

CREEP-FATIGUE LIFE EVALUATION FOR WELDMENT OF MODIFIED 9Cr-1Mo STEEL

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ABSTRACT

In order to evaluate the creep-fatigue life for the welded joint of Modified 9Cr-1Mo steel, a series of tests were conducted and creep-fatigue properties of the welded joint were investigated. The creep-fatigue life can be as short as 20% of the pure fatigue, the magnitude of reduction being the larger, the longer the holding time, and saturating for 60 min of holding. Fracture in creep-fatigue takes place in the HAZ rather than in the base metal as is the case of pure fatigue. A method of evaluating the creep-fatigue life of the welded joint has been proposed. In the method, the welded joint is regarded to consist of the base metal part and the weld metal part, and the creep-fatigue damage is assessed individually: the fatigue damage is calculated on the Miner's rule, while the creep damage, by the ductility exhaustion rule, and the two elements are combined by the linear damage summation rule. This method has an accuracy of a factor of two on life.

KEYWORDS

Creep-fatigue, Mod.9Cr-1Mo, Welded joint, Ductility exhaustion rule

INTRODUCTION

The Modified 9Cr-1Mo steel, which has been developed primarily for the use in the demonstrator fast breeder reactor (FBR), has already been put to use in some of the recent power boilers. Although these components are designed with a sufficient margin of safety with regard to the creep-fatigue strength, we feel more is needed to further the rational designing, particular in the area of predicting the creep-fatigue life of the welded joint still remaining after a long-term operation, because this steel tends to produce softened regions in the weld heat affected zone (HAZ).

In this paper, we have studied the welded joint for following points:

1. determination of the creep-fatigue characteristics by conducting creep-fatigue tests;
2. proposition of a rational method of evaluating the creep-fatigue damage, and determination of its accuracy pertaining to the life prediction; and
3. examination of the effects of aging by conducting the creep-fatigue tests on specimens artificially aged to simulate the long-term exposure in the actual component.

TESTING METHOD

The sample was a plate of A 387 GR. 91 CL, which was used as normalize-and-tempered ($1060^{\circ}\text{C}\times 1\text{ h}$, air cooling, $760^{\circ}\text{C}\times 1\text{ h}$, air cooling). The welded joint specimens were made by the automatic TIG practice in three different ways, and called the Joints A, B, and C. Then they were subjected to the same post weld heat treatment ($740^{\circ}\text{C}\times 8.4\text{ h}$).

Fig. 1 shows the macrostructure and the hardness distribution of Joint C. Here, we observe in (a), which shows a full thickness section taken perpendicular to the weld, that HAZ is about 2 mm in width along an about 20 mm wide weld metal. In (b), we notice that the hardness scan conducted along a 1/4 thickness line has revealed the existence of softened regions of Hv 200 or so in the vicinity of HAZ-base metal boundary against Hv 250 of the weld metal and Hv 220 of the base metal. We shall call these regions the HAZ softened region.

Fig. 2 presents the test piece, the testing setup, and the loading waveform. The test piece was machined out at 1/2 the thickness part of the welded joint specimen in the direction perpendicular to the weld and so as to contain HAZ at the center of its 25 mm gauge section, which comprises 12 mm of base metal, 2 mm of HAZ, and 12 mm of weld metal. The test was conducted keeping the test piece at 600°C with a high frequency induction heater, and holding the strain amplitude in the gauge section at $\Delta\varepsilon_t = 0.5\%$ by controlling the application of the load in the trapezoidal waveform. The major parameter was the holding time, t_H , which was 10, 30, or 60 min.

RESULTS AND DISCUSSION

Creep-Fatigue Life and Examination of Failed Test Piece

Fig. 3 shows the creep-fatigue lives, together with the results obtained in a series of pure fatigue tests, i.e., creep-fatigue with $t_H = 0$ (open and solid circles). We find here that, in the case of Joint A, the ratio of the creep-fatigue life to the pure fatigue life is ca. 0.3 for $t_H = 10$ min and ca. 0.2 for both $t_H = 30$ and 60 min, whereas it is ca. 0.5 for $t_H = 10$ and ca. 0.3 for $t_H = 30$ in the case of Joint C. The larger aggravation of life in A is ascribable most probably to its welding conditions, which may not have been quite adequate. Another point is that though the aggravation is the larger, the longer the holding time, it tends to saturate for $t_H = 60$ min.

Fig. 4 represents the observations made on the fracture position of the welded joint specimens. It will be seen that where the fracture took place in the base metal near HAZ in the Joint C when it was pure fatigue (Fig. 4 (a)), it was in the center of HAZ when creep-fatigued, accompanied by occurrence of local thickness reduction in the HAZ softened region (Fig. 4 (b)). It may have been that this phenomenon arose from concentration of the creep deformation in HAZ during the strain holding time. In the case of Joint A, on the other hand, the fracture took place along the HAZ-weld metal boundary when creep-fatigued (Fig. 4 (c)), which was probably another manifestation of the difference in the welding condition mentioned above.

In the hardness distribution shown in Fig. 5, we note that, where fatigue brings about uniform reduction of hardness in base metal, HAZ, and weld metal alike (though the hardness decrease in HAZ is somewhat larger), creep-fatigue not only incurs largest hardness decrease, but equalizes the hardness for all three parts.

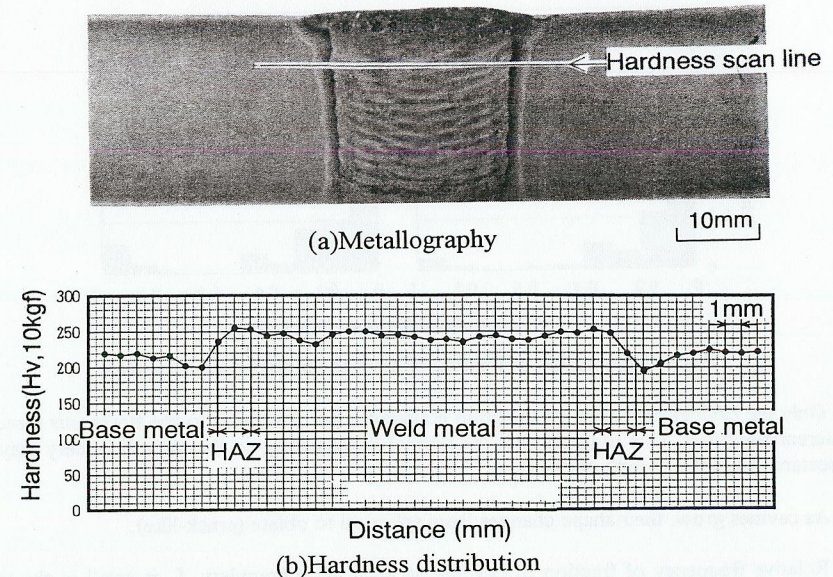
Proposition of a method of predicting the creep-fatigue life for welded joints

Fig. 1 Macrostructure and hardness distribution in the welded joint of Mod.9Cr-1Mo steel (Joint C).

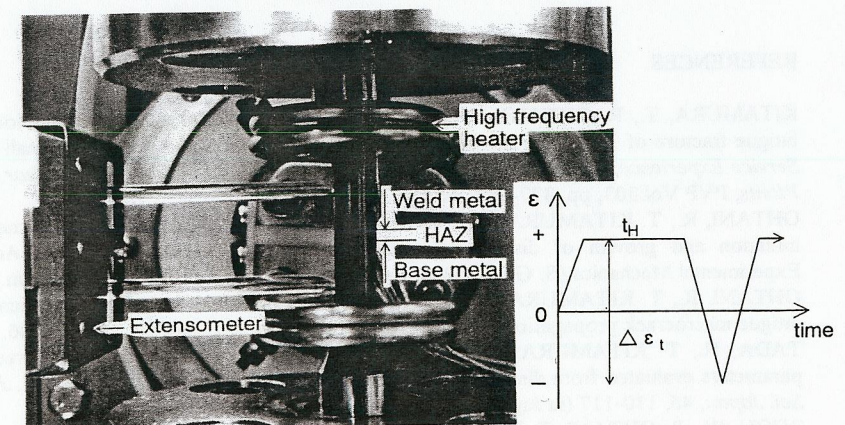


Fig. 2 Specimen, testing setup, and loading waveform for the creep-fatigue test.

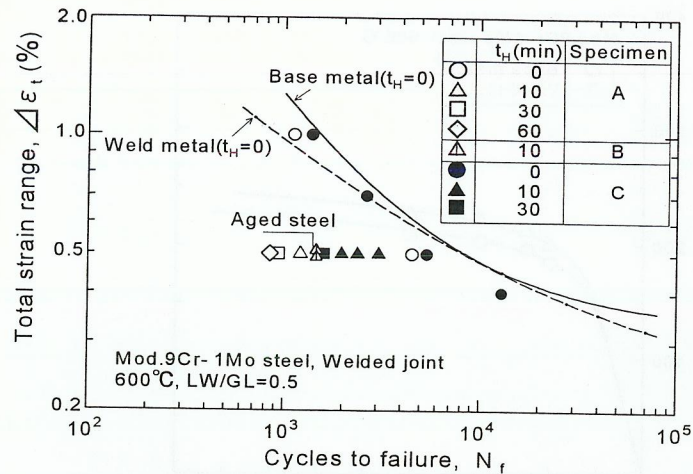


Fig.3 Creep-fatigue life of Mod.9Cr-1Mo steel welded joint.

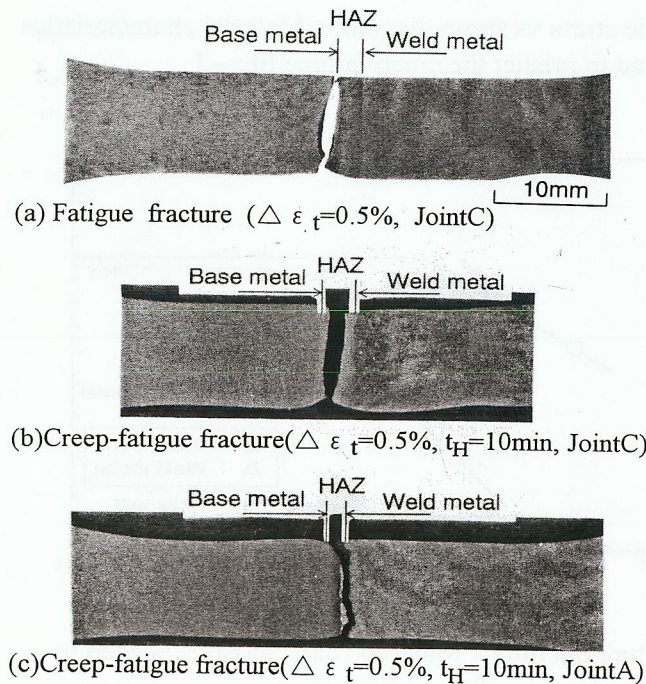


Fig.4 Fracture position of welded joint(Joints C and A).

Fig. 6 depicts the method of predicting the creep-fatigue life for welded joints we have been able to develop in the present study, based on the method of predicting the fatigue life we have reported previously (Nonaka, 1982, 1984). Here, the life is determined by calculating the creep-fatigue life for the base metal part and the weld metal part individually, then taking the smaller of the two, and the respective lives are to be obtained by first determining the fatigue damage on the Miner's rule, then calculating the creep damage by the ductility exhaustion rule as we have shown (Nonaka, 1995), and finally obtaining the creep-fatigue damage on the linear damage summation rule.

The data needed to perform those calculations are the fatigue curves for base metal and weld metal (shown in Fig. 3 as a side information), the cyclic stress vs strain diagram for base metal and weld metal (Fig. 7), the stress relaxation curve for the welded joint, and the relationship held between the fracture strain ϵ_f and the strain rate $\dot{\epsilon}$ for base metal and weld metal (Fig. 8, where $\dot{\epsilon}$ is the minimum creep rate, although the ultimate ϵ_f for large $\dot{\epsilon}$ is the one that was obtained in the tensile test). In Fig. 8, we notice that ϵ_f 's for small $\dot{\epsilon}$'s are much larger for the base metal than for the weld metal.

Precision of Prediction

As the result of life prediction, we find that the creep-fatigue life is always smaller for base metal than for weld metal ($N_{CF}^B < N_{CF}^W$), reflecting the empirical observation that fracture takes place in the base metal. Fig. 9 shows creep-fatigue damage evaluation diagram in comparison with the failure criterion line of $D_C + D_F = 1$. We observe here that, where the creep damage was evaluated adequately by the ductility exhaustion rule and fall reasonably about the criterion line, the time exhaustion rule tends to underestimate the creep damage.

The life predictions thus made are presented in Fig. 10. It is to be seen that, where the time exhaustion rule predicts the life too optimistically (here, the bent line of Fig. 9 is used for the failure criterion line), the ductility exhaustion rule predicts the life correctly by a factor of two on life. The exceptions are the case of the Joint A, particularly when t_H was 30 or 60 min, but then, as we have remarked earlier on, the welding conditions for this specimen may not have been adequate. We conclude therefore that the method of creep fatigue life prediction shown in Fig. 6 has an accuracy of a factor of two on life.

Effect of Aging

To see the effects of long-term exposure to the environment of actual component on degradation of material quality, creep fatigue test was performed on Joint B by aging it through a $600^\circ\text{C} \times 3,000 \text{ h} + 700^\circ\text{C} \times 500 \text{ h}$ treatment. The result is already shown in Fig. 3. As the result agrees with that of the non-aged counterpart, we conclude that aging of this magnitude does not give rise to substantial influence on the steel's behavior, or conversely that the Mod. 9Cr-1Mo steel is resistive to aging.

CONCLUSIONS

- 1) The creep-fatigue life of the welded joint of Mod. 9Cr-1Mo steel can be as short as 20% of the pure fatigue, the magnitude of reduction being the larger, though dependent on the welding condition, the longer the holding time, and saturating for 60 min of holding.

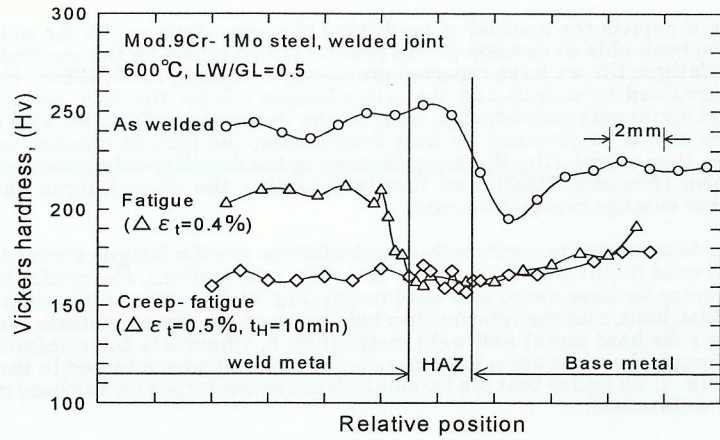


Fig.5 Effects of fatigue and creep-fatigue on the hardness distribution for welded joint of Mod.9Cr-1Mo steel.

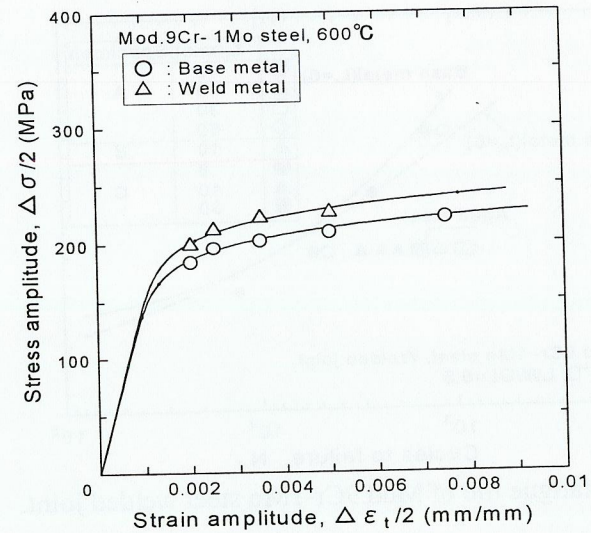


Fig.7 Cyclic stress vs strain diagram : Material characteristics needed to predict the creep-fatigue life - 1.

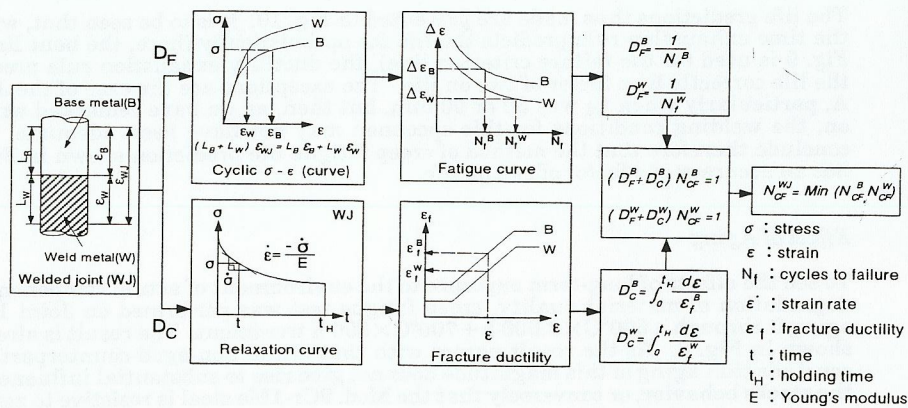


Fig.6 Flowchart for determining the creep-fatigue life of Mod.9Cr-1Mo steel welded joint .

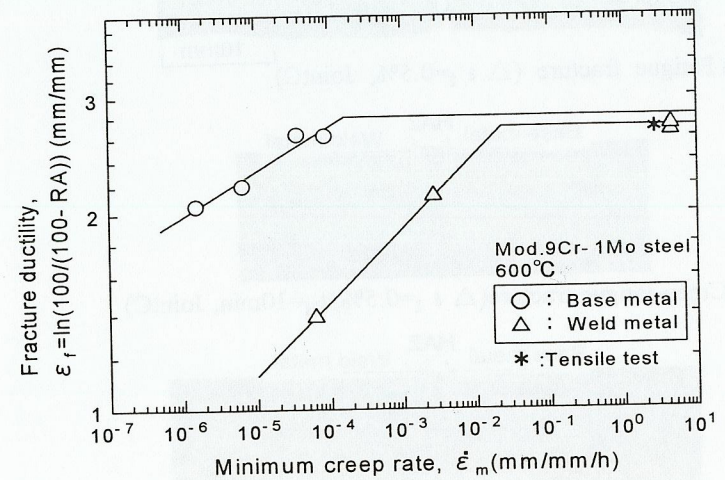


Fig.8 Fracture ductility : Material characteristics needed to predict the creep-fatigue life - 2.

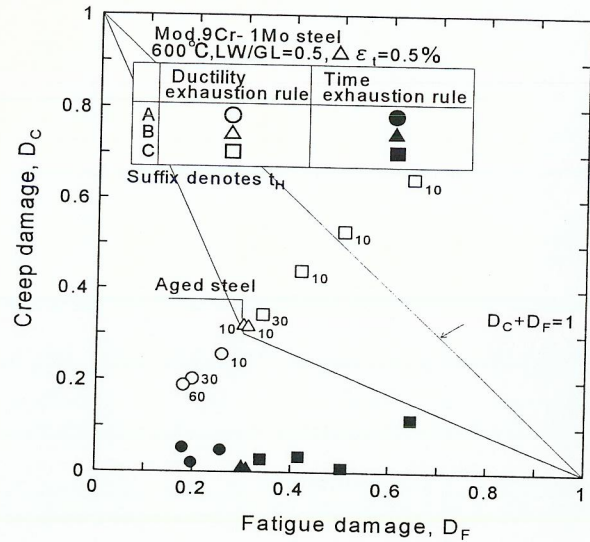


Fig.9 Creep-fatigue damage evaluation diagram for the base metal part of Mod.9Cr-1Mo steel welded joint.

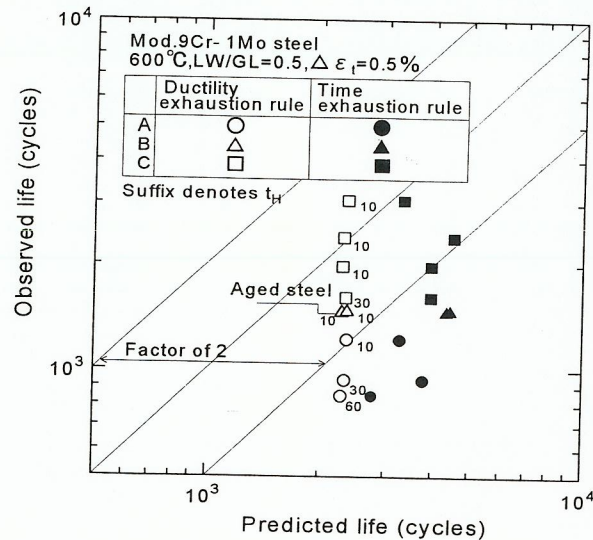


Fig.10 Results of creep-fatigue life prediction for Mod.9Cr-1Mo steel welded joint.

- 2) Fracture in creep-fatigue takes place in the HAZ rather than in the base metal as is the case of pure fatigue. As local thickness reduction was observed to occur in HAZ, moreover, it was thought possible that creep strain would concentrate in the HAZ softened region during the strain holding periods.
- 3) Creep-fatigue brings about reduction in hardness as pure fatigue does, but the reduction is larger for the weld metal than for HAZ and base metal, so that the hardness tends to be equalized throughout the welded joint.
- 4) A method of evaluating the creep-fatigue life of welded joint has been proposed. In the method, the welded joint is regarded to consist of the base metal part and the weld metal part, and the creep-fatigue damage is assessed individually: the fatigue damage is calculated on the Miner's rule, while the creep damage, by the ductility exhaustion rule, and the two elements are combined by the linear damage summation rule to give rise to two sorts of creep-fatigue lives, the smaller of which determining the joint's life.
- 5) This method has an accuracy of a factor of two in predicting the creep-fatigue life. The method that makes use of the time exhaustion rule tends to predict the life too optimistically.
- 6) Aging treatment of the order of $600^{\circ}\text{C} \times 3,000 \text{ h} + 700^{\circ}\text{C} \times 500 \text{ h}$ does not produce appreciable change in the steel behavior. Therefore, Mod. 9Cr-1Mo steel is expected to be resistive to aging degradation in the actual service environment.

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