Fatigue Crack Growth Behavior in Welded Joints of High-Strength Steel under Low Temperatures*

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Fatigue crack growth rates in the base metal and welds of HT80 steel welded joints were evaluated at temperatures ranging from room temperature down to 93 K. For the welds, the crack growth rates between room temperature and 173 K were dominated by residual stresses rather than temperatures. As temperatures decreased below 123 K, the crack growth rates of the base metal and welds increased markedly because of cyclic cleavage during striation growth. The crack growth rates of the welds were correlated with an effective stress intensity factor range, ΔK_{eff} , which was estimated by superposition of the respective stress intensity factors for the residual stress fields and for the applied stresses when the crack growth was dominated by striation formation.

Key Words: Fatigue, Crack Growth, Welded Joint, Residual Stress, Crack Closure, Stress Ratio, Superposition, Low Temperature, Fracture Mechanics

1. Introduction

Some defects such as undercuts or lack of penetration are sometimes introduced into welds in structures due to restrictions of the welding procedure. When a structure containing these defects with high stress concentration was subjected to cyclic loadings under low temperatures, fatigue cracks sometimes initiated from the defects and propagated to such an extent that unstable fracture occurred. In particular, fatigue crack growth is accelerated at low temperature, becoming unstable because of reduced fracture toughness of the welds. To prevent such failure introduced by fatigue cracks growing from welding defects, it is important for us to obtain further knowledge concerning the behavior of fatigue crack growth and fracture toughness of welds under low temperatures. Numerous data on the fatigue crack growth of welds at room temperature have been obtained. However, data concerning welds at low temperatures are

less commonly reported^{(1)~(3)}. As regards the study of fatigue crack growth in welds at low temperatures, it has been shown that the crack growth rate is mainly affected by the fracture mechanisms with reducing fracture toughness and the residual stresses. The influence of residual stresses on the fatigue crack growth rate has been evaluated using an effective stress intensity factor range estimated based on crack closure measurement⁽³⁾. Application of this approach to real large welded structures, however, may be often difficult from a practical point of view. As the superposition principle is applicable for an elastic body with a crack, the crack growth rates in material with residual stresses at room temperature have hence been evaluated by superposition of the respective stress intensity for the residual stress fields and for the applied stresses^{(4)~(12)}. Fatigue cracks at low temperatures mainly behave elastically. Therefore it may be possible to evaluate the fatigue crack growth rate, da/dN , by applying the superposition approach. In this study, we assume that the effect of residual stresses on crack growth rate is equivalent to the stress ratio effect, the fatigue crack growth behavior of welded joints and the base metal in a HT80 steel at tempera-

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tures ranging from room temperature down to 93 K is evaluated using the effective stress intensity factor range which takes into account the residual stresses and temperatures. The effects of low temperatures on the fracture mechanisms during the fatigue crack growth and the fatigue fracture toughness are also examined.

2. Material and Specimens

The material used in this study was a 3 080 mm long, 1 830 mm wide, and 16 mm thick HT80 steel plate. The mechanical properties of the plate from room temperature down to 93 K are shown in Table 1. The plate was divided into ten strips, each $300 \times 1\,580 \times 16$ mm, by fusion cutting across the rolling direction. A pair of strips was machined with a double-V groove and butt-welded with a manual arc welding technique. The welding parameters are summarized in Table 2. Two types of specimens, compact type (CT) specimens with a 14 mm thickness and a 100 mm width, and center-cracked tension (CCT) specimens with 4 or 8 mm thickness and 100 mm width were machined from the welded strips. The notch in each specimen was oriented so that the crack passes through the weld metal parallel to the welding direction. The specimen geometry for the base metal was CT with a width of 100 mm and a thickness of 14 mm.

Table 1 Mechanical properties of the base metal

Temperature K	0.2% Proof strength MPa	Tensile strength MPa	Elongation %	Young's modulus MPa
Room temp.	760	817	26.0	197.6
223	785	873	19.8	198.3
173	893	939	18.8	202.2
123	981	1020	17.0	208.1
93	1000	1059	15.3	214.5

Table 2 Welding parameters

Parameter	Value
Groove	Double V
Position	Plate
Electrode dia.	4 and 8 mm
Current	180 - 220 A
Arc voltage	35 V
Welding speed	180 - 220 mm/min
Heat input	17.2 - 25.7 kJ/cm
Number of runs	6

Heat treatment was not performed for all specimens.

3. Experimental Procedures

Fatigue crack growth tests were carried out at room temperature (around 293 K) and 223, 173, 123, and 93 K using a 196 kN closed-loop servo-hydraulic fatigue machine attached to a refrigeration chamber. The stress ratios, R , were 0.05, 0.25, 0.5, and 0.8; and the frequencies ranged from 10 to 25 Hz. Low temperatures were achieved by controlling the flow quantity of liquid nitrogen into the refrigeration chamber, as reported elsewhere⁽¹²⁾. Changes in the crack length during the fatigue tests at room temperature were measured by using a traveling microscope at 50 times with a vernier scale. For low temperatures, direct measurement of the crack length was not possible; therefore the crack length was measured by using both the crack gages and beach mark methods in combination. The fatigue crack growth rates were determined graphically by taking the slopes of the crack growth curve at various crack lengths. The stress intensity factor for the CT specimens was estimated by Srawley's equation⁽¹³⁾, and that for the CCT specimens was evaluated by Isida's equation⁽¹⁴⁾ which takes into account the effect of an eccentric crack in the specimen. Crack closure during fatigue crack growth was measured at 0.05 Hz by using the unloading elastic compliance method. Welding residual stresses were measured by the sectioning method using rosette-type strain gages of 1 or 2 mm in length mounted on the specimens.

4. Results and Discussion

4.1 Fatigue crack growth behavior

Figure 1 shows the relationship between fatigue crack growth rate, da/dN , and stress intensity factor range, ΔK , for the base metal at temperatures ranging from room temperature down to 93 K. As compared with the crack growth rates in each temperature for the same stress ratio, R , the crack growth rates at temperatures ranging from room temperature to 123 K showed a tendency to decrease slightly with decreasing temperatures. As temperatures decreased below 123 K, however, the crack growth rates were markedly accelerated because of the changing fracture mechanism during the crack growth due to reducing fracture toughness of the material. The reduction in the crack growth rates at low temperatures may be related to the result of increasing yield strength and Young's modulus of the material used. In fact, Tobler and Reed⁽¹⁵⁾ reported that nitrogen temperature is correlated with the strain intensity factor range, $\Delta K/E$. As can be seen in Table 1, Young's modulus of the base metal increased with decreasing temperature;

hence the crack growth rates for the base metal may be affected by the changing of Young's modulus which depended on the temperature. Figure 2 shows a comparison of the crack growth rates of the base metal and welds at room temperature. At ΔK above 10 $\text{MPa}\sqrt{\text{m}}$ the crack growth rates of the welds measured using CCT specimens are nearly the same as those of the base metal, whereas the crack growth

rates of the welds obtained using CT specimens decreased markedly, as compared with those of the base metal. Similar tendencies have been reported under different welding processes and heat inputs for the other specimens of different materials⁽¹⁶⁾. At ΔK below 10 $\text{MPa}\sqrt{\text{m}}$, the crack growth rates of welds in CCT specimens are insensitive to the stress ratios, R , and approximately agree with that of the base metal at $R=0.8$. The discrepancy of the growth rates in welds between the CCT and CT specimens may be related to the difference of the residual stress distributions between both specimens. Figure 3 shows the crack growth rates of the welds at temperatures ranging from room temperature down to 93 K. The crack growth rates of the base metal above 1×10^{-8} m/cycle at room temperature are given by a dotted line in the same figure for the sake of comparison. As can be seen in the figure, the resistance of crack growth of the welds in CT specimens is superior to the welds in CCT specimens even under low temperatures. Furthermore, no systematic correlation can be seen between temperature and the growth rates in the welds. This fact may suggest that the growth rates in welded joints are dominated by residual stresses rather than temperatures. At temperatures of 123 K and 93 K, the growth rates of the welds in CCT specimens increased markedly in the ranges of ΔK above 20 and 15 $\text{MPa}\sqrt{\text{m}}$, respectively. This phenomenon is related to change of the fracture mechanism during the fatigue crack growth, as well as the base metal. The maximum stress intensity factor (K_{max}) at

Fig. 1 Relationship between fatigue crack growth rate, da/dN , and ΔK in base metal at temperatures ranging from room temperature down to 93 K

Fig. 2 Comparison of fatigue crack growth rate between base metal and welds at room temperatures

Fig. 3 Relationship between fatigue crack growth rate and ΔK in welds at temperatures ranging from room temperature down to 93 K

final failure—that is, fatigue fracture toughness (K_{fc})—of the welds is also affected by specimen configuration. Figure 4 shows the relationship between K_{fc} and temperature for the welds and the base metal. The values of K_{fc} for the welds in CT specimens are higher than those of the base metal, whereas the values of K_{fc} for the welds in CCT specimens are lower than the base metal. Therefore values of K_{fc} may also be affected by residual stresses, as well as the crack growth behavior in the welds. From the above results, it is concluded that the fatigue crack growth behavior of welded joints under low temperatures is dominated by the residual stresses and fracture mechanism related with reduction of fracture toughness of the material.

4.2 Fracture mechanisms during fatigue crack growth

As a result of fractographic analysis, the fatigue crack growth of both the welds and base metal was dominated by the mechanism of striation formation at temperatures ranging from room temperature down to 173 K, regardless of specimen configuration and specimen thickness. At temperatures of 123 K and 93 K, however, traces of cleavage that show evidence of cyclic cleavage were formed like bands on the fracture surface of both materials (Fig. 5), except for some of the welds in CT specimens. It is found, therefore, that the acceleration of crack growth below 123 K was associated with the occurrence of cleavage during striation formation because of the reduced fracture toughness of the materials. The occurrence of cleavage was not observed in some welds in CT specimens even at 123 K. This fact suggests that the initiation of cleavage is also affected by residual stresses. The occurrence of cyclic cleavage has been reported in a structural steel⁽¹⁷⁾; the presence of the cleavage during crack growth was shown due to local

deterioration of the material caused by cyclic straining in front of the crack tip. In order to examine whether or not the cyclic cleavage in HT80 steel is formed by the same mechanism as that in the structural steel mentioned above, the width of the cleavage band, Δa , formed at 123 K was plotted against the cyclic plastic zone size, R_p , or the maximum plastic zone size, R_p (Fig. 6). As can be seen in the figure, Δa is larger than R_p , independent of the materials and specimen configuration. This result indicates that the growing cleavage crack was brought to a halt in the

Fig. 5 Fractographs showing cyclic cleavage which occurred during fatigue crack growth under low temperatures

Fig. 4 Effect of temperature on fatigue fracture toughness in base metal and welds

Fig. 6 Relationship between width of cleavage, Δa , and plastic zone size, R_p and R_y

region beyond the cyclic plastic zone because fracture toughness in the plastic zone in front of the growing fatigue crack decreased as compared to the region outside of the plastic zone due to local deterioration of the material caused by cyclic straining. Accordingly, cyclic cleavage occurs in the plastic zone at the fatigue crack tip. When the value of K_{max} at which the cyclic cleavage occurred is below the fracture toughness of the material, the propagating crack after passing through the plastic zone is stopped in the regions surrounding the plastic zone which has not been subjected to cyclic straining, and a transition from the cleavage to the fatigue occurs. As expected before, it is therefore concluded that the presence of the cleavage band in the welds and base metal of HT80 steel is related to local deterioration of the material at the crack tip, as well as the structural steel reported previously⁽¹⁷⁾.

4.3 Residual stress distributions in the specimens

Figure 7 shows the redistributions of longitudinal welding residual stresses, which are parallel to the direction of the external applied stress, due to extension of saw-cut notches in the welds in the CCT specimen. The transverse residual stresses, which lie in the direction of crack growth, are excluded from the figure to avoid complication. The redistributed longitudinal residual stresses in the welds in the CCT specimen are always tensile at the notch tips independent of the notch length. Thus, the crack growth rates of the welds measured with CCT specimens are found to be higher than the base metal, whereas the values of K_{fc} of the welds determined with CCT specimens

are lower than the base metal because the crack tips in the welds in CCT specimens are always in the fields of tensile residual stresses. The crack growth rates of the welds in CCT specimens with stress ratios from 0.05 to 0.8 were insensitive to the stress ratio, and roughly the same as those of the base metal at $R=0.05$ in the entire range of ΔK , except for the crack growth rates of which cyclic cleavage occurred. This result suggests that the tensile residual stresses which corresponded to $R=0.8$ existed in the welds in CCT specimens. Measurement of the redistribution of the residual stresses of the welds in the CT specimen was not performed. The longitudinal welding residual stresses of the welds in the CT specimen are compressive near both sides of the specimen, whereas the longitudinal stresses are tensile at the mid-width of the specimen, as shown in Fig. 8. From the above results and some reports with respect to residual stress distributions of the welds in CT specimens^{(3),(16)}, the vicinity of the crack tip in welds in CT specimens is always in the field of compressive residual stresses even if the crack should extend. As a measurement of crack closure during crack growth, the crack opening levels were counteracted by the compressive residual stresses; accordingly, the resistance of crack growth in the welds measured with CT specimens was found to be superior to that in the welds measured with CCT specimens. Since the phenomenon of crack closure was suggested by Elber⁽¹⁸⁾, the effect of the stress ratio on the crack growth rates has widely been evaluated using the effective stress intensity factor range, ΔK_{eff} , which is based on an assumption that crack

Fig. 7 Redistribution of residual stresses in weld metal of CCT specimen

Fig. 8 Residual stress distribution in weld metal of CT specimen

$$f(\epsilon, \theta) = [1 + 0.295\sqrt{1 - \theta^2}(1 - \cos u)]g(\epsilon, \theta)$$

$$g(\epsilon, \theta) = \sqrt{\tan u} \frac{1 \pm (\sin v / \sin u)}{\sqrt{1 - (\cos u / \cos v)^2}},$$

where $u = \pi\epsilon/2$, $v = \pi\theta/2$, a is the crack length from the center line of the specimen width, w is half the specimen width, and $\sigma_R(x)$ is the residual stress distribution.

Substituting R_{res} into R in Eq. (1) or (2), the crack opening ratio which takes into account the residual stresses, U_R , can be obtained. Consequently, the effective stress intensity factor range which takes into account the residual stresses, ΔK_{effR} , is written as follows:

$$\Delta K_{effR} = U_R \Delta K = (\gamma + \delta R_{res}) \Delta K \quad (7)$$

where γ and δ are constants which were given by Eq. (1) or (2).

The above equation is valid as R_{res} is positive. In the case in which R_{res} is negative, ΔK_{effR} is defined as $\gamma(K_{max} + K_{res})$ because the negative portion of one loading cycle does not induce the stress intensity.

4.5 Estimation of the crack growth rates and fatigue fracture toughness in residual stress fields

The fatigue crack growth rates in the range from 5×10^{-9} to 7×10^{-6} m/cycle in the welds shown in Fig. 3 were replotted against ΔK_{effR} expressed by Eq. (7). The result is shown in Fig. 10. The data for the welds

Fig. 10 Relationship between fatigue crack growth rate, da/dN , and effective stress intensity factor range considering residual stress, ΔK_{effR} , in welds at temperatures ranging from room temperature down to 93 K

fall around a straight line given by Eq. (3) for the crack growth rates of the base metal, except for the data represented by slashed symbols in which cleavage occurred during the fatigue crack growth. As can be seen in the figure, the crack growth rates of the welds are correlated with ΔK_{effR} regardless of residual stresses, temperatures, specimen types and specimen thicknesses, when the crack growth mechanism was dominated by striation formation.

As mentioned above, the crack growth rates in the temperatures ranging from room temperature down to 177 K are insensitive to the temperatures. In contrast, the transition from the fatigue crack to the final failure was markedly affected by the temperatures. The value of fatigue fracture toughness, K_{fc} , in the welds affects not only the temperatures but the residual stresses because the value of K_{fc} in the welds is dependent on the specimen configuration, as well as the crack growth rates. Under low temperatures, the size of the plastic zone formed at the crack tip is relatively small, and the crack propagates under the condition of small scale yielding until failure. Hence it may also be possible to apply the superposition approach for the evaluation of K_{fc} . The fatigue fracture toughness which takes into account the residual stresses, K_{fcR} , may be expressed as a sum of the stress intensity factors due to residual stresses and due to the maximum applied stress, as shown by Eq. (8):

$$K_{fcR} = K_{res} + K_{max}. \quad (8)$$

The data represented in Fig. 4 were replotted against K_{fcR} instead of K_{fc} . Figure 11 shows the relationship between K_{fcR} and temperature for the welds and the base metal. It is found that the values of K_{fcR} for the welds are roughly the same regardless of specimen types. Consequently, the fatigue fracture toughness for the welds under low temperatures can

Fig. 11 Relationship between fatigue fracture toughness considering residual stress, K_{fcR} , and temperature

be evaluated using the superposition approach.

5. Conclusions

The main results obtained in this study are as follows.

(1) As the fracture mechanism during the fatigue crack growth was dominated by striation formation, the crack growth rates of the base metal and the welds were relatively insensitive to temperature. Hence the crack growth rates of the welds were dominated by residual stresses rather than temperatures. In contrast, the fatigue fracture toughness was markedly influenced by temperatures.

(2) Fatigue crack growth rates in the range from 5×10^{-9} to 7×10^{-6} m/cycle for the base metal and welds were correlated with the effective stress intensity factor range, ΔK_{effR} , estimated by superposition of the respective stress intensity factors for the residual stress fields and the applied stresses regardless of residual stress distributions, temperatures and specimen configurations, when the crack growth was dominated by striation formation.

(3) Fatigue fracture toughness, K_{fc} , in the welds in the CCT specimen was lower than that in CT specimen regardless of temperature, because the crack tips in the welds in the CCT specimen always existed in the fields of tensile residual stress, whereas the crack tip in the welds in the CT specimen was always in the fields of compressive residual stress. The influence of residual stresses on the K_{fc} can be evaluated using a superposition approach.

(4) As the temperatures decreased below 123 K, fatigue crack growth rates of the base metal and welds increased markedly because of the occurrence of cyclic cleavage during striation formation. The cyclic cleavage formed due to local deterioration of the material caused by cyclic straining in front of the fatigue crack tip.

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