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CREEP-FATIGUE EVALUATION METHOD FOR MOD.9Cr-1Mo WELDMENT

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1 INTRODUCTION

It is urged to develop a creep-fatigue evaluation method for weldments of structural materials of the pressure vessels and the coolant systems of future large scale fast breeder reactors (1). The authors have shown that creep-fatigue evaluation of welded joint of 304 stainless steel can be successfully performed based on the concept that the discontinuity of mechanical properties between base and weld metals causes strain concentration within the welded joint (2). Discussed here is a creep-fatigue evaluation method for weldment of Mod.9Cr-1Mo steel which is the most promising candidate material for steam generators of large scale FBRs.

2 EXPERIMENTAL PROCEDURE

2.1 Material and specimen

Two kinds of welded joints were made using hot rolled plate and forged base metals and two kinds of 316 type weld wires by narrow gapped tungsten welding. Post weld heat treatment was performed. Round bar welded joint specimens were taken so that the axis of the specimens were perpendicular to the weld line. The specimens had a diameter of 10mm and a gauge length of 25mm. Hardness distribution in the gauge length before fatigue and creep-fatigue tests is shown in Fig.1. The softest portion is observed in the HAZ.

2.2 Test condition

Strain controlled uniaxial fatigue and creep-fatigue tests were conducted at 550℃ using a servo-hydraulic test machine. Strain rate was 0.1%/s and strain hold time was 10 minutes. Strain waveform was triangular and strain was hold at a tensile peak. Strain range varied from 0.5 to 1.5%.

2.3 Test results

Result of fatigue tests and creep-fatigue tests of welded joints are shown in Fig. 2. Fatigue life of welded joints was a little bit shorter than base metal and was almost the same as weld metal. Creep-fatigue life of welded joints was significantly shorter than that of base and weld metals. Fatigue failure occurred in the base metal and creep-fatigue failure occurred in the weld metal near the interface between base and weld metals.

Figure 3 shows the stress-strain response at mid-life of welded joints. Both base and weld metals showed softening under creep-fatigue loading. But for welded joints, the softening under creep-fatigue loading was not so clear as for base and weld metals.

3 EVALUATION OF TEST RESULTS BASED ON STRAIN / STRESS CONCENTRATION

3.1 Procedure of evaluation

Procedure of creep-fatigue damage evaluation is illustrated in Fig. 4. The purpose of the procedure is to predict not only fatigue and creep-fatigue life but also location of failure, because location of failure is very important in the utilization of welded joints. First, a welded joint is modeled as a serial combination of three elements, that is, base metal, HAZ and weld metal. Secondly, the mechanical properties, such as cyclic stress-strain response, cyclic softening behavior, creep curve, fatigue strength and creep strength are assumed for each element. Thirdly, the strain concentration and stress concentration are analysed by FE-method. Finally, accumulated fatigue damage and acuumulated creep damage are calculated considering the effect of cyclic softening.

3.2 Model of Mod.9Cr-1Mo welded joint

For 304 welded joint, we have proposed a '2-element model', which is consisted of base metal and weld metal. The discontinuity of mechanical properties between the two elements causes a strain/stress concentration within the welded joint. In the case of Mod.9Cr-1Mo welded joint, HAZ is the softest part in the joint as shown in Fig. 1, where strain concentration may occur. Therefore, '3-element model'(see Fig.4(a)) which is consisted of base metal, weld metal and HAZ was employed in the present study.

3.3 Parameters for analysis

Parameters used for the analysis are summarized in Table 1. The difference of stress-strain response of base metal, weld metal and HAZ are represented by determining σ_p in the following equation for each element (see Fig.4(b)).

$$\log_{10}(\Delta\sigma - 2\sigma_P) = A_0 + A_1 \log_{10}(\Delta\varepsilon - \Delta\sigma/E) \qquad (1)$$

where, $\Delta\sigma$, $\Delta\varepsilon$, σ_P and E are stress range, strain range, proportional limit and elastic modulus, respectively. A0 and A1 are constants. For weld metal, σ_P was determined considering the average trend of the test results. For HAZ, as there was no cyclic stress-strain response data available, it was assumed to be in the range of 0.85 - 1.0 times the value of the base metal, considering the result of hardness distribution test shown in Fig. 1.

3.4 Estimation of strain concentration and stress concentration

Strain concentration and stress concentration were analysed by FE-method using the '3-element model'. Figure 5 shows a typical behavior of strain concentration and stress concentration at the surface of the specimen when a tensile strain of a half of the strain range is imposed. The maximum strain concentration was observed in the base metal about 3-4 mm from the fusion line, although the softest portion was HAZ. It was considered to be the result of plastic constraint on the deformation of HAZ. The maximum stress concentration occurred in the weld metal near the fusion line. As the stress relaxation proceeds and the stress distribution gets less pronounced compared with the beginning of the strain hold period.

3.5 Estimation of fatigue damage and creep damage

Accumulated fatigue damage and creep damage were calculated for base metal, HAZ and weld metal. Failure of welded joint was defined by the failure of one of the three elements.

Mod.9Cr-1Mo steel is a typical cyclic softening material. In the case of welded joint, base metal, weld metal and HAZ show non-uniform cyclic softening behavior. Therefore, strain / stress concentration behavior depend on the number of cyclic strain. For example, as shown in Fig.6, the location of the maximum strain concentration moves from the fusion line to base metal as repeated strain is imposed. This means that fatigue damage and creep damage per one cycle also depend on the number of cyclic strain.

Hardness distribution after the fatigue test and creep-fatigue test is shown in Fig. 1. It is to be noted that after fatigue and creep-fatigue tests the hardness of HAZ is identical to that of base metal. It is inferred that cyclic softening of HAZ was so small that the hardness of base metal and HAZ coincided during the fatigue / creep-fatigue loading.

Based on the above, a model shown in Fig. 4(c) was assumed. Two assumptions were made, that is, first, cyclic softening is finished in the middle of life and secondly, the ratio of the yield stress between base and weld metal are always constant but that between the base metal and the HAZ changes according to the cyclic strain.

Fatigue damage is calculated as follows: the strain ranges in the base metal, weld metal and HAZ are estimated by FE-analysis using the model shown in Fig.4(c) for all the cycles until failure of welded joint was predicted. The fatigue damage per one cycle df was defined as 1/Nf, where Nf is fatigue life. Creep damage is calculated as follows: the initial strain of stress relaxation in the base metal, weld metal and HAZ were determined by Fig. 4(c) and stress relaxation was calculated by FE-analysis for all the cycles until failure was predicted. The creep damage per one cycle was defined as $\int dt/tr(\sigma)$, where dt and tr are time increment and fracture time, respectively.

Figure 7 shows an example of the accumulation of fatigue damage and creep damage during the cyclic strain at base metal, weld metal and HAZ. Although in the beginning of cyclic strain, fatigue damage is maximum in HAZ, as cyclic softening proceeds, fatigue damage in base metal becomes dominant as a result of change of strain concentration behavior. On the contrary, the behavior of creep damage is almost the same throughout the cyclic strain, that is , creep damage in the base metal is always dominant.

Based on Fig. 7, fatigue life and creep-fatigue life was evaluated based on the linear damage summation rule. Campbell type criterion with the limit value of (Df, Dc)=(0.3, 0.3) was employed for base metal and HAZ, and the Campbell type criterion with the limit value of (Df, Dc) =(0.1, 0.1) was employed for weld metal(3), where Df and Dc are accumulated fatigue damage and creep damage, respectively. As a result, it was predicted that fatigue failure occur in the base metal and creep-fatigue failure occurs in the weld metal. As far as the present study concerns, either fatigue failure nor creep-fatigue failure were predicted to occur in HAZ.

The result of life prediction is shown in Fig. 8. Fatigue and creep-faigue life as well as location of failure was successfully predicted by the model proposed in the present study.

4 CONCLUSION

It was shown that fatigue and creep-fatigue life as well as the location of failure of Mod.9Cr-1Mo welded joint could be successfully predicted by FE-analysis provided the mechanical properties of the elements which compose a welded joint were known.

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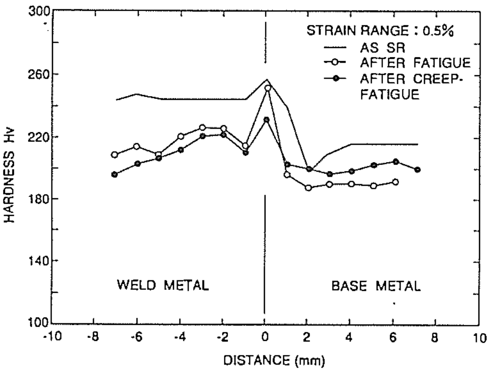
Table 1 List of parameters

Parameter	HAZ	WM
Proportional limit	0.85-1.0xBM	1.15xBM
Fatigue strength	Identical to BM	Average of WM
Creep strength	Identical to BM	Identical to BM
Creep curve	Identical to BM	Average of WM



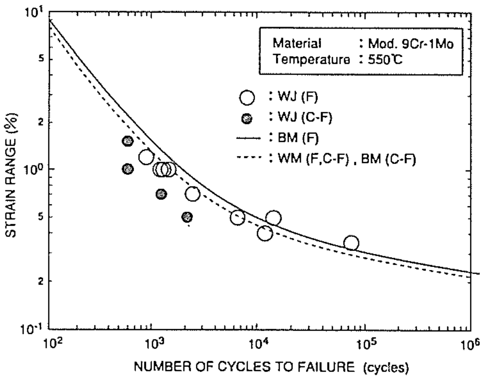


Fig.1 Hardness distribution in gauge length

Fig.2 Result of creep-fatigue tests

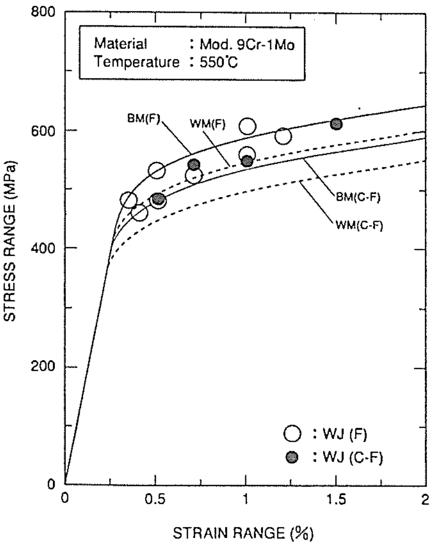


Fig. 3 Stress-strain response

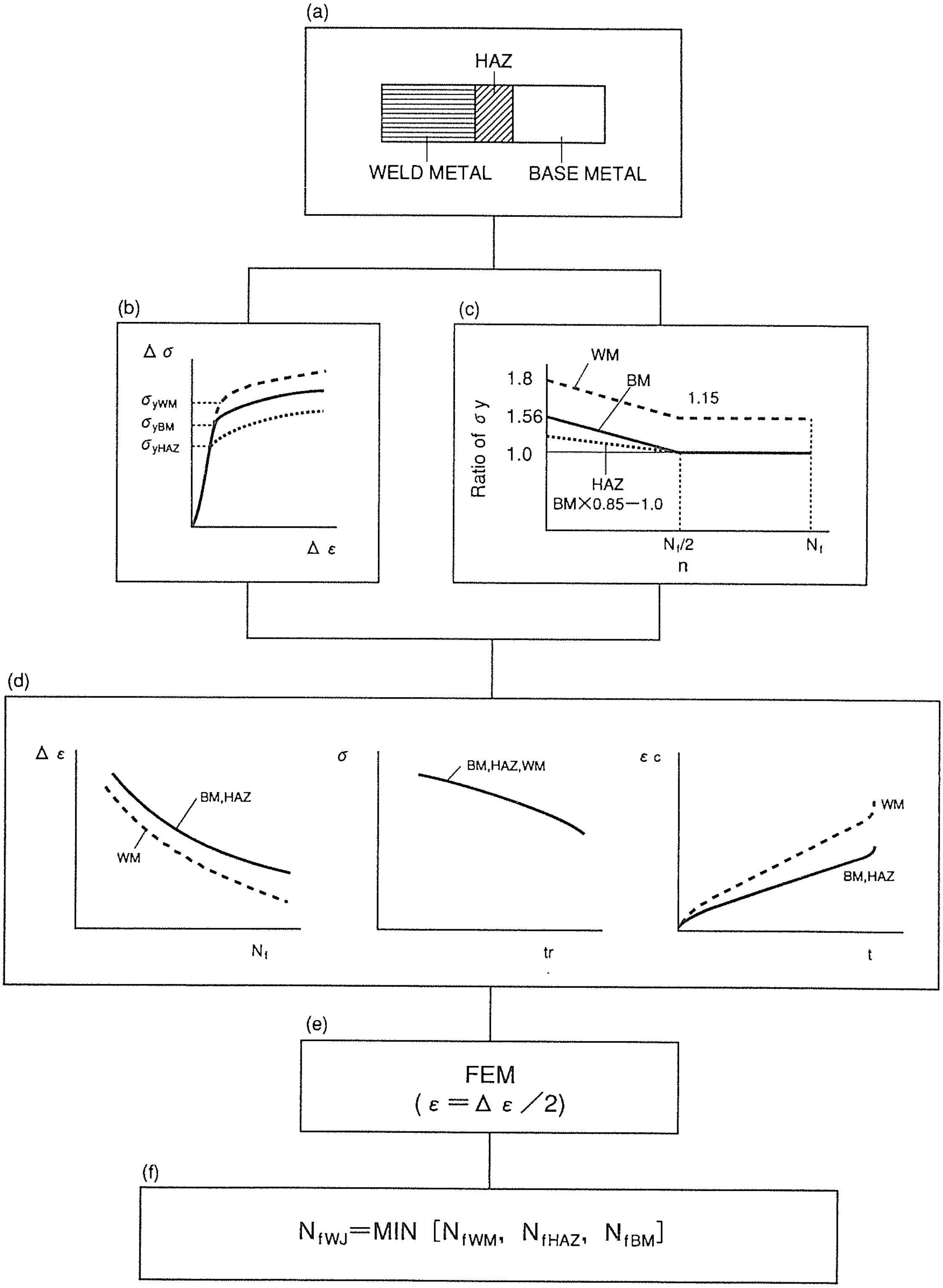


Fig.4 Flow of damage evaluation of welded joint

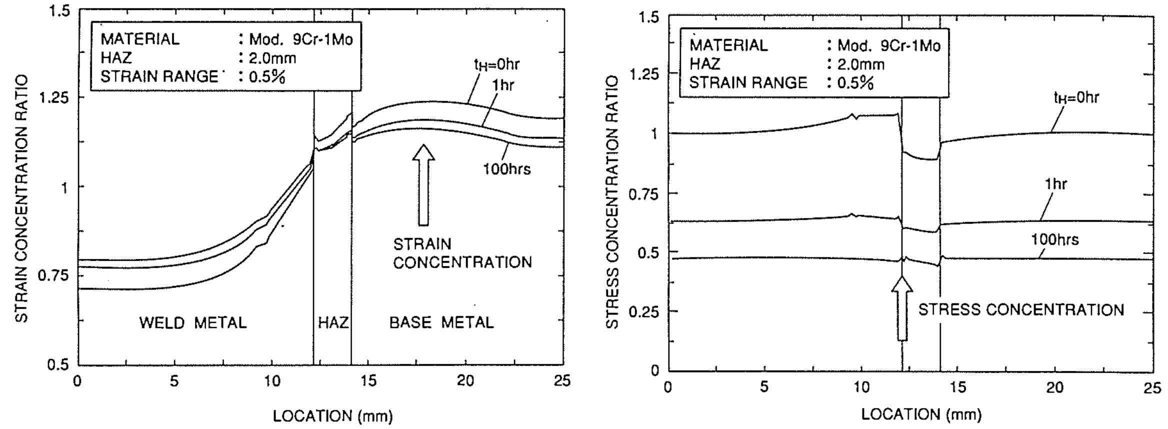


Fig.5 Distribution of strain concentration and stress concentration

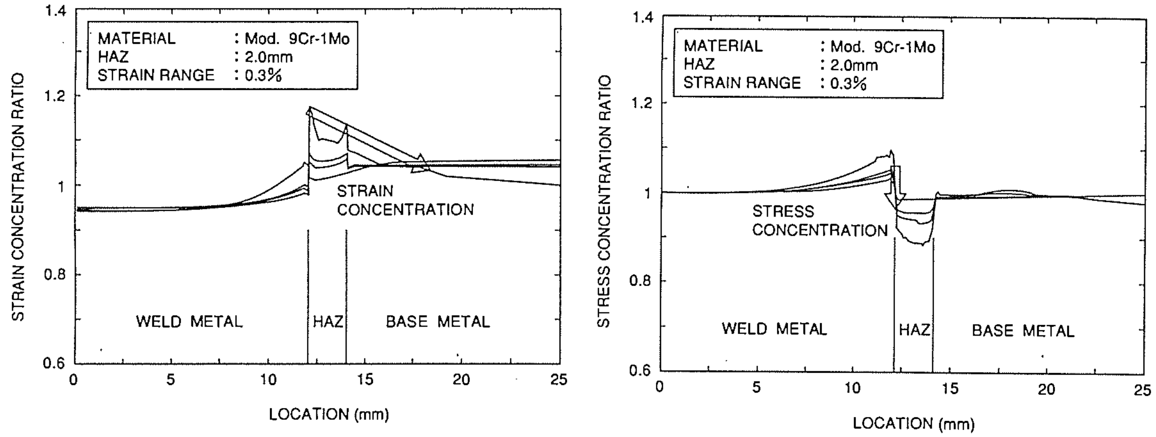
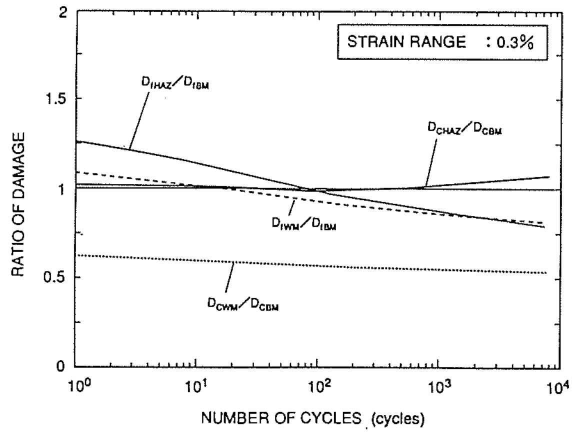


Fig.6 Change of strain / stress distribution during cyclic strain



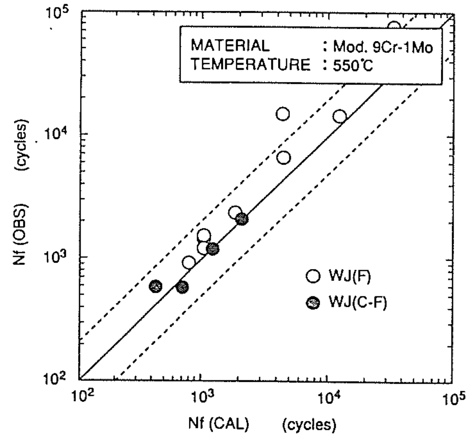


Fig.7 Accumulated fatigue damage and creep damage

Fig.8 Result of creep-fatigue life prediction