FATIGUE CRACK PROPAGATION IN THE WELD BOND REGION OF A TYPE 304 STAINLESS STEEL WELDMENT

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ABSTRACT

The fatigue crack growth in a Type 304 stainless steel welded joint was investigated. In particular, attention is focussed to the fatigue crack growth behavior of the "cross-bond type" crack, the front of which is inhomogeneous and consists of two regions; one is the weld metal region and the other is the parent metal region.

Although the effect of residual stress on the fatigue crack growth rate was quite significant, that of the microstructure of the weld metal was also found to be significant: The growth rate of a weld metal specimen was higher than that of a parent metal specimen when the growth rate was plotted against effective stress intensity range. The effect of residual stress on fatigue crack growth rate can be found even after solution treatment (1050°C for 1.5 hr). Hence, it may be conservative to consider that after usual PWHT, residual stress which can have an effect on fatigue crack growth rate is still present. For the cross-bond type specimens, it was found that the cracks in the weld metal and parent metal regions did not interact with each other and propagated independently in each region: The fatigue crack in the weld metal region propagated faster than in the parent metal region.

KEYWORDS

Fatigue; fatigue crack propagation; welded joint; SUS304 stainless steel

INTRODUCTION

A large number of studies on the fatigue crack growth in welded joints has been carried out (see Ref.). Many of them are concerned with the effect of residual stress and investigations related to the effects of microstructure and of heterogeneity in mechanical properties are quite few. For example of the latter case, Pickard, Ritchie and Knott (1975) have investigated the crack growth behavior in the case for which the direction of crack growth is perpendicular to the welding direction and the crack grows across the weld metal. However, in previous work, attention is focussed only on to the case when mechanical properties and microstructure along the crack front can be considered to be homogeneous.

When the crack grows in the bond region of X-, K-, or V-grooved welded joints in the welding direction, mechanical properties and microstructure along the crack front are inhomogeneous. In the present study, this type of specimen is called a "cross-bond type" specimen because the crack front crosses the bond region. The fatigue crack growth behavior of this case has not yet been clarified. In this study, the crack growth behavior of the cross-bond type specimen, the crack front of which is inhomogeneous and consists of two regions (the weld metal region and the parent metal region), as well as of the parent metal and the weld metal specimens is investigated in detail. The crack growth behavior of the specimen which has a crack perpendicular to the welding direction is also investigated.

EXPERIMENTAL PROCEDURE

The material used is a Type 304 stainless steel rolled plate of 19 mm thickness, the chemical composition and mechanical properties of which are shown in Table 1 and 2, respectively. A welded joint was produced by using SMAW with the welding conditions indicated in Table 3. Seven types of specimens, as shown in Table 4, were prepared. The specimen geometry is shown in Fig.1.

Table 1 Chemical composition (wt%)

C	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.049	0.66	1.20	0.033	0.008	8.38	18.16	0.11	0.10

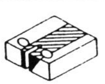
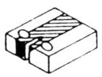
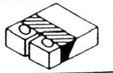
Table 2 Mechanical properties

Yield Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
304	720	73

Table 3 Welding conditions

Welding electrode	JIS D 308
Welding current	150 Amp.
Arc voltage	26 Volt
Welding speed	15 cm/min
Weld heat imput	16 kJ/cm
Number of pass	6 + 1

Table 4 List of specimens tested

PM specimen	the parent metal specimen	
WM specimen	the crack grows in the weld metal in the welding direction	
WMST specimen	the solution treated (1050°C for 1.5hr) WM specimen	
SPM specimen	the sensitized (650°C for 2hr) parent metal specimen	
CB specimen	the crack front crosses the bond and consists of the weld metal and the parent metal regions	
CBST specimen	the solution treated (1050°C for 1.5hr) CB specimen	
T specimen	the crack grows in the direction perpendicular to the welding direction	

Micrographs of the welded bond region, the weld metal region and the solution treated (1050°C for 1.5hr) weld metal region are shown in Fig. 2(a),(b) and (c), respectively. As can be seen from the figure, in the weld metal region, delta ferrite and micro-inclusions were in the austenitic matrix. From the results of hardness measurements, very little difference in hardness between the parent metal and the weld metal was found and the hardnesses were almost equal to H_V = 260. From the results of residual stress measurements, the residual stress in the direction perpendicular to the direction of crack growth was compressive.

Fatigue crack growth tests were performed on a 98 kN servohydraulic MTS testing machine, operating at a frequency of 40 Hz (sine wave) in air at room temperature. Only one value of stress ratio was used; $R = K_{min}/K_{max} = 0.05$. Optical microscopy (×30) was used to measure the crack length. The stress intensity range ΔK was derived using the following equation.

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4),$$

where ΔP is the load amplitude, $\alpha = a/W$, a is the crack length, W the effective width of the specimen and B the specimen thickness. The crack closure points were determined by using the electric compliance method (Kikukawa, Jono and Hora, 1977) to discuss the effect of the residual stress on the crack growth of WM specimens.

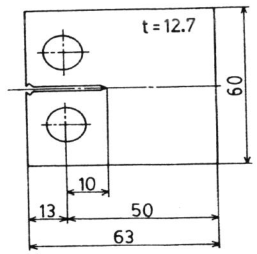
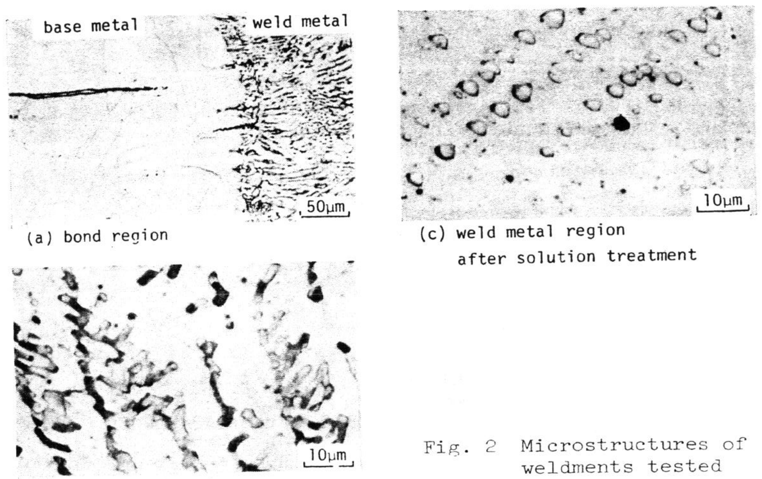


Fig. 1 Dimensions of CT specimen

RESULTS AND DISCUSSION

PM, WM AND SPM SPECIMENS: The relationships between crack growth rate and stress intensity range in PM, WM, WMST and SPM specimens are shown in Fig. 3. As can be seen from the figure, the crack



(a) bond region

(c) weld metal region after solution treatment

(b) weld metal region

Fig. 2 Microstructures of weldments tested growth rate of the WM specimen which has the residual compressive stress near the crack front is lower than that of the PM specimen. Although an almost perfect solution treatment (1050°C for 1.5hr) was carried out, it seems that the residual compressive stress which can influence the crack growth rate was still present. From the fractographic observations, a large number of inclusions and dimples was observed on the fracture surfaces of the WM and WMST specimens. From EPMA analysis, Si and Mn were main constituents of the inclusions.

As can be seen from Fig. 3, the crack growth rate of the SPM specimen agrees with that of the PM specimen and the apparent effect of the sensitivity treatment was hardly found. However, from the fractographic observations, as shown in Fig. 4(c), intergranular fracture facets were often found and the significant effect of the sensitivity treatment was recognized at least on the fracture surface.

The relationship between crack growth rate and effective intensity range ΔK_{eff} which is calculated by using the load range from the crack opening load to the maximum load was investigated to discuss seperately the effect of mechanical and microstructural factors. The relationships in PM, WM and WMST specimens are shown in Fig. 5. As can

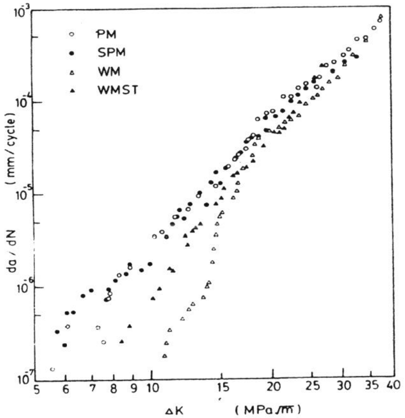
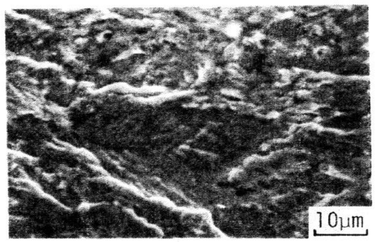
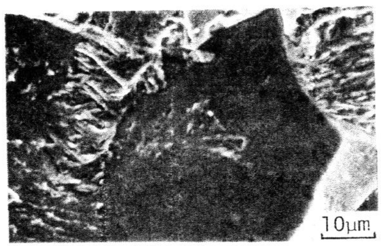


Fig. 3 Fatigue crack growth rate as a function of stress intensity range

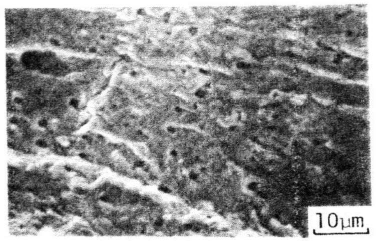


(a) PM specimen



(c) SPM specimen

direction of crack growth



(b) WM specimen

Fig. 4 Fractographs of (a) PM specimen, (b) WM specimen and (c) SPM specimen

be seen from the figure, the crack growth rates of the WM and WMST specimens are almost same and higher than that of the PM specimen. The result indicates that the crack growth rate of the weld metal used here depends not only on a mechanical factor (residual stress) but also on a microstructural factor. The microstructural factors influencing the crack growth rate can be considered to be (1) grain size, (2) inclusions, (3) delta ferrite, (4) martensitic transformation, etc. From the result of the fatigue crack growth test of the PM specimen with large grain diameter of 950 μm, which is almost equal to the width of dendrite structure in the weld metal, as shown in Fig. 6, the crack growth rate was in good agreement with that for the WM specimen. From the observations of martensitic transformation by using the "Magnetic Viewer" where colloidal magnetic particles (γ-Fe_2O) are utilized, martensitic transformation was found near the fracture surface of the PM specimen with large grain diameter of 950 μm as well as in the weld metal region of the WM and WMST specimens, while no martensitic transformation was recognized in the PM specimen with normal grain diameter of 80 μm. Bathias and Pelloux (1973) have shown that the crack growth rate in martensitic steels is markedly higher than that for austenitic steels. Therefore, the main microstructural factor is seemed to be that the dendrite structure of the weld metal is too coarse to easily cause martensitic transformation.

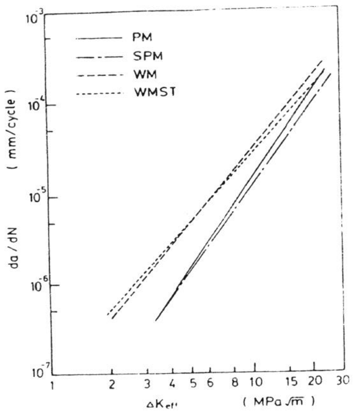


Fig. 5 Fatigue crack growth rate as a function of effective stress intensity range

CB SPECIMEN: Figrue 7 shows the relationship between number of cycles and crack lengths measured on the parent metal side and on the weld metal side in a CB specimen. As can be seen from the figure, the crack on the weld metal side grows faster than that on

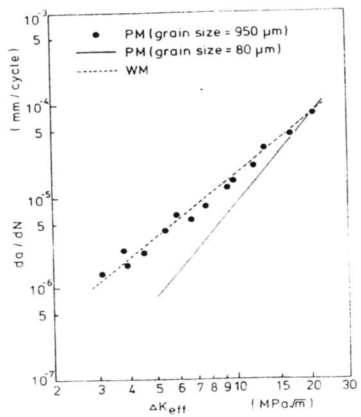


Fig. 6 Fatigue crack growth rate as a function of effective stress intensity range

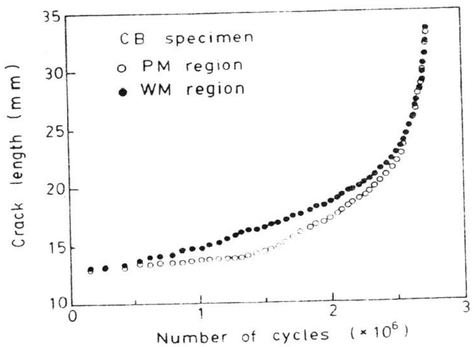


Fig. 7 Crack length vs. number of cycles curves for a CB specimen

the parent metal side. The tendency was also observed in a CBST specimen. Although three-dimensional analysis may be required to obtain the values of K along the crack front which is not straight, the relationship between the crack growth rate and effective stress intensity range ΔK_{eff} was investigated using the crack lengths measured on each surface and also using the macroscopic and average crack opening points measured by using a clip guage. The results are shown in Fig. 8. As can be seen from the figure, the crack growth rate on the weld metal side is faster than that on the parent metal side, even though the difference of the growth rate is smaller than that between the PM and WM specimens shown in Fig. 5. Actually, since the crack in the weld metal region grows faster as shown in Fig. 7, the crack closure in the weld metal region is considered to occur earlier than that in the parent metal region. In the case of a CB specimen, the significance of the closure point measured by using a clip guage is not clear. Supposing such an extreme case that the closure point measured corresponds to that in the weld metal region and no crack closure in the parent metal region, the effective stress intensity range in the parent metal region can be reduced as shown by the solid line with dots in Fig. 9. In the extreme case, the difference in the crack growth rate between the parent metal and the weld metal regions is more significant than that between the PM and WM specimens shown in Fig. 5. From the foregoing results, in the CB specimen, although the crack growth behaviors in the weld metal and the parent metal regions may influence each other slightly, at least the intermediate behavior between them is not observed, and instead, isolated crack growth behavior seems to occur in each region.

From the fractographic observations, as shown in Fig. 9, a relatively large step was found along the boundary between the weld metal and parent metal regions. The result is considered to show that the cracks grow along isolated paths in each region and this does not contradict the previous statement that isolated crack growth behavior occurs in each region.

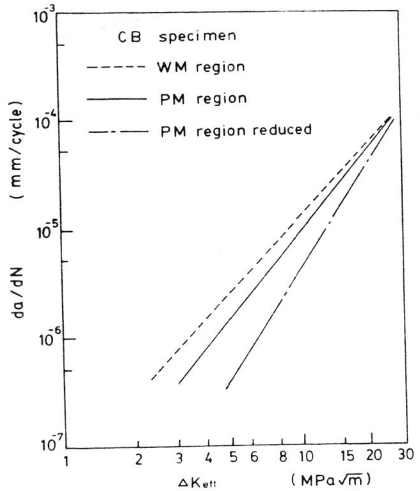


Fig. 8 Fatigue crack growth rate as a function of effective stress intensity range for a CB specimen

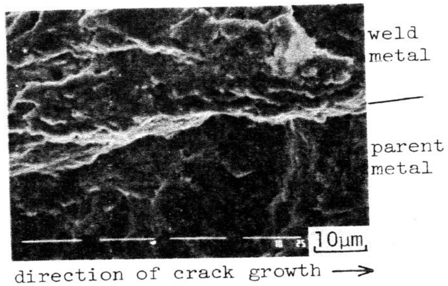


Fig. 9 A fractograph of a CB specimen

T SPECIMEN: A ΔK-constant test (ΔK = 25 MPa√m) was carried out. The relationship between crack growth rate and crack length is shown in Fig. 10. The crack growth rate of the weld metal (WM) region is smaller (by about one order of magnitude) than that of the WM specimen at the same ΔK-level, which is shown in Fig. 3. This is cuased mainly by the difference of residual stress levels along and perpendicular to the welding direction: The U-value of the T specimen was about 0.2 and that of the WM specimen at the same ΔK-level was about 0.6. The relationship between crack growth rate and effective stress intensity range is shown in Fig. 11. In the figure, the results of the PM and the WM specimens are also shown by using solid and broken lines, respectively. The crack growth rates of the T and PM specimens almost agree in the PM region. On the other hand, the crack growth rate of the T specimen seems to be rather higher than that of the WM specimen in the WM region. Although the reason is not always clear, this phenomenon seems to be cuased by the heterogeneity of microstructure in the weld metal, which is produced during solidification. In the CB region, which corresponds to the CB specimen mentioned in the previous section, the crack growth rate agrees with that of the WM specimen or the WM region of the T specimen. This results from the fact that the crack length was measured on the weld metal side and does not contradict the previous statement that the isolated crack groth behavior occurs in each region.

CONCLUSIONS

(1) In the range of the material used, the effect of microstructure as well as of residual stress on crack growth rate of the weld metal specimen was significant.

(2) The effect of residual stress on crack growth rate was found even in a solution treated weld metal specimen. Therefore, it may be conservative to consider that even after usual stress relief treatment, a residual stress of sufficient magnitude of influence the crack growth rate still remains.

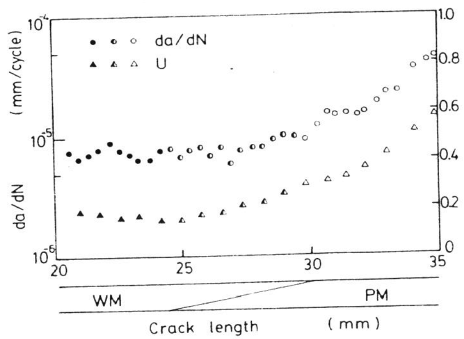


Fig. 10 Fatigue crack growth rate and crack opening ratio, U, plotted against crack length for a T specimen

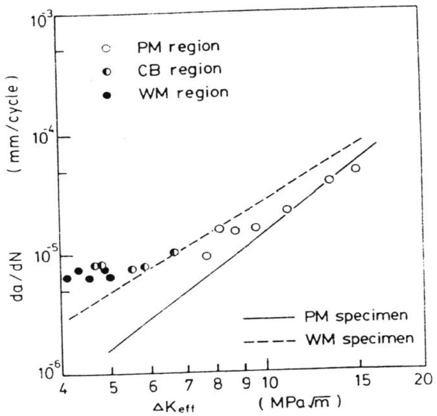


Fig. 11 Fatigue crack growth rate as a function of effective stress intensity range for a T specimen

(3) The main microstructural factor accelerating the crack growth rate in the weld metal is seemed to be that dendrite structure of the weld metal is too coarse to easily cause martensitic transformation.

(4) In the case of the "cross-bond type" (CB) specimen, the crack front of which has both the weld metal and the parent metal regions, isolated crack growth behavior seemed to occur in each region and intermediate behavior between the two regions was hardly observed.

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