation of the MPCS of the target materials to the control material are found to be possible measuring the steady state creep rate of the target materials by the short time range experiments.

	Applied stress (MPa)	Creep fracture life (hr) of the base metal, $t_{f\mathrm{BM}}$ and the weld joint, $t_{f\mathrm{WJ}}$	Converted stress (MPa), σ_{WCB}	Converted stress ratio, $\eta\left(=\frac{\sigma_{WCB}}{\sigma_W}\right)$, σ_{WCB}: converted stress σ_W: actual applied stress for the weld joint η: converted stress ratio	Ratio of fracture life of weld joint to that of base metal, $\frac{t_{fWJ}}{t_{fBM}}$
Base metal	135	183.6	135	1.0	1.0
Weld joint		9.5 7.2 (predicted by QL^*)	187	1.39	0.052
Base metal	113	1519.3	113	1.0	1.0
Weld joint		55.13 39.3 (predicted by QL^*)	160	1.41	0.035

Table 4.
Converted stress and the ratio of converted stress to actual applied stress of the weld joint.

4. Discussions

4.1 Application of this theory to the case of C (T) specimens of the weld joint for P91 and P92 steels

The QL^* map of the base metal and weld joint for the ASME grade P92 steel and ASME grade P91 steel are shown in **Figure 14** [14]. Weld metal is 12Cr steel and 9Cr steel, respectively.

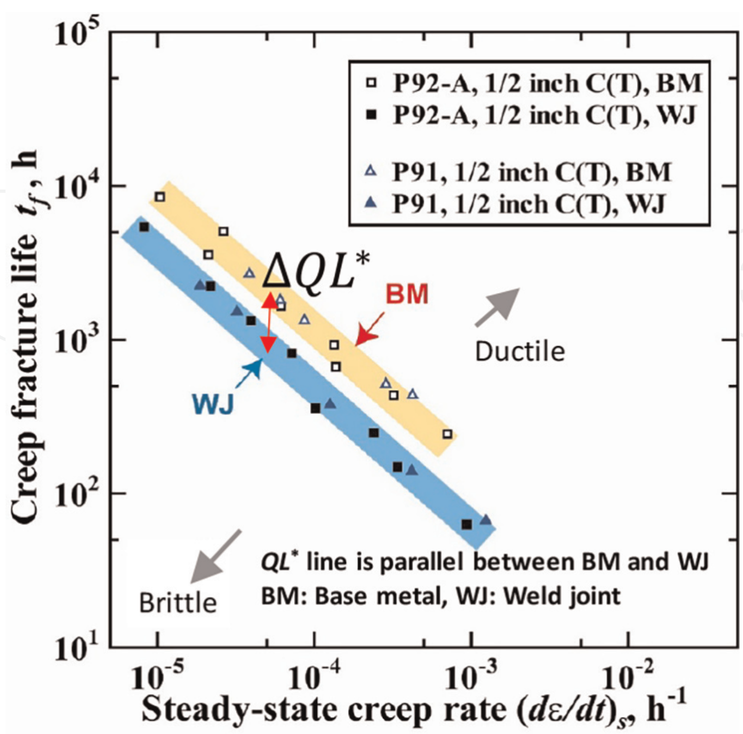

Figure 14.
*QL*map of the base metal and weld joint for the P92 and P91 steels [14].*

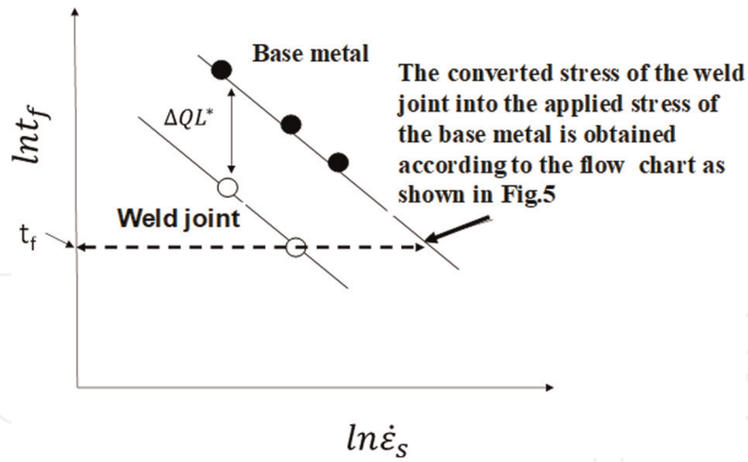

Figure 15.
The prediction and derivation methods of creep fracture life and the converted stress of the weld joint into that of the base metal.

These results showed that the QL^* line of the weld joint is parallel to and lower of ΔQL^* than that of the base metal. Therefore, one creep fracture test of the short range life is necessary to determine the value of ΔQL^*, after that, as shown in **Figure 15**, the converted stress of the weld joint in to the applied stress of base metal, σ_{WCB} and its ratio, η are feasible to obtain according to the flow chart given by **Figure 5**.

4.2 Application of this theory to the case of a smooth specimen and a notched specimen

The QL^* map of a double edge notched and a smooth specimen for Cr-Mo-V steel is shown in **Figure 16**.

These results showed that the QL^* line of the smooth specimen is parallel to and lower of ΔQL^* than that of the notched specimen [12]. Therefore, one creep fracture test of the short range life is necessary to determine the value of ΔQL^*, after that, as shown in **Figure 17**, the converted stress of the smooth specimen in to the applied stress of the notched specimen and its ratio, η are feasible to obtain according to the flow chart given by **Figure 5**.

5. Summary

The experimental law on the relationship between the steady state creep rate and creep fracture life given by Eq. (21) was well known as the Monkman –Grant law [18], however, Yokobori, et al. showed this law is only valid under limited case, and the data band is essentially different depending on the creep ductility as shown in **Figure 3** [11].

Furthermore, however the similar equation as Eq. (21) was found to be valid for creep ductile materials and it was correctly written by Eq. (8).

$$t_f \times \dot{\varepsilon}_s = Const. \tag{21}$$

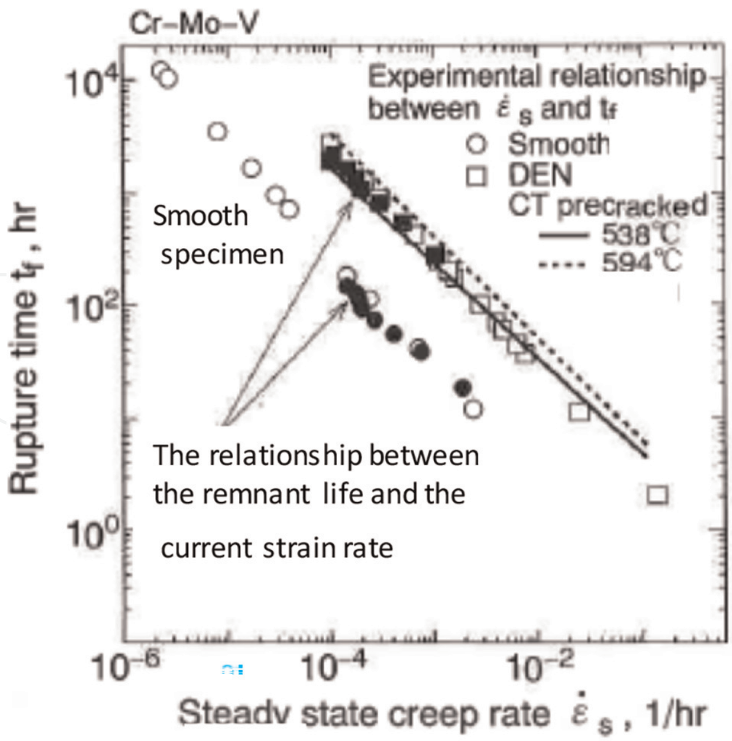

Figure 16.
*QL*map of a notched specimen and a smooth specimen for the Cr-Mo-V steel [12]. DEN: a double edge notched specimen of a plate specimen. CT: a C (T)specimen. Open mark: steady state creep rate. Solid mark: remnant life of creep fracture for the current creep rate. Experimental data of solid mark exist on the same QL* line and the QL* line of the notched specimen is parallel to that of smooth specimen.*

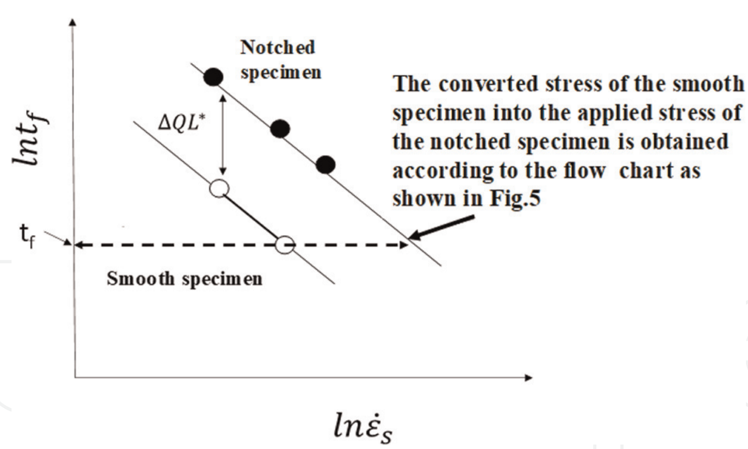

Figure 17.
The prediction method of creep fracture life and the converted stress of the applied stress of a smooth specimen into that of a notched specimen.

In this study, for creep ductile materials, QL^* line was found to be written by Eq. (8) and its parallel lines of a notched and a smooth specimen for the base metal and the weld joint.

On the basis of these results mentioned above, the prediction of the creep fracture life and the quantitative estimation of the MPCS were found to be possible using the QL^* map and the concept of converted stress, with the short experimental period, the small number of specimens, the reasonable accuracy and an economic efficiency. It is significant from engineering point.

The experimental data obtained by the commissioned research with Tohoku Electric Power Co.Inc. from April 2016 to March 2019 were used in the section of 3.3 in this proof [20].

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Conflict of interest

The author declares that there is no conflict of interest associated with this study.

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