FATIGUE LIFE EVALUATION OF WELDED JOINTS BASED ON NOMINAL STRESS AND FINITE ELEMENT ANALYSIS

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ABSTRACT

In the first part, experimental study on the fatigue behavior of a material, SM 490 A was carried out on double V-grooved butt welded plates such as reinforcement removed, as-welded and weld toe ground. In addition, welded plates with transverse fillet welded web, load carrying cruciform fillet welded plates, non-load carrying cruciform fillet welded plate and longitudinal butt welded plates were tested. The obtained S-N curves for the weld details are compared each other.

In the second part, to simulate the observed fatigue behavior, taking into account the residual stress relaxation, the modified Goodman diagram, notch effect and nominal stress, we propose a model to evaluate fatigue life of welded joints with residual stresses. After analyzing the welding process by finite element method, we conducted elastic-plastic finite element analysis to quantify the degree of residual stress relaxation due to applied loadings. Maximum tensile residual stress on the surface of the specimen decreased gradually and changed to compressive stress as the applied loading was getting higher. Using the developed model we evaluated the fatigue life of the butt-welded joints from the S-N curve for the parent material. The estimated results are in a good agreement with the experimental results.

1 INTRODUCTION

A lot of study on welding residual stress has been conducted in experimental and numerical areas but the effect of residual stresses on fatigue life has not been clearly explained until yet. Some results show the effect of welding residual stresses on fatigue life is significant. On the other hand, other results show specimens with initial tensile residual stresses have even longer fatigue lives [1]. These unclear conclusions seem to be mainly concerned with residual stress relaxation during fatigue tests and the metallurgical difference of the weld metals and parent materials. Several authors proposed fatigue life evaluation methods of welded joints taking into account residual stress. They used local strain approaches. Eqns. (1-3) are the relations between local and nominal values proposed by Reemsnyder et al. [2], Lawrence [3] and Seeger et al. [4] respectively when an applied loading reaches the maximum point.

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

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

$$\sigma_{\max}\varepsilon_{\max} = \frac{(K_f S_{\max})^2}{E}+\frac{\sigma_{\max}\sigma_{r_{ini}}}{E} \tag{3}$$

where $\varepsilon_{\max}$: maximum local strain; $\sigma_{\max}$: maximum local stress; σ_{ini}: initial residual strain; $S_{\max}$: maximum nominal stress; E : Young's modulus; K_f :fatigue notch coefficient.

When the applied loading reaches the minimum point the relation between local and nominal values is written as :

$$\sigma_{\min}\varepsilon_{\min} = \frac{(K_f \Delta S)^2}{E} \tag{4}$$

where $\varepsilon_{\min}$: minimum local strain; $\sigma_{\min}$: minimum local stress; ΔS : stress variation.

Eqns. (1-4) can be solved by using the Ramberg-Osgood relation (5) :

$$\frac{(\Delta\sigma)^2}{E}+2\Delta\sigma\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} = \frac{(K_f \Delta S)^2}{E} \tag{5}$$

Where K' and n' are material cyclic deformation properties.

The above methods can evaluate roughly fatigue lives of welded joints with residual stress. But it is difficult to take into account residual stress relaxation by an applied loading. To analyze the residual stress relaxation by an applied loading for complex welded joints, finite element method is very useful. In the next section, an approach to predict fatigue life of welded joints with residual stress is described and applied to simulate test results.

2 FATIGUE LIFE EVALUATION OF WELDED JOINTS

2.1 Effect of residual stress, notch and post weld heat treatment

Fig. 1 is a schematic explanation for the effect of residual stress, notch and post weld heat treatment (PWHT). The line AE is the S-N line for the parent material with PWHT. The fatigue strength at 2×10^6 cycles is S_f. The line AF is the S-N line considering only the notch effect of welded joints. The fatigue strength at 2×10^6 cycles is S_f / K_f. The fatigue strength at one cycle is assumed to be the same as that of the parent material. The line CG is the S-N line for the material with notches and PWHT. Fatigue strength may increase or decrease due to metallurgical changes by PWHT. The line BDH is the S-N line considering notch and residual stress effect. The effect of residual stress is different on the line AD and DH. At point D, the sum of the applied maximum stress and initial residual stress, ($S_{max} + \sigma_{r_{ini}}$) is equal to the yield strength of the material, S_y. On DH ($S_{max} + \sigma_{r_{ini}}$) $\leq S_y$, therefore the initial residual stress plays as a mean stress. On BD ($S_{max} + \sigma_{r_{ini}}$) $\geq S_y$, the initial residual stress relaxes by the applied loading. The quantity of relaxation depending on the applied loading and material properties can be calculated by finite element analysis.

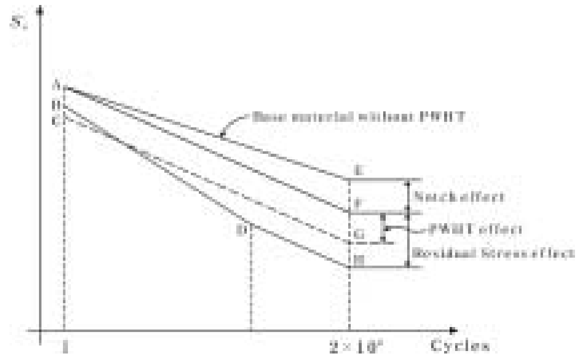


Figure 1: Effect of residual stress and notch

2.2 PROCEDURES OF FATIGUE LIFE EVALUATION

First of all, the S-N curve of a parent material is obtained (line AE in Fig. 1). The largest stress concentration factors K_t of a welded joint is calculated by finite element analysis, then fatigue notch coefficient K_t is obtained from Peterson's or Neuber's formula [5]. The fatigue strength corresponding at point F, $S_f^{'}$ is obtained from the modified Goodman equation :

$$\frac{S_f^{'}}{S_f / K_f} + \frac{S_{mean}}{S_u} = 1 \tag{6}$$

The line AF is expressed by the Basquin's formula :

$$S_a = AN^m \tag{7}$$

The fatigue strength corresponding at point H, $S_f^{''}$ is obtained from the modified Goodman equation :

$$\frac{S_f''}{S_f'} + \frac{(S_{mean} + \sigma_{r_{ini}})}{S_u} = 1 \qquad (8)$$

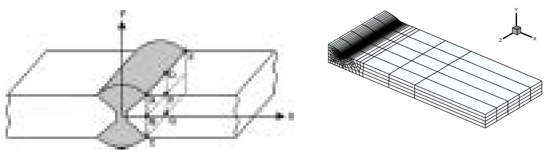
The line HD is parallel to the line FA. On BD ($S_{max} + \sigma_{r_{ini}}) \geq S_y$, to take into account the residual stress effect, remaining residual stress, σ_r' after relaxation under an applied loading, S_{max} corresponding to S_a is calculated by finite element analysis. The fatigue strength, S_f''' corresponding to S_a is obtained from the modified Goodman equation :

$$\frac{S_f'''}{S_f'} + \frac{(S_{mean} + \sigma_r')}{S_u} = 1 \qquad (9)$$

On the line BD, fatigue strength corresponding to cycle *N*, is less than the fatigue strength on the line AF by $(S_f' - S_f'')$.

2.3 APPLICATION TO BUTT-WELDED JOINTS

Fig. 2 show a butt-welded specimen of size 100×25×10 with yield strength 350 MPa, and tensile strength 520 MPa and 3-dimensional finite element model. K_t=1.6 and K_f=1.52 are obtained.



(a) Butt welded specimen (b) Finite element model

Figure 2: Finite element model for welding analysis

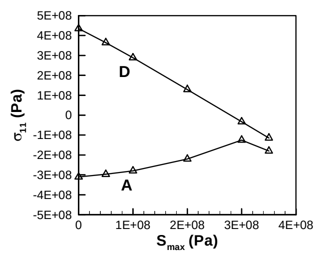


Figure 3: Residual stress relaxation

Fig. 3 shows the residual stress relaxation by applied loadings at the points A and D in Fig. 2. Tensile stress at the point D decreases and changes to compressive stress as the applied loading increases. Fig. 4 and 5 show the predicted and measured fatigue lives of butt-welded specimens. The predicted lives are in a good agreement with test results. Fig. 6 shows the predicted results with and without consideration of residual stress relaxation by the Lawrence model presented in introduction and S.W.T. parameter [5]. The S.W.T. parameter is written as :

$$\sigma_{max}\varepsilon_a E = (\sigma_f')^2 (2N_f)^{2b} + \sigma_f' \varepsilon_f' E (2N_f)^{b+c} \qquad (10)$$

where the material constants b, c, $\sigma_f^{'}$ and $\varepsilon_f^{'}$ measured by Han et al. [6] on a similar material were used. It seems that the effect of residual stress according to the Lawrence model is significant. The predicted lives are much shorter when $\sigma_{r_{ini}}$ = 435 MPa.

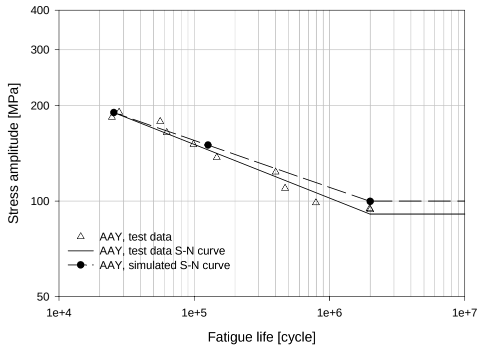


Figure 4: AAY: PWHT

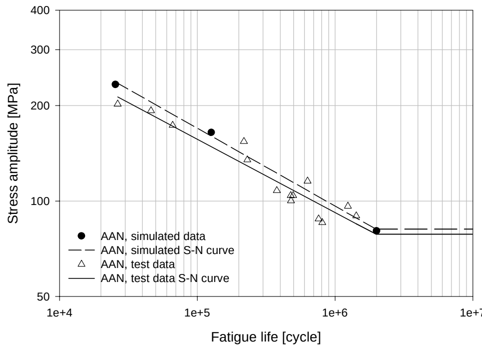


Figure 5: AAN: as- welded

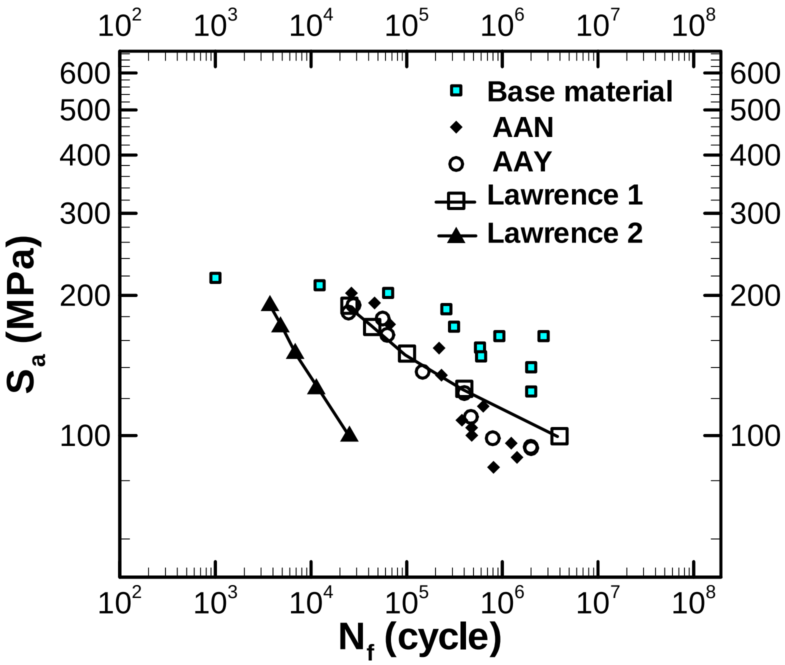


Figure 6: Lawrence 1 $\sigma_{r_{ini}} = 0$; Lawrence 2 $\sigma_{r_{ini}} = 435\,\text{MPa}$

REFERENCES

(1) Takanashi M., Iida K., "Relaxation of Welding Residual Stresses by Reversed and Repeated Loadings," Japanese Welding Society, Vol. 19, No. 1, pp. 129-139, 2001.

(2) Reemsnyder H., Experimentation and Design in Fatigue: Evaluating the Effect of Residual Stresses on Notched Fatigue Resistance, pp. 273-295, 1981.

(3) Lawrence F. V., Burk J. D., Yung J. Y., "Influence of Residual Stress on the Predicted Fatigue Life of Weldments," ASTM STP 776, pp. 33-43, 1982.

(4) Vormwald M., Seeger T., Residual stresses in Science and Technology: Crack Initiation Life Estimations for Notched Specimens with Residual Stresses Based on Local Strains, pp. 743-750, 1987.

(5) Stephens R. I., Fatemi A., Stephens R. R., Fuchs H. O., Metal Fatigue in Engineering, John Wiley & Sons, Inc., pp. 196-205, 2001.

(6) Han J. W., Han S. H., Shin B. C., Kim J. H., "Fatigue Life Evaluation of Various Welding Details based on Notch Strain Approach," Proceedings of the Seventeenth Conference on Mechanical Behaviors of Materials, The Korean Institute of Metals and Materials, pp. 365-372, 2003.