High temperature crack growth behavior in a Cr-Mo steel weldment

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Abstract— Creep deformation and creep crack growth experiments have been conducted on Cr-Mo steel weldment in order to provide information on residual life prediction of structural component weldment containing cracks. The stress exponent of creep deformation equation for the base metal and weldment at 823K were found to be 10.2 and 7.3, respectively. The creep rate of the weldment was much lower than that of the base metal. The creep crack growth rate of the weldment was almost twice as high as that of base metal under a fixed value of C^*. This may indicate that the weldment is stronger than the base metal in view of creep deformation and is more brittle during creep crack growth due to the intrinsic bainite microstructure.

Keywords: GTAW welding, Creep crack growth, D.C. potential drop method, Creep deformation rate, C*

I. INTRODUCTION

Cracks of high temperature components generally initiate at the weldment due to high thermal stress resulting from difference in thermal expansion coefficients. These cracks grow and reach final fracture under creep condition. In this case, the remaining life of the component corresponds to the time from crack propagation to final unstable fracture. Therefore, high temperature crack growth rates of the weldment are needed to evaluate remaining life. For high temperature crack growth behavior, there are several estimation methods by parameters, such as stress intensity factor K, energy rate line integral C*, and Q* [1-3].

High temperature crack growth investigation has mainly focused on base metal. However, cracking of thick plate at high temperatures is mainly generated at weldment containing defects such as pores. Therefore, mechanical properties such as high temperature deformation and crack growth rate of the weldment as well as base metal are necessary to predict the remaining life of a thick plate with weldment. The high temperature damage behavior of weldment is inconsistent and scattered, depending on welding conditions. In general, creep crack growth rates of weldment are reported to be three to five times higher than those of their base metals [4]. However, the data are limited and even information on creep deformation of weldment is very limited. There will be large error if we adopt the mechanical properties of the base metal rather than the weldment when we predict the remaining life of high temperature components such as boiler header. This restriction results in limitation as to safe design, operation and maintenance of structure containing components.

The purpose of this investigation was to characterize the high temperature crack growth of weldment of 2.25Cr-1Mo steel which is used for components of power generation plants and chemical plants. The aim of this study was to compare, for a base metal and a weldment, the high temperature deformation and crack growth at 823K due to the two materials' different microstructures. The temperature was chosen because of typical working temperature of this type of weld joint in components.

II. EXPERIMENTAL PROCEDURES

50 mm-thick 2.25Cr-1Mo steel plates with double V grooves were butt welded by GTAW (gas tungsten arc welding). The chemical compositions of the base metal and weld wire are given in Table 1. The welding parameters are given in Table 2. The creep deformation and creep crack growth specimens were extracted from the welded plate as shown in Fig. 1. The compact tension (CT) specimen geometry with 3mm thickness, as shown in Fig. 2, was used for creep crack growth studies. The specimen was cut from a welded plate with a notch made by electro-discharge machining. The notch is 0.4 mm wide and has a tip with a 0.2 mm radius.

All the creep deformation tests were conducted at 823K in air using dog-bone type specimens with diameter of 4.8 mm and gage length of 28.6 mm under stresses ranging 180 ~ 500 MPa. The displacement during creep was measured using a linear variable differential transformer (LVDT), accurate to 1.7×10^{-3} mm.

One of the most widely used techniques to remotely monitor crack length at high temperature is the electrical potential drop (PD) method. As a crack propagates, the effective cross-sectional area of the specimen decreases and the electrical resistance increases. Given a constant electrical current input, the magnitude of the voltage difference between two fixed points on either side of the crack increases and can be related to the crack length. It is necessary to acquire calibration curve to convert PD into crack length. Calibration curves are generally given in the form of V/V_o versus a/W where a and W are the experimentally measured crack length and the length between loading line and the end of specimen (=40 mm), respectively. V and V_o are the measured and initial voltage during crack propagation, respectively. In this study, the calibration of the PD for the CT geometry was obtained using a 0.8 mm thick SUS 304 stainless steel specimen with the same sized CT as that of 2.25Cr-1Mo steel, as shown in Fig. 2. The crack length was measured optically with a traveling microscope. Direct current of 15A was supplied to the CT (compact tension) specimen.

From the PD experiments, the PD ratio (V/V_0) as a function of the normalized crack length (a/W) for the CT geometry was determined using a second-order polynomial; that is, $a/W = -0.0485 + 0.41659(V/V_0) - 0.0559(V/V_0)^2$ (Fig. 3). There is difference between the experimental curve and curve predicted by Johnson relation [5] due to the difference in location of electrical input. High temperature crack growth testing was conducted on CT specimens using lever type creep machine. A pre-crack of about 1 mm from the notch was prepared and load line displacement was measured using LVDT.

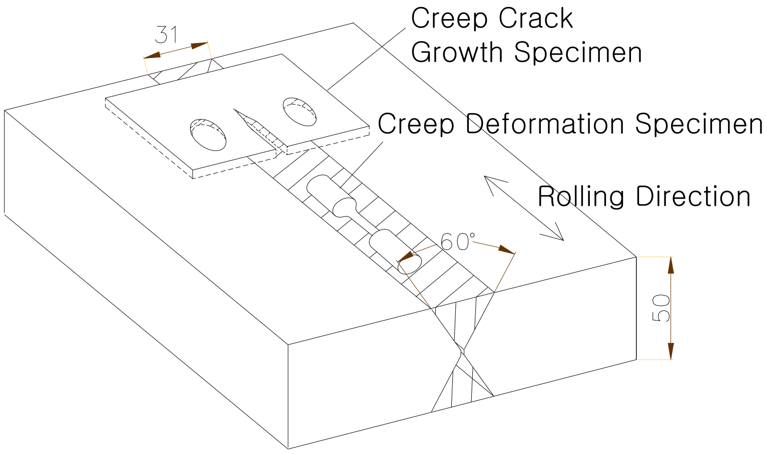


Fig. 1 Orientation of creep deformation and creep crack growth specimens in welded plate

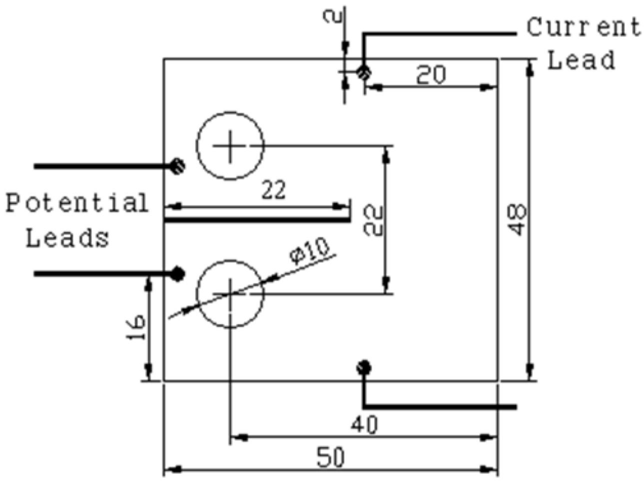


Fig. 2 Geometry of compact tension specimen

Table 1 Chemical compositions of the 2.25Cr-1Mo base metal and welding wire (wt. %)

Materials	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
base metal	0.05	0.51	0.93	0.008	0.006	2.54	0.98	-	bal.
Welding wire	0.1	0.2	0.47	0.009	0.011	2.22	1.01	0.08	bal.

Table 2 GTAW welding conditions

Dia.(mm)	Pass	Current(A)	Gas	Root(mm)	Speed(mm/sec)
2.4	50	DC 41	Argon	2	1.42

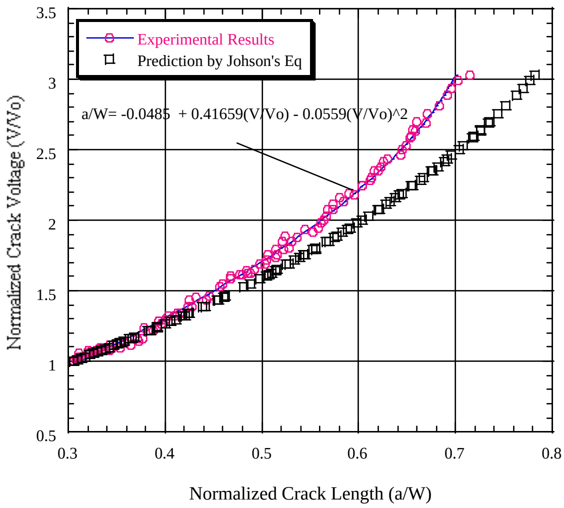


Fig. 3 Calibration curve for crack length during potential drop test

III. EXPERIMENTAL RESULTS AND DISCUSSION

The results of steady-state creep tests are plotted in Fig. 4 in the form of a steady state creep rate, $\dot{\varepsilon}$, against the applied tensile stress, σ, on a logarithmic scale at 823K. The value of the stress exponent, n= $d\ln\dot{\varepsilon}/d\ln\sigma$, were found to be 10.2 and 7.3 for the base metal and weldment, respectively, suggesting that the creep behavior of these alloys was controlled by a dislocation climb process at 823K. The value of the stress exponent is in good agreement with the value reported by other researcher [6] for the same alloy. As can be seen in Fig. 4, creep rate of the weldment is at least 1000 times lower than that of base metal. The relationships between creep rate and applied stress for the base metal and weldment at the stress range from 180 to 500 MPa are as follows;

$$\dot{\varepsilon} = 1.75\times10^{-31}\sigma^{10.2} \text{ (in MPa and sec) : for base metal} \quad (1)$$

$$\dot{\varepsilon} = 1.32\times10^{-27}\sigma^{7.3} \text{ (in MPa and sec) : for weldment} \quad (2)$$

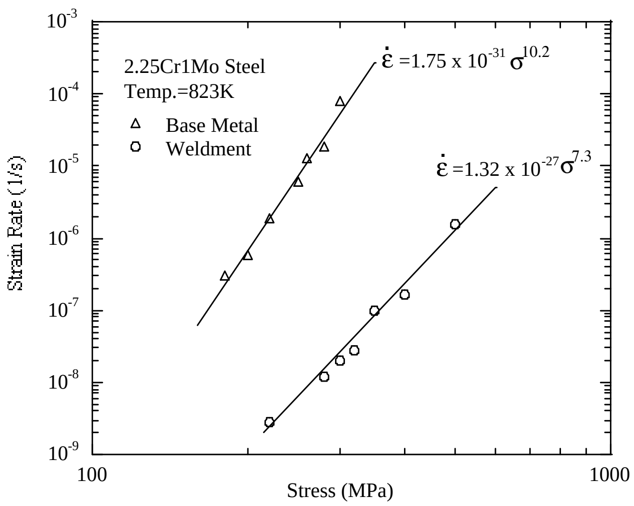


Fig. 4 Steady state creep strain rate vs. applied stress for the base metal and weldment of 2.25Cr-1Mo steel

Two creep crack growth tests were performed at 823K on CT specimens for base metal and weldment under a static load of 1960 N and 2394 N. The increase in the creep crack growth rates with time is shown in Fig. 5. The near-tip stress and strain rate fields under stationary creep conditions are characterized by the C* parameter. The calculation of the values of C* for the CT geometry are based on the assumption that the specimen is under plane stress condition because of the thin thickness of the specimen. The high temperature crack growth rate parameter C* was determined using the following equations [7].

$$C^* = g_2 \frac{P}{B_n(W-a)} \dot{\delta} \quad (3)$$

where $\dot{\delta}$ is the load line displacement rate and B_n is the specimen thickness. The stress exponent n of steady-state creep rate were found to be n = 10 and n = 7 for the base metal and weldment, respectively. The geometric factor of the CT specimen g_2 in plane strain condition can be determined.

$$g_2 = \frac{1.274 + 3.209(a/W) - 5.276(a/W)^2 + 2.247(a/W)^3}{(a/W)^{-0.242}} \quad \text{: for base metal} \quad (4)$$

$$g_2 = \frac{0.197 - 0.878(a/W) + 2.152(a/W)^2}{0.074 + (a/W)^3} \quad \text{: for weldment} \quad (5)$$

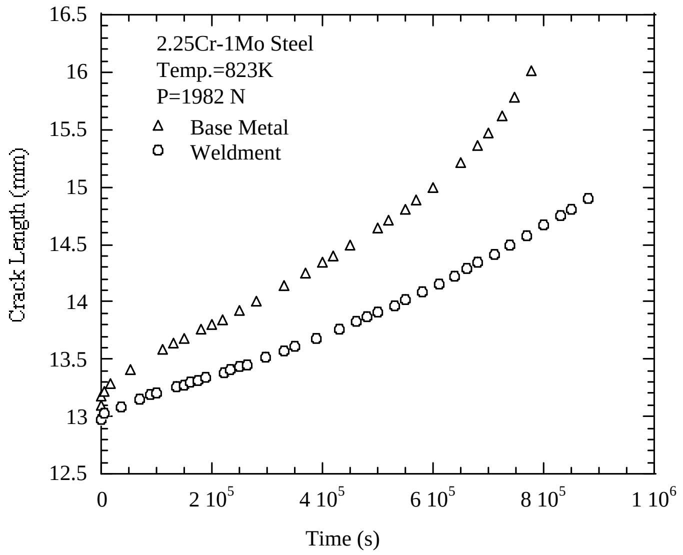


Fig. 5 Creep crack growth as a function of time for the base metal and weldment

In Fig. 6, the crack growth rate, da/dt, is plotted as a function of C*. A good correlation can be observed in the experimental data from the two different loading conditions (P = 1960 N and 2394 N), indicating that C* is a proper parameter for expressing the creep crack growth rates of these materials under the current testing conditions. The high temperature crack grow rate of 2.25Cr-1Mo steel base metal and weld zone at 823K under mode I can be described as follows;

$$da/dt = 1.81 \times 10^{-8} (C^*)^{0.84} \quad \text{: for base metal} \quad (6)$$

$$da/dt = 8.58 \times 10^{-9} (C^*)^{0.92} \quad \text{: for weldment} \quad (7)$$

Fig. 6 shows that the crack growth rate of base metal is twice as high as that of the weldment at the same value of C*. As mentioned previously, the creep rate of the base metal is at least 1000 times higher than that of the weldment. From these facts, it can be judged that the strength of the weldment is very strong; however, the zone is very vulnerable to cracking due to brittleness, indicating that crack propagation in this zone occurs with low energy. This assumption can be verified by the fact that the creep strain to failure of the base metal is larger than that of the weldment under the same testing condition. For example, the creep strain to failure of the base metal and the weldment were 38% and 18%, respectively, at the applied stress of 300 MPa.

The tensile strength at ambient temperature and creep strength of 2.25Cr-1Mo steel are known to be largely influenced by solid solution strengthening with alloy elements (for example, Mo, Mn) and by carbide size and distribution which block dislocation movement. Grain size and morphology affect these strengths. A smaller grain size causes higher diffusion of atoms, resulting in a higher creep rate. The microstructures of base metals and weldments before and after creep test were observed using optical microscope. Optical photographs of the (a) base metal, (b) weldment, (c) base metal after creep deformation and (d) weldment after creep deformation are shown in Fig. 7. As can be seen in Fig. 7(a), the base metal has ferrite grain size of 18.5 μm; these grains contain tiny carbides and small amount of bainite. The microstructure of weldment contains lower banite phase, as shown in Fig. 3(b). The different microstructures between the base metal and weldment may cause by heat history during weld process. The stronger creep strength of weldment results from the bainite phase; this can be compared to the strength of the base metal, which has a weaker ferrite phase. The bainite microstructure of the weldment resulted in acceleration of high temperature crack growth in the weldment due to inherent brittleness even though the bainite exhibits very low creep strain rate. The base metal shows coarse precipitates formed by decomposition of tiny carbides in the ferrite grain after creep deformation, as shown in Fig. 7(c). These coarse precipitates cannot block the dislocation movement effectively and the creep strength of the base metal comes to deteriorate with time. The ferrite grain size shown in Fig. 3(c) was measured to be 22.3 μm after grain growth. The microstructure of the weldment becomes tiny tempered bainite after longer creep testing, as shown in Fig. 7(d).

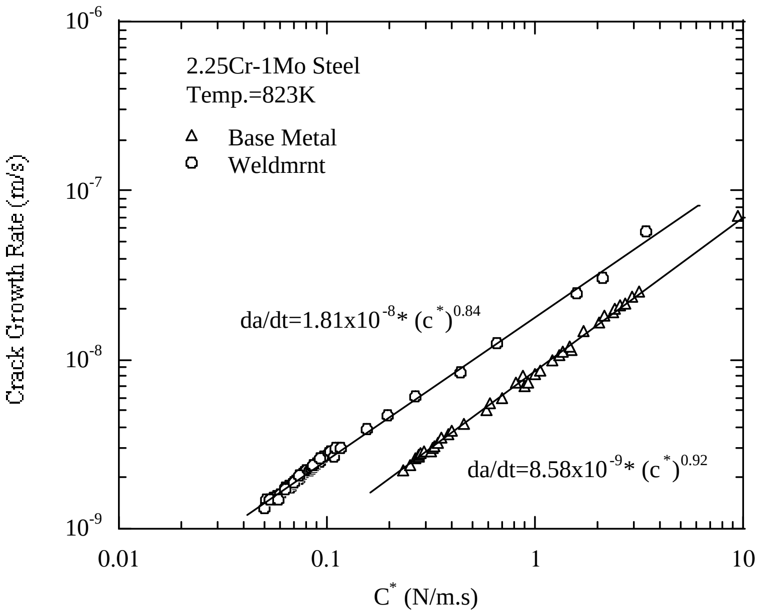
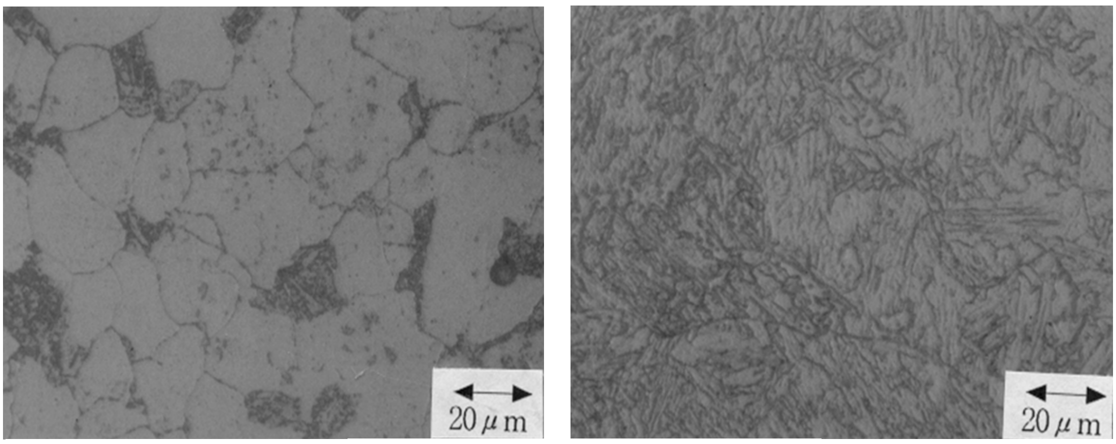
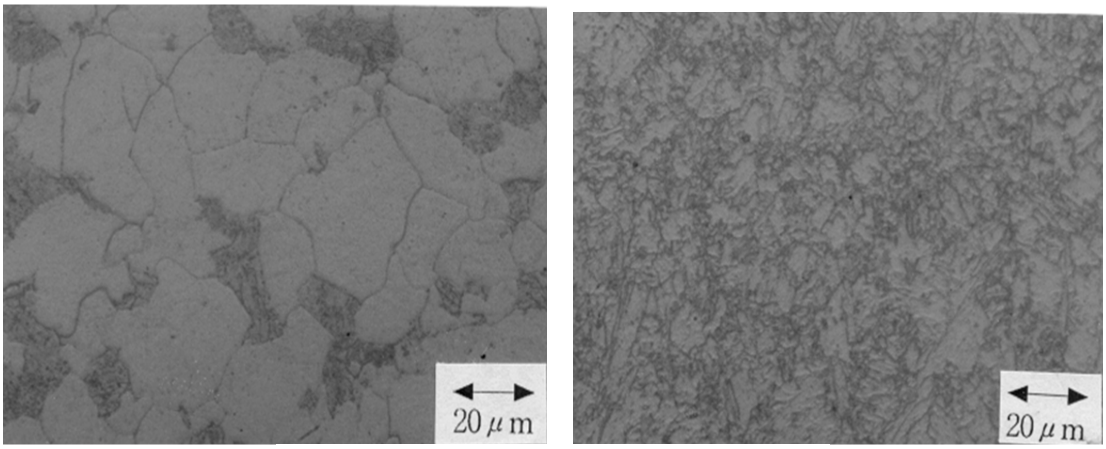


Fig. 6 Creep crack growth rate of 2.25Cr-1Mo steel base metal and weldment at 823K



(a) (b)



(c) (d)

Fig. 7 Optical microstructures of (a) base metal, (b) weldment, (c) base metal after creep deformation and (d) weldment after creep deformation

IV. CONCLUSION

The following conclusions are drawn for the high temperature deformation and crack growth rate of base metal and weldment of 2.25Cr-1Mo steel. For the testing temperature of 823K at applied stress levels ranging from 180 to 500 MPa, creep rate of the weldment is at least 1000 times lower than that of base metal. And, the stress exponent n were found to be 10.2 and 7.3 for the base metal and weldment, respectively, suggesting that the creep behavior of these alloys was controlled by a dislocation climb process at the testing temperature. C* is a proper parameter for expressing the creep crack growth rates of these materials under the current testing conditions. The crack growth rate of base metal is twice as high as that of the weldment at the same value of C*. The much stronger creep strength and slightly stronger creep crack growth resistance of weldment are partially due to the intrinsic bainite microstructure, compared to the case of the base metal.

ACKNOWLEDGMENT

This study was financially supported by the Research Program funded by the Seoul National University of Science and Technology.

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