Fatigue Life Evaluation of Welded Joints by a Strain-life Approach Using Hardness and Tensile Strength

Byeong-Choon Goo*, Seung-Yong Yang
Rolling Stock Division, Korea Railroad Research Institute,
360-1 Wolamdong, Uiwangsi, Kyunggido 437-050, Korea

To evaluate the fatigue lifetime of structures, it is necessary to identify the values of parameters through tests. From the viewpoint of time and cost it is difficult for engineers to get the necessary data through tests. In this study, we surveyed literature and proposed a procedure to identify the fatigue parameters expressed with the Brinell hardness and elastic modulus. After obtaining stress concentration factors by finite element analysis, we calculated fatigue notch factors using Peterson's formula. Taking into account the welding residual stress, which was also obtained by finite element analysis, we evaluated the fatigue lifetime of four kinds of welded joints using the proposed approach. The estimated results are in a good agreement with the experimental results.

Key Words : Brinell Hardness, Fatigue Lifetime, Finite Element Analysis, Residual Stress Relaxation, Strain-Life Approach, Welded Joints

1. Introduction

There are several methods to evaluate the fatigue lifetime of structures. For the application of the methods it is necessary to identify relevant parameter values from tests or literatures. However, a lot of fatigue tests are necessary to obtain the values of parameters for the fatigue characteristics. These fatigue tests require test equipments and skilled engineers, and also time and cost can be difficulties (Park and Song, 1995; Roessle and Fatemi, 2000). For these reasons, many researchers have been developing such methods, for example tensile tests, that can describe fatigue characteristics. If we can obtain reliable fatigue properties from the results of simple tests like hardness and tensile tests, time and cost can be saved significantly.

* Corresponding Author,
E-mail : bcgoo@krri.re.kr
TEL : +82-31-460-5243; **FAX** : +82-31-460-5279
Rolling Stock Division, Korea Railroad Research Institute, 360-1 Wolamdong, Uiwangsi, Kyunggido 437-050, Korea. (Manuscript **Received** March 3, 2005; **Revised** December 1, 2005)

There are two main approaches to evaluate the fatigue lifetime. The first is the traditional one based on the nominal stress (σ-N approach), and the second is using local strain to consider local behaviour at a notch (ε-N approach).

The expression of the fatigue life evaluation based on the nominal stress is the Basquin's equation (Stephens et al., 2001),

$$\Delta S/2=\sigma_f'(2N_f)^b \tag{1}$$

for stress ratio $R=S_{\min}/S_{\max}=-1$. $\Delta S/2$ is the stress amplitude and N_f is the number of cycles to failure. Two parameters, the fatigue strength coefficient σ_f' and exponent b are used in this equation. For non-zero average stress, the modified Goodman diagram or other methods reflecting the effect of the average stress can be used.

Also, there are many expressions for the fatigue lifetime evaluation using local strain. For the case of R=−1, the representative one is the Coffin-Manson equation (Stephens et al., 2001):

$$\begin{aligned}\frac{\Delta\varepsilon}{2}&=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2}\\&=\frac{\sigma_f'}{E}(2N_f)^b+\varepsilon_f'(2N_f)^c\end{aligned} \tag{2}$$

$\Delta\varepsilon/2$, $\Delta\varepsilon_e/2$ and $\Delta\varepsilon_p/2$ are the amplitudes of the total strain, elastic strain, and plastic strain, respectively. ε_f' is the fatigue ductility coefficient. c is the fatigue ductility exponent. For the case with average stress, the representative one is the S.W.T. parameter as follows:

$$\sigma_{\max}\varepsilon_a E=(\sigma_f')^2(2N_f)^{2b}+\sigma_f'\varepsilon_f' E(2N_f)^{b+c} \quad (3)$$

A concept of transition lifetime is used for the fatigue lifetime, which means the lifetime at a point where the elastic component equals the plastic one,

$$N_t=\frac{1}{2}\left(\frac{\sigma_f'}{\varepsilon_f' E}\right)^{1/(c-b)} \quad (4)$$

In this paper, a method to evaluate the fatigue lifetime by using simple material characteristics of hardness and elastic modulus will be presented.

2. Relation Between Fatigue and Tensile Properties

2.1 Relation between hardness, tensile strength and transition life

In this section we follow the Roessle and Fatemi (Roessle and Fatemi, 2000) to express the fatigue properties with hardness and elastic modulus. For low, medium, and high strength steels and alloy steels, the relation between the Brinell hardness HB and the tensile strength S_u may be expressed by a linear relationship as (Roessle and Fatemi, 2000)

$$S_u\approx 3.45HB\ (\mathrm{MPa}),\ \text{for } HB<350HB \quad (5)$$

Taking quadratic approximation up to HB 500, it is expressed as follows:

$$\begin{aligned}&S_u\approx 3.3HB+0.0012(HB)^2\\&\text{for } HB<500HB\end{aligned} \quad (6)$$

where a correlation coefficient R is given by $R^2=0.96$. The Brinell hardness and the fatigue limit S_f at 10^6 cycles is given by the least square fit as follows:

$$S_f\approx 1.43HB \quad (7)$$

The fatigue limit is often estimated from the ultimate tensile stress S_u:

$$\begin{aligned}&S_f\approx 0.5S_u,\ \text{for } S_u\leqq 1400\ \mathrm{MPa}\\&S_f\approx 700\ \mathrm{MPa},\ \text{for } S_u\geqq 1400\ \mathrm{MPa}\end{aligned} \quad (8)$$

The constant fatigue strength for the tensile strength above 1400 MPa seems due to the existence of inclusions. There is scattering in the results of tensile strength and fatigue limit, and fatigue limits predicted by the tensile strength in equation (8) are different from experimental data and do not give conservative results for most steels. Traditionally many fatigue tests were conducted by rotary bending tests. In rotary bending tests, fatigue limit is high because parts carrying high load are smaller and the defect probability is lower than in the tensile tests.

From data of tensile and rotary bending fatigue tests, the relation between the tensile strength and the fatigue limit may be expressed as follows:

$$S_f\approx 0.38S_u \quad (9)$$

The relation between the transition life and the Brinell hardness may be expressed as follows ($R^2=0.89$, R: correlation coefficient) (Roessle and Fatemi, 2000):

$$\log(2N_t)=5.755-0.0071HB \quad (10)$$

2.2 Relation between tensile and fatigue characteristics

In this section we also follow the Roessle and Fatemi (2000). The fatigue strength coefficient σ_f' is similar to the tensile fracture stress σ_f of tensile tests and is in the range of $(0.92\sim1.15)\sigma_f$. The fatigue strength coefficient depends strongly on the Brinell hardness and tensile strength, and it is estimated as follows:

$$\sigma_f'=4.25HB+225\,(\mathrm{MPa}) \quad (11)$$

$$\sigma_f'=1.04S_u+345\,(\mathrm{MPa}) \quad (12)$$

According to the literatures, it is hard to find a close relationship between the fatigue strain coefficient ε_f' and the true fracture strain ε_f of the tensile test, and it is in the wide range of $(0.15\sim1.15)\varepsilon_f$. Therefore, it can cause large error to infer the fatigue strain coefficient from the true fracture strain. Recently, Roessele and Fatemi

(2000) proposed the following expression on the basis that the Brinell hardness and elastic modulus are closely related. From Eq. (4)

$$\varepsilon_f' = \frac{\sigma_f'(2N_t)^b}{E(2N_t)^c} \tag{13}$$

where the fatigue strength coefficient σ_f' can be obtained from (11) or (12). The numerator is the transition fatigue strength $S_t = \sigma_f'(2N_t)^b$ corresponding to the transition lifetime N_t. S_t and the Brinell hardness have a close relationship ($R^2 = 0.97$) as follows (Roessle and Fatemi, 2000):

$$S_t = 1.15HB + 0.004(HB)^2 \tag{14}$$

Plugging N_t into the denominator after getting it from equation (10), and putting (14) into the numerator of Eq. (13), ε_f' is given as follows:

$$\varepsilon_f' = \frac{1.15HB + 0.004(HB)^2}{E[10^{(5.755-0.0071HB)}]^{-0.56}} \tag{15}$$

Expanding the polynomial of (15) and approximating up to the second order, one can get the following expression which coincides with experimental results for $150 < HB < 700$.

$$\varepsilon_f' = \frac{-487HB + 0.32(HB)^2 + 191000}{E} \tag{16}$$

Morrow (Stephens et al., 2001) proposed a relationship between the cyclic hardening exponent n', fatigue strength exponent b, and fatigue strain exponent c as follows:

$$b = \frac{-n'}{1+5n'},\ c = \frac{-1}{1+5n'} \tag{17}$$

But these predictive expressions do not give results agreeing with experiment results. b is in the interval of $-0.057 \sim -0.140$, and the average is -0.09. c is in the interval of $-0.39 \sim -1.04$, and the average is -0.60.

According to the study by Roessele and Fatemi (2000) the average of the fatigue strength coefficient b is -0.09. Since it is similar to the exponent of the modified universal slope method, it is assumed that the value is constant -0.09. And the average value of the fatigue strain exponent c is assumed constant -0.56 since it is similar to the exponent of the modified universal slope. Plugging above fatigue constants into Eq. (2), one can obtain the following expression:

$$\frac{\Delta\varepsilon}{2} = \frac{4.25HB + 225}{E}(2N_f)^{-0.09} + \frac{-487HB + 0.32(HB)^2 + 191000}{E}(2N_f)^{-0.56} \tag{18}$$

Some researchers have done similar works as above to find a relation between the strain and fatigue lifetime from tensile properties. Park and Song (1995) evaluated steel, alloy steel, aluminum alloy, titanium alloy, etc. by using six expressions in the literature. They showed that the following modified universal slope gives the best correlation.

$$\frac{\Delta\varepsilon}{2} = 0.623\left(\frac{S_u}{E}\right)^{0.832}(2N_f)^{-0.09} + 0.0196(\varepsilon_f)^{0.155}\left(\frac{S_u}{E}\right)^{-0.53}(2N_f)^{-0.56} \tag{19}$$

Meanwhile, in Song's research on 49 kinds of steel, he showed that a modified four-point correlation produced the best result (Song, 1993).

For the case with mean stress, the Basquin's relation of (1) can be expressed as follows.

$$\sigma_a = \Delta\sigma/2 = \sigma_f'(2N_f)^b \tag{20}$$

After multiplying (20) to (18) and arranging it in the similar form to the S.W.T. parameter of equation (3), one gets

$$\frac{\sigma_a \Delta\varepsilon E}{2} = (4.25HB + 225)^2(2N_f)^{-0.18} + (4.25HB + 225)[-487HB + 0.32(HB)^2 + 191000](2N_f)^{-0.65} \tag{21}$$

When applying (21), for the case of $R \neq -1$, $\sigma_a = \sigma_{mean} + \Delta\sigma/2$ is used (Stephens et al., 2001). When this expression is used for the lifetime evaluation, only the elastic modulus E and the Brinell hardness HB are necessary.

3. Fatigue Lifetime Prediction Method Considering Notch and Residual Stress

Structures are commonly joined by welding and most fatigue fractures take place in weldments. For the reliable evaluation of the fatigue lifetime of the structures, it is necessary to take the notch and residual stress into consideration. To consider the effect of the residual stress on the fatigue behavior, Reemsnyder (1981), Seeger (Vormwald and Seeger, 1987) and Lawrence (1982) used respectively the following expressions for the lifetime estimation by local strain.

$$\sigma_{max}\varepsilon_{max}=\frac{1}{E}\left(\frac{K_f S_{max}}{1-\sigma_{r_{ini}}/\sigma_{max}}\right)^2 \tag{22}$$

$$\sigma_{max}\varepsilon_{max}=\frac{(K_f S_{max})^2}{E}+\frac{\sigma_{max}\sigma_{r_{ini}}}{E} \tag{23}$$

$$\sigma_{max}\varepsilon_{max}=\frac{(K_f S_{max}+\sigma_{r_{ini}})^2}{E} \tag{24}$$

where the subscript max represents the maximum values and $\sigma_{r_{ini}}$ is the initial residual stress in the direction of applied load. Equations (22)~(24) are necessary to calculate the local stress and strain at the moment when the external loading reaches the maximum value S_{max}. At the minimum loading, the minimum local strain ε_{min} and local stress σ_{min} are expressed by:

$$(\sigma_{max}-\sigma_{min})(\varepsilon_{max}-\varepsilon_{min})=\frac{(K_f \Delta S)^2}{E} \tag{25}$$

where subscript min denotes the minimum values. Stress and strain at the maximum and minimum loads can be obtained by using equations (22)~(25) with the following Ramberg-Osgood equation (Stephens et al., 2001) describing the stress-strain relation in cyclic loading. For the initial loading:

$$\varepsilon_{max}=\frac{\sigma_{max}}{E}+\left(\frac{\sigma_{max}}{K'}\right)^{1/n'} \tag{26}$$

and for later cyclic loadings:

$$\frac{(K_f \Delta S)^2}{E}=\frac{(\Delta\sigma)^2}{E}+2\Delta\sigma\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \tag{27}$$

where K' is the strength coefficient for the cyclic deformation of the material, and $\Delta\sigma$ and ΔS are the respective differences of local and applied stresses.

Cyclic strength coefficient K' and cyclic hardening exponent n' are necessary to obtain local stress and strain from the above equations. Although it is accurate to get these values from experiments, they can be approximately obtained from the hardness and the elastic modulus. The cyclic hardening coefficient n' and the cyclic strength coefficient K' can be expressed from the fatigue strain coefficient and fatigue strength coefficient (Roessele and Fatemi, 2000):

$$n'=\frac{b}{c}=0.15 \tag{28}$$

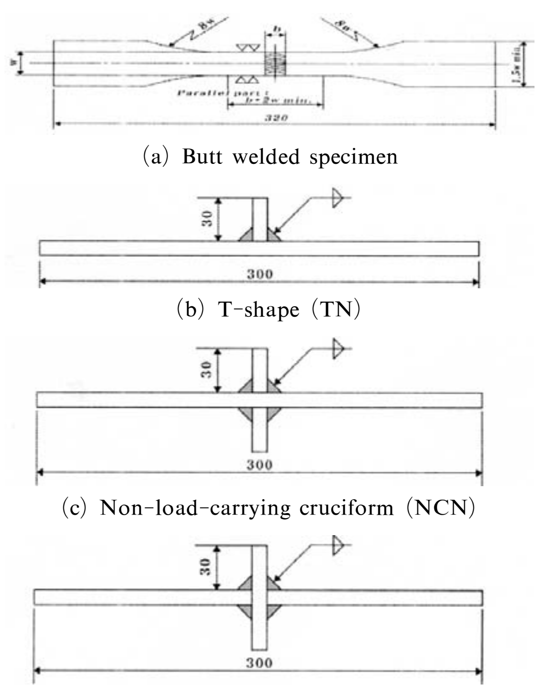
$$\begin{aligned}K'&=\frac{\sigma_f'}{(\varepsilon_f')^n}\\&=\frac{E^{0.15}(4.25HB+225)}{[-487HB+0.32(HB)^2+191000]^{0.15}}\end{aligned} \tag{29}$$

4. Lifetime Estimation of Weld Specimens

4.1 Weld specimens and finite element model

Lifetime estimation was carried out for the 4 types of weld specimens shown in Fig. 1.

Butt welded specimen in Fig. 1(a) is 3-pass arc welded and the remaining specimens are 1-pass.



(a) Butt welded specimen

(b) T-shape (TN)

(c) Non-load-carrying cruciform (NCN)

(d) Load-carrying cruciform (CN)

Fig. 1 Specimens for test and analysis

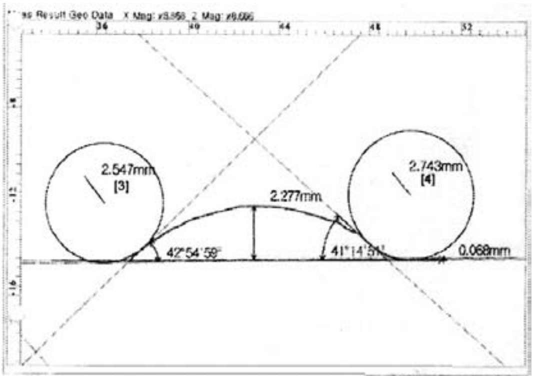


Fig. 2 Measurement of the weld profile

To obtain the stress concentration factors at the weld toes by finite element analysis, the shapes of weld beads are measured on a contour measuring instrument, Mitutoyo CV-3000S4 with a resolution of 0.0002 mm. Fig. 2 shows an example of the measurement of the flank angles and toe radii (Goo et al., 2004).

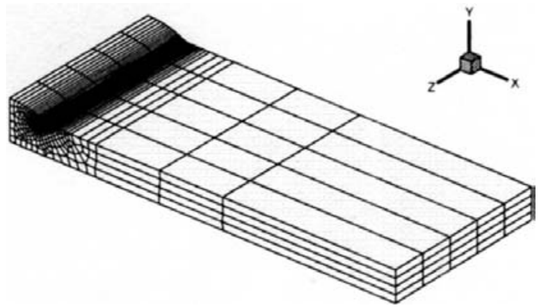
Figure 3 shows the finite element models. Only the half models are considered by symmetry. From finite element analysis we obtained the stress concentration factor $K_t=2.0$ for the butt weld, $K_t=2.71$ for TN, $K_t=3.64$ for NCN, $K_t=4.22$ for CN. We checked the convergence of the stress concentration factors with varying element sizes. 6-node triangular elements were used under the plane-strain assumption and ΔX in the figure denotes the length along one side of the element near the notch. One can see that the factors converged enough as the meshes are fined (Fig. 4). The fatigue notch factors, K_f's are obtained by the Peterson's formula (Stephens et al., 2001):

$$K_f=1+\frac{K_t-1}{1+a/r} \tag{30}$$

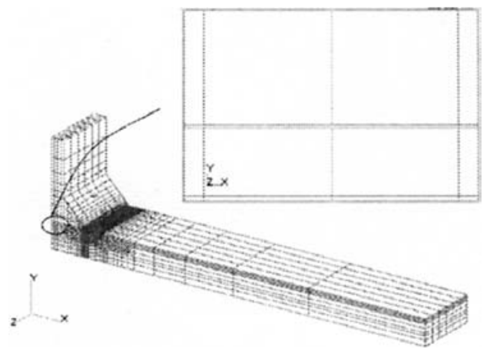
where $a=0.0254(2070/S_u)^{1.8}$ is a characteristic length depending on the material, which is determined empirically. From Eq. (30), the notch coefficients K_f's are obtained and given in the following Table 1.

4.2 Analyses of welding residual stress

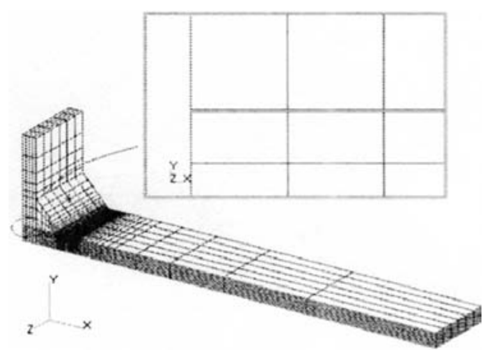
Welding analysis is composed of transient heat analysis and thermal stress analysis. The stress



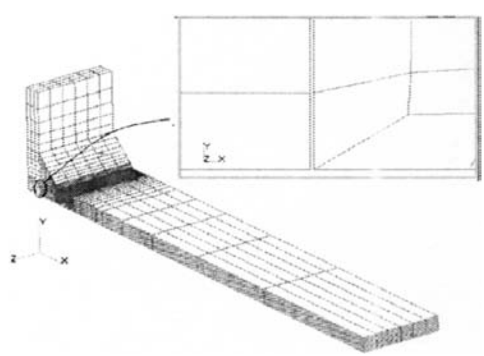
(a) Butt welded specimen



(b) TN specimen



(c) NCN specimen

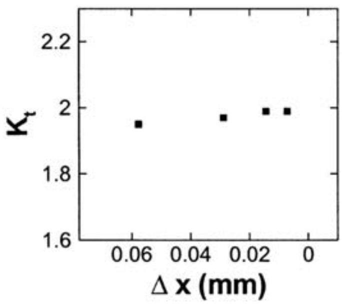


(d) CN specimen

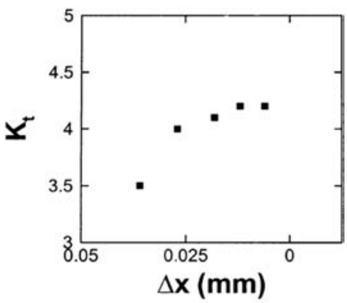
Fig. 3 FE models of the specimens

Table 1 Fatigue notch coefficients

Specimen types	K_t	K_f
Butt weld	2.00	1.88
TN	2.71	1.63
NCN	3.64	1.93
CN	4.22	2.40



(a) Butt weld



(b) CN

Fig. 4 Convergence of K_t with respect to element size

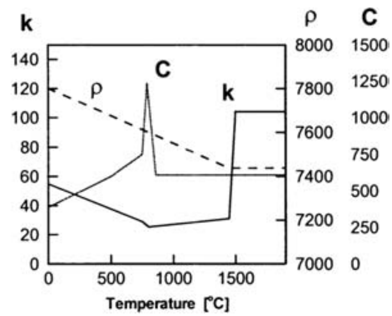
analysis uses the thermal field from the heat transfer analysis to compute the thermal stress field. In the heat transfer analysis, element birth function on ABAQUS was employed. And moving heat flux was applied along the welding line to simulate the GMAW (Gas Metal Arc Welding) procedure as close as possible. The material is rolled steel for weld structures (SM490A, C 0.2 max wt.%). To obtain the body heat flux the following expression was used.

$$q_0 = \frac{\eta_a VI}{\pi} \frac{3}{r_b^2}$$
$$q = q_0 e^{-3\left(\frac{r}{r_b}\right)^2} \tag{31}$$

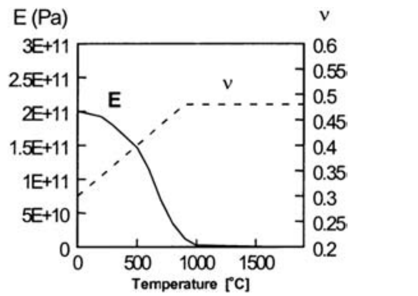
Using the welding conditions in Table 2, one can

Table 2 Parameters for weld analysis

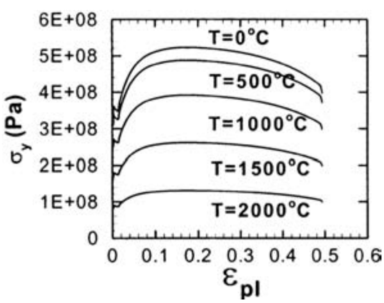
Parameters	Butt weld	TN, CN, NCN
Ambient temp.	20℃	20℃
Filler metal temp.	2,000℃	2,000℃
Solidus temp.	1,465℃	1,465℃
Liquidus temp.	1,544℃	1,544℃
Liquidation latent heat	247,000 J/kg	247,000 J/kg
Arc efficiency η_a	0.4	0.4
Voltage V	100	28
Current I	170	270
Arc beam radius r_b	0.005 m	0.005 m
Heat convection coefficient	10 J/sm²℃	10 J/sm²℃



(a) Conductivity k, density ρ, specific heat C



(b) Young's modulus E [Pa], Poisson's ratio ν



(c) Yield strength σ_y [Pa]

Fig. 5 Material properties

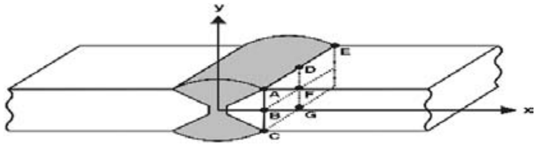


Fig. 6 Butt weld specimen

get $q_0 = 260 \times 10^6 (\mathrm{J/m^2 s})$ for the case of the butt weld. Therefore, assuming 0.5 for the value of the exponential function, heat flux is given by $q = 130 \times 10^6 (\mathrm{J/m^2 s})$. The temperature-dependent mechanical properties are plotted in Fig. 5 (Pilipenko, 2001). Elasto-plastic analysis was employed for the residual stress analyses. The maximum tensile residual stress in the longitudinal direction (loading direction) is located near points D and G in Fig. 6. The maximum residual stresses for the butt welded, TN, NCN and CN specimens are 350, 490, 475, and 455 MPa respectively.

4.3 Fatigue lifetime analysis

To carry out the evaluation of the fatigue lifetime using hardness, the hardness value was measured for the post-weld annealed specimens (AAY) and as-welded specimens (AAN). Fig. 7 shows the hardness measurement points and Fig. 8 is the test results for 5 kg Vickers hardness. Generally fatigue fracture takes place near the boundary between the weld metal and the heat affected zone. At these regions, the Vickers hardness was about 150 Hv, and the Brinell hardness at 3000 kg was 147～156HB. In our numerical analyses the Brinell hardness of 150HB was used.

Figures 9～12 are the predicted fatigue lifetimes by the lifetime evaluation method using the hard-

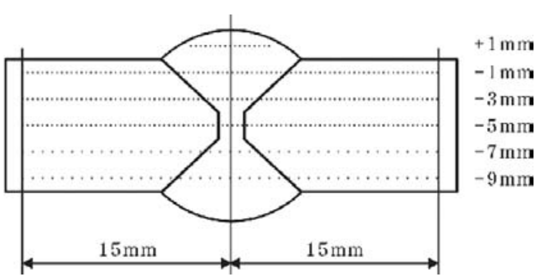
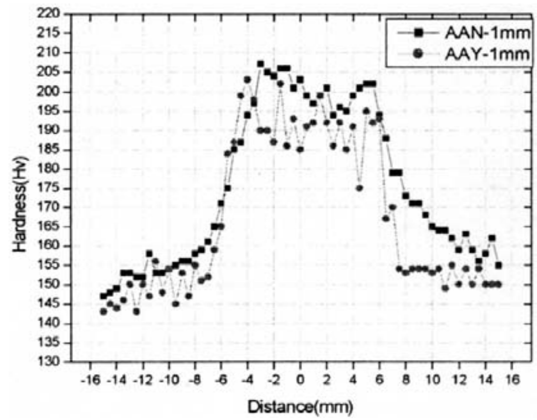
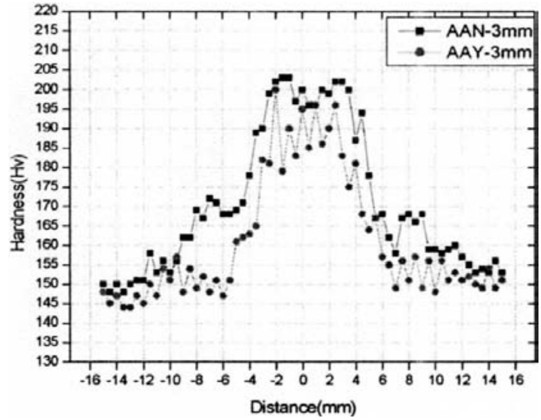


Fig. 7 Hardness measurement points



(a) Vickers hardness at depth −1 mm



(b) Vickers hardness at depth −3 mm

Fig. 8 Vickers hardness

ness. The initial stress is set as zero in case of without residual stress, and in the case of with residual stress, the relaxation of residual stresses, average stress and strain amplitude were obtained by solving Eqs. (24) ~ (27). The number of cycles to failure N_f is obtained by (21). The experimental results of Figs. 9～12 are from the as-welded specimens. Fatigue tests were carried out according to ASTM E 466 on an Instron model 8802 (25 ton) at 15～20 Hz. The stress ratio of the applied axial load was 0.1. (Goo et al., 2004). We can observe that taking residual stress into consideration, the predicted results are closer to the experimental results. It is shown that the effect of welding residual stress on the fatigue lifetime is greater in the high stress range than in the low stress range.

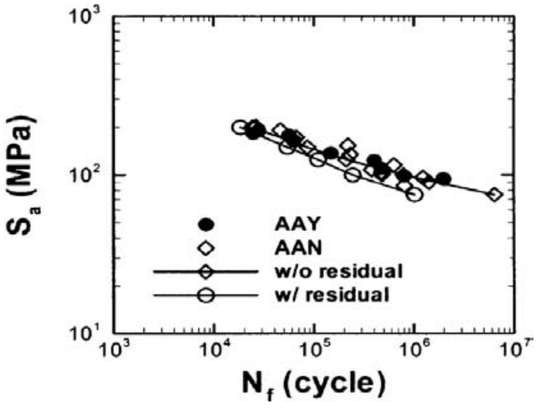


Fig. 9 Butt weld

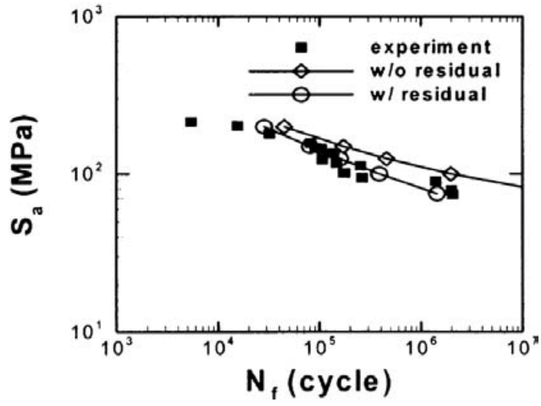


Fig. 10 T-shape fillet weld (TN)

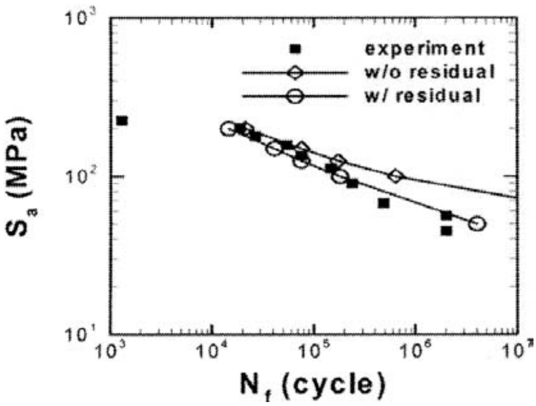


Fig. 11 Non-load-carrying cruciform (NCN)

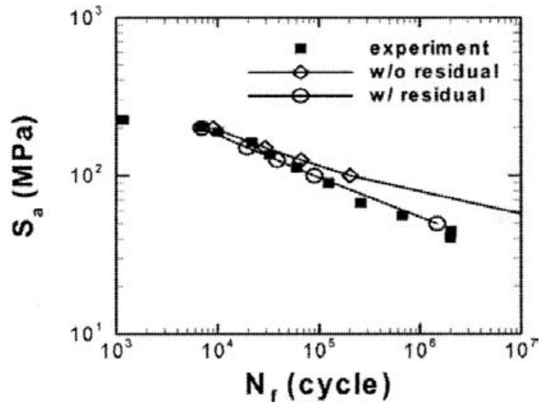


Fig. 12 Load-carrying cruciform (CN)

5. Discussion and Conclusions

We surveyed literature and proposed a procedure to identify the fatigue parameters from the Brinell hardness and elastic modulus. And the fatigue properties of the S.W.T. parameter are expressed in the function of the Brinell hardness and elastic modulus. For the four kind of welded specimens, the simulated fatigue lifetimes by the developed approach agree well with the experimental lifetimes. Therefore, this kind of approach seems to be very useful and effective from the viewpoint of time and cost.

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