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Corrosion-Fatigue Cracking in HY-80 and HY-130 Steels

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14. ABSTRACT

An investigation was carried out to characterize the effects of environment (including [NaCl] concentration) and load ratio on fatigue crack growth kinetics of HY-80 and HY-130 steels. Fracture mechanics wedge-opening-load (WOL) specimens oriented in the longitudinal direction (LT) were used in the current study. The test environments were vacuum, ambient air, and saltwater with [NaCl] concentrations ranging from 0.1 to 15%. Three load ratios, corresponding to R = 0.1, R = 0.5, and R = 0.85, were examined. The results indicate: (1) the fatigue crack growth rates and fatigue crack growth threshold, ΔK_{th}, for HY-80 steel and HY-130 steel are comparable at similar stress ratios in each of the three test environments (vacuum, ambient air, and 1% NaCl solution); (2) in the low stress intensity region, the fatigue crack growth rates of both HY-80 steel and HY-130 steel are higher and ΔK_{th} are lower at a high load ratio than those obtained at lower load ratios; (3) the fatigue crack growth rates of HY-80 steel and HY-130 steel obtained in ambient air and in 3.5% NaCl solution are comparable and are significantly higher than those obtained in vacuum; (4) the fatigue crack growth responses of HY-130 steel are not affected by the change in [NaCl] concentration; and (5) cathodic protection of HY-130 steel in saltwater does not lower its corrosion-fatigue cracking resistance.

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INTRODUCTION

HY-80 and HY-130 steels are quenched and tempered low-carbon alloy steels with minimum tensile strength of 552 MPa (80 ksi) and 896 MPa (130 ksi), respectively. These alloys are extensively used in marine structures and heavy construction equipment because of their high tensile strengths, good ductility and notch toughness, good weldability, low cost, easy fabrication, and well established manufacturing industries. These steels are often exposed to the unique naval environments such as saltwater, salt fog, and near-coastal ocean spray.

A study was conducted to determine the effects of environments (vacuum, ambient air, and saltwater with [NaCl] concentration varying from 0.1 to 15%), and load ratio (R = 0.1 to 0.85) on fatigue crack growth kinetics (Stages 1 and 2 and ΔK_{th}) of HY-80 and HY-130 steels. Since these steels are often cathodically protected by Zn-coupling in marine environments, the effect of Zn-coupling on corrosion-fatigue crack growth was also examined. The results are compiled into this report.

EXPERIMENTAL PROCEDURE

Materials used in this study were 12.7 mm-thick HY-80 and HY-130 steel plates.

For fatigue crack growth studies, 12.7-mm-thick, 64.8-mm-wide wedge-opening-load (WOL) fracture mechanics specimens, with crack propagation direction perpendicular to the plate rolling direction (LT), were used. The stress-intensity factor range (ΔK) for the WOL specimens was computed from the relationship (reference 1):

$$\Delta K = [\Delta P/(BW^{1/2})]\,[(2 + a/W)(0.8072 + 8.858\,(a/W) - 30.23\,(a/W)^2 + 41.088\,(a/W)^3 - 24.15\,(a/W)^4 + 4.951\,(a/W)^5]/(1 - a/W)^{3/2}, \quad (1)$$

where ΔP = applied load amplitude, B = specimen thickness, W = specimen width, and a = crack length. The fatigue test environments include vacuum ($< 6 \times 10^{-6}$ Pa background pressure), ambient air (20 °C and 42% relative humidity), and in saltwater solution with [NaCl] concentration varying from 0.1 to 15 wt%. In addition, corrosion-fatigue crack growth tests were carried out with and without Zn-coupling. The fatigue crack growth experiments were conducted in accord with ASTM E647 with a cyclic load frequency of 10 Hz, a sine waveform, and load ratios, R, ranging from 0.1 to 0.85. Fatigue crack length and fatigue crack growth rate were continuously monitored by a compliance technique. After fatigue tests, the fatigue-fractured surfaces were studied by scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) analysis.

RESULTS AND DISCUSSION

HY-80 STEEL

EFFECT OF LOAD RATIO

Manuscript approved November 14, 2014.

The effect of load ratio on fatigue crack growth of HY-80 steel in vacuum, ambient air, and 3.5% NaCl solution are shown, respectively, in Figs. A-1a, A-1b, and A-1c.As shown in Fig. A-1, the fatigue crack growth rates above $\Delta K = 10$ MPa$\sqrt{m}$ at load ratios of 0.1, 0.5, and 0.85 are comparable in each of the test environments. Below ΔK of 10 MPa$\sqrt{m}$, the fatigue crack growth rate curves tend to spread out and the fatigue crack threshold stress intensity factor range, ΔK_{th}, is the highest at R = 0.1, followed by that at R = 0.5, and is the lowest at R = 0.85. The fatigue crack growth rate curves obtained in vacuum environment are more compact as the differences among rate curves are small when load ratio varies from 0.1 to 0.85. In more aggressive ambient air and 3.5% NaCl solution, the load ratio effects are more prominent.

The effects of load ratio on ΔK_{th} in three environments are shown in Fig. A-2. As shown in Fig. A-2, in general, the ΔK_{th} decreases with increasing load ratio. The ΔKth at R = 0.1 can be as much as twice that at R = 0.85 in ambient air and in 3.5% NaCl solution.

EFFECT OF TEST ENVIRONMENT

The effect of test environment on fatigue crack growth of HY-80 steel at R = 0.1 and at R = 0.85 are shown, respectively, in Figs. A-3a and A-3b. It is interesting to note that the fatigue crack growth rates of HY-80 steel obtained in ambient air and in 3.5% NaCl solution are comparable at similar stress intensities. This indicates that HY-80 steel has good corrosion-fatigue cracking resistance in saltwater environment as there is no further increase in fatigue crack growth rate when test environment changes from ambient air to a “more aggressive” saltwater. Also shown in Fig. A-3, the fatigue crack growth rates are significantly lower and the ΔK_{th} higher in vacuum than those obtained in ambient air and in saltwater.

The effect of test environment on ΔK_{th} of HY-80 steel is shown in Fig. A-2. As shown in Fig. A-2, the ΔK_{th} is highest in inert vacuum environment, followed by in 3.5% NaCl solution, and is lowest in ambient air environment. The reason that ΔK_{th} is slightly higher and the fatigue crack growth rate slightly lower in the near-threshold region in saltwater than those in ambient air can be attributed to the corrosion-product induced wedging phenomenon. The fracture surfaces of HY-80 steel corrode badly in saltwater. The corrosion products, or rust, can accumulate in the crack tip region and wedge open the crack tip during unloading part of the fatigue cycle. This would reduce the effective stress intensity at the crack tip and gives an “apparently higher” ΔK_{th} and lower fatigue crack growth rate in a more aggressive saltwater environment.

Depending on the applied stress intensity, the fatigue crack growth rates of HY-80 steel in ambient air and in saltwater are as much as an order-of-magnitude higher than those obtained in inert vacuum environment, as shown in Fig. A-3. It has been established before that the hydrogen, which is produced as a result of water/steel fracture surface reaction, enters the crack tip region and lowers the fracture stress by hydrogen embrittlement mechanism (references 2 - 5). Because the ambient air fatigue tests are carried out at relative humidity of 42%, the fatigue crack tip region is covered by liquid

water due to capillary condensation. This explains why the fatigue crack growth rates of HY-80 steel in ambient air and in saltwater are comparable in medium and high ΔK regions.

HY-130 STEEL

EFFECT OF LOAD RATIO

The effect of load ratio on fatigue crack growth of HY-130 steel in vacuum, ambient air, and 3.5% NaCl solution are shown, respectively, in Figs. A-4a, A-4b, and A-4c. The general load ratio dependency of HY-130 steel is similar to that of HY-80 steel, and the discussions on Figs. A-1 and A-2 of HY-80 steel can be applied to HY-130 steel, as shown in Figs. A-4 and A-5.

EFFECT OF TEST ENVIRONMENT

The effect of test environment on fatigue crack growth of HY-130 steel at R = 0.1 and at R = 0.85 are shown, respectively, in Figs. A-6a and A-6b. Again, the environmental response of HY-130 steel is similar to that of HY-80 steel, and the discussions of result on HY-80 steel as shown in Fig. A-3 can be applied here in Fig. A-6. The cause of lower fatigue crack growth rates of HY-130 steel tested in saltwater at R = 0.1 in the low stress intensity region when compared to those obtained in ambient air, as shown in Fig. A-6a, can be attributed to corrosion-product induced crack tip wedging as discussed in the previous section.

EFFECT OF [NaCl] CONCENTRATION

The effects of [NaCl] concentration on fatigue crack growth of HY-130 steel at R = 0.1 is shown in Fig. A-7. As shown in Fig. A-7, HY-130 steel does not exhibit [NaCl] dependency as the fatigue crack growth responses in 0.1%, 3.5%, and 15% NaCl are identical. In addition, the ΔK_{th} of HY-130 steel in these saltwater environments are also comparable, as shown in Fig. A-8.

EFFECT OF Zn-COUPLING

Because cathodic protection such as Zn-coupling is often applied to steel structures in marine environments, the protected steel structures are cathodic and the hydrogen thus generated can enter the crack tip region. Depending on the material and the amount of hydrogen generated, the load carrying capability of the steel can be significantly compromised by a phenomenon called “hydrogen embrittlement”. Therefore, it is important to establish the effect of Zn-coupling on fatigue crack growth of HY-130 steel, which is often subjected to such “hydrogen embrittlement” conditions.

The effect of Zn-coupling on fatigue crack growth of HY-130 steel at R = 0.1 and R = 0.85 in 3.5% NaCl solution is shown in Fig. A-9. As shown in Fig. A-9, Zn-coupling has no effect on fatigue crack growth responses of HY-130 steel in 3.5% NaCl solution, at

either low or high load ratios. That is, HY-130 steel is resistant to the “hydrogen embrittlement” condition generated by Zn-coupling.

COMPARISON OF FATIGUE CRACK GROWTH RESPONSES OF HY-80 STEEL AND HY-130 STEEL IN SALTWATER

The fatigue crack growth responses of HY-80 steel and HY-130 steel are compared, at the same load ratios and in the same test environments, in Figs. A-10 through A-12. As shown in these figures, the fatigue crack growth responses of HY-80 steel and HY-130 steel, obtained at similar load ratios and in the same environment, are comparable.

FRACTURE PATHS EXAMINATION BY ELECTRON BACKSCATTER DIFFRACTION (EBSD) ANALYSIS

Because the fracture surfaces of both HY-80 and HY-130 specimens tested in 3.5% NaCl solutions were heavily corroded, the fracture paths under fatigue loading cannot be determined by a conventional SEM analysis. To circumvent this difficulty, EBSD analysis is performed on the crack tip of fatigue cracked specimens with the goal to determine whether the fracture paths are intergranular or transgranular, or both. The results of EBSD analyses on HY80 steel and HY-130 steel are shown in Fig. A-13 through A-16 for various specimens tested at different load ratios and environments. Because the grain sizes of HY-80 and HY-130 are very fine and are only several times larger than the EBSD sampling steps, sometimes it is difficult to determine the fracture paths. Even with this difficulty, the fracture paths in HY-80 steel are predominantly transgranular in both saltwater and vacuum environments. The transgranular nature of the fracture path is particularly evident for HY-80 steel fatigue tested in saltwater as shown in Fig. A-12.

The fatigue fracture paths in HY-130 steel as shown in Figs. A-13 and A-14 are not clear. While some larger-grain areas show transgranular fracture, which is evident in Fig. A-13, yet intergranular separation cannot be ruled out when the crack goes through smaller-grain areas.

CONCLUSIONS

The fatigue crack responses of HY-80 steel and HY-130 steel, obtained at the same load ratio and in the same test environment, are comparable. Their ΔK_{th} under similar conditions are also comparable.

In the low stress intensity region, the fatigue crack growth rates of both HY-80 steel and HY-130 steel are higher and ΔK_{th} are lower at a high load ratio than those obtained at lower load ratios.

The fatigue crack growth rates of HY-80 steel and HY-130 steel obtained in ambient air and in 3.5% NaCl solution are comparable and are significantly higher than those obtained in vacuum. The ΔK_{th} obtained in ambient air and in 3.5% NaCl solution are significantly lower than that obtained in vacuum.

The fatigue crack growth responses of HY-130 steel are not affected by the change in [NaCl] concentration. Fatigue crack growth rates and ΔKth are the same for HY-130 steel fatigue tested in 0.1% and 15% NaCl solutions.

Corrosion-fatigue crack growth responses of HY-130 steel in 3.5% NaCl with and without Zn-coupling are similar. Cathodic protection of HY-130 steel in saltwater does not lower its corrosion-fatigue cracking resistance.

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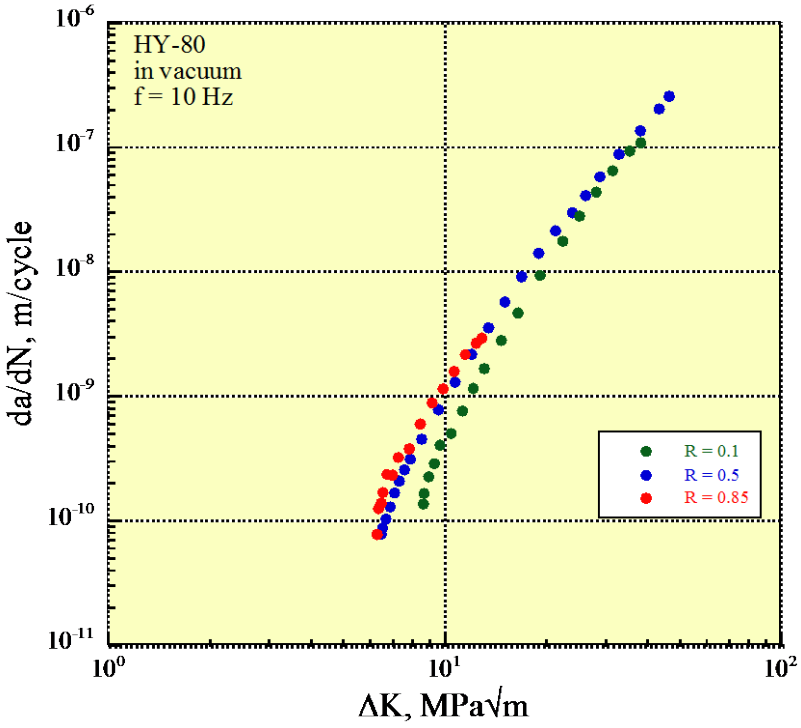
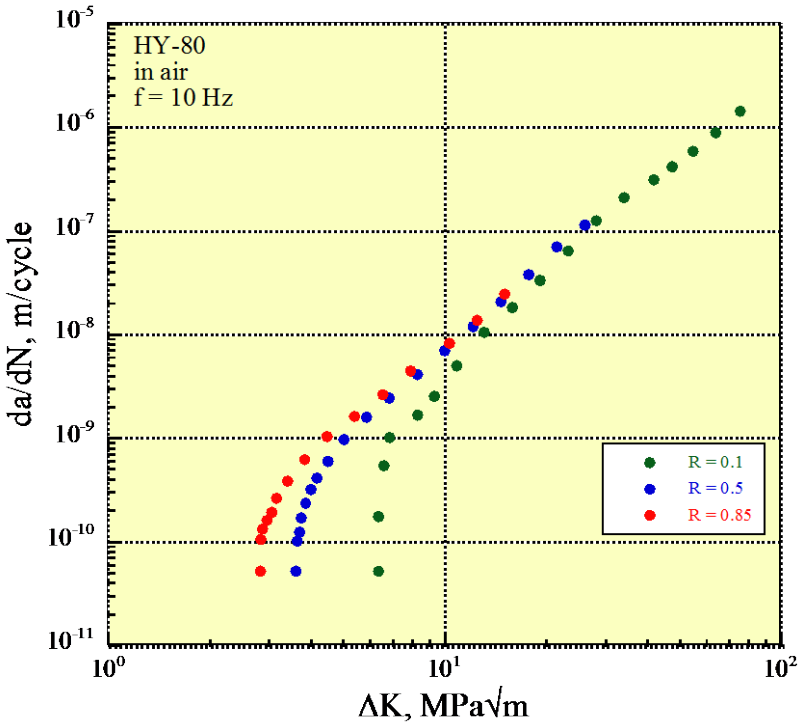
5. S.J. Hudak and R.P. Wei, Metall. Trans. A, 1976, Vol. 7A, p. 235.

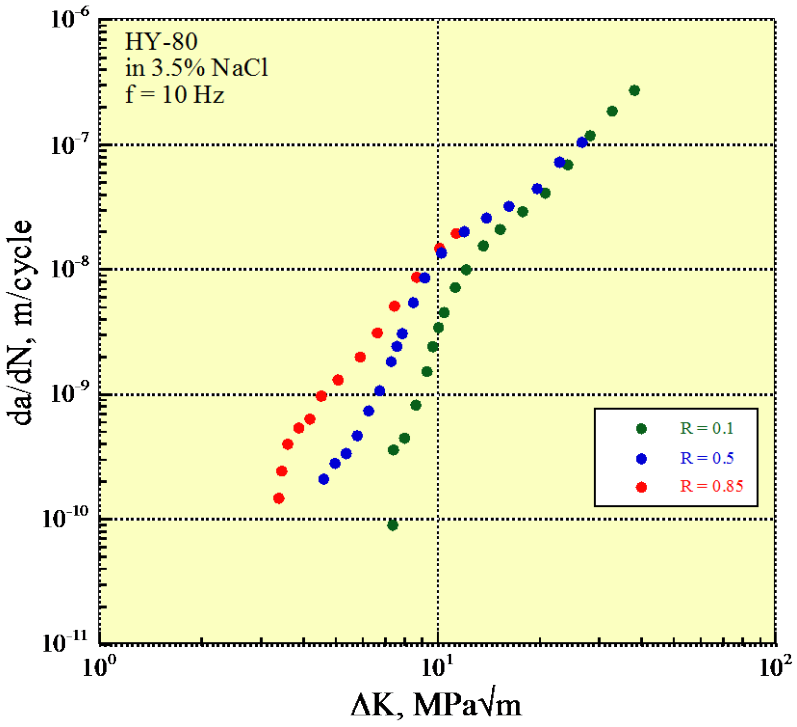
APPENDIX A
FIGURES


HY-80
in vacuum
f = 10 Hz
R = 0.1
R = 0.5
R = 0.85
da/dN, m/cycle
ΔK, MPa√m

(a)


HY-80
in air
f = 10 Hz
R = 0.1
R = 0.5
R = 0.85
da/dN, m/cycle
ΔK, MPa√m

(b)



(c)

Figure A-1: Fatigue crack growth of HY-80 steel in (1) vacuum, (b) ambient air, and (c) 3.5% NaCl.

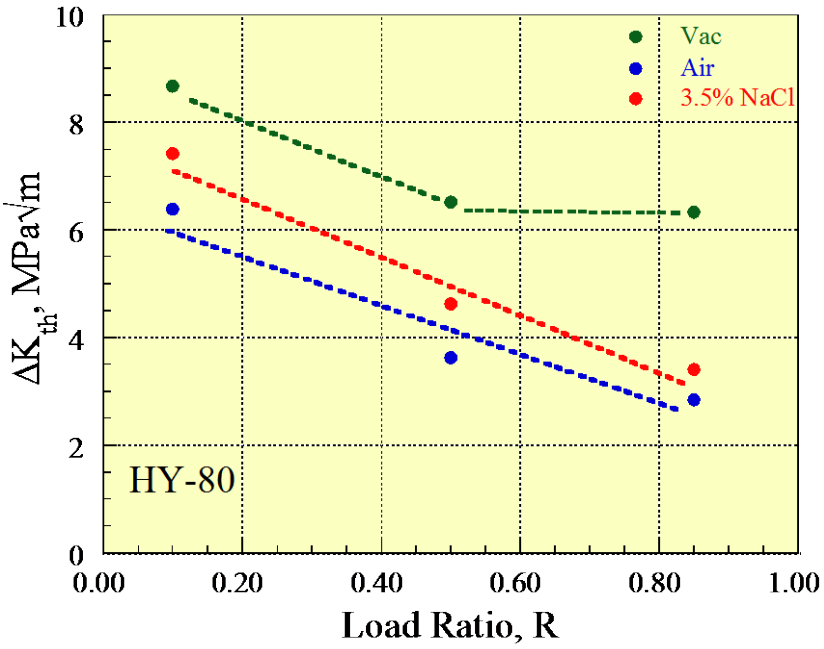
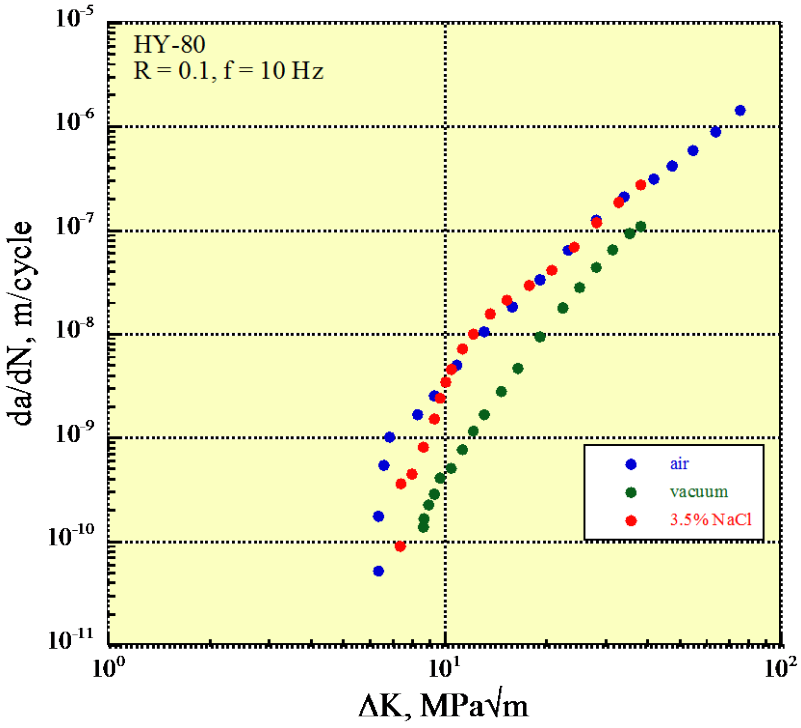
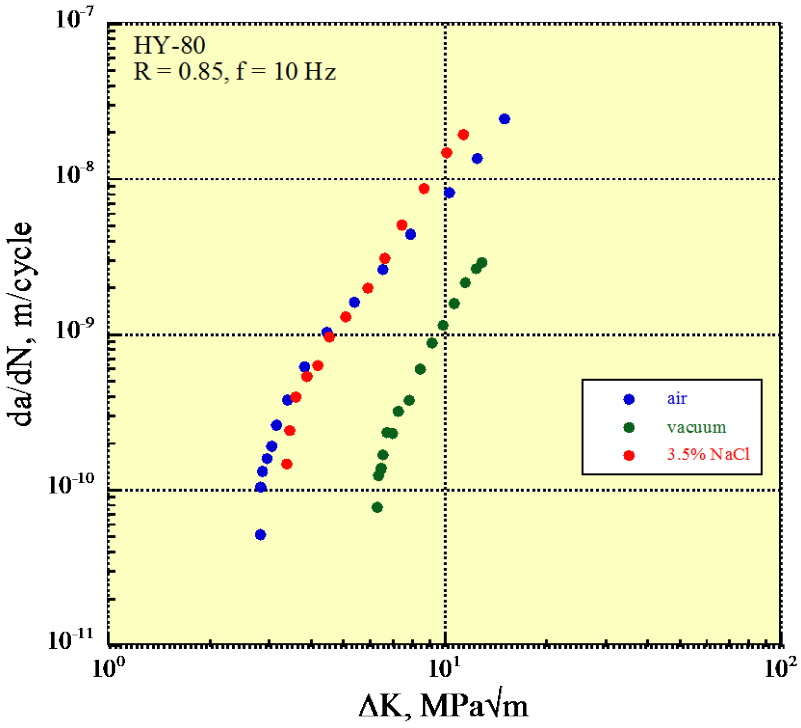


Figure A-2: Effect of load ratio on ΔK_{th} in vacuum, ambient air, and 3.5% NaCl for HY-80 steel.

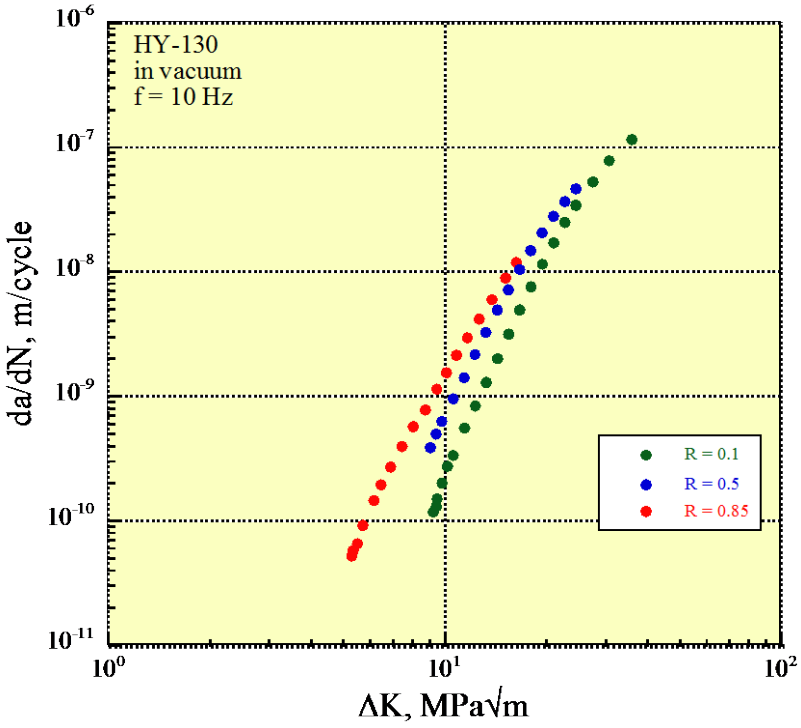


(a)

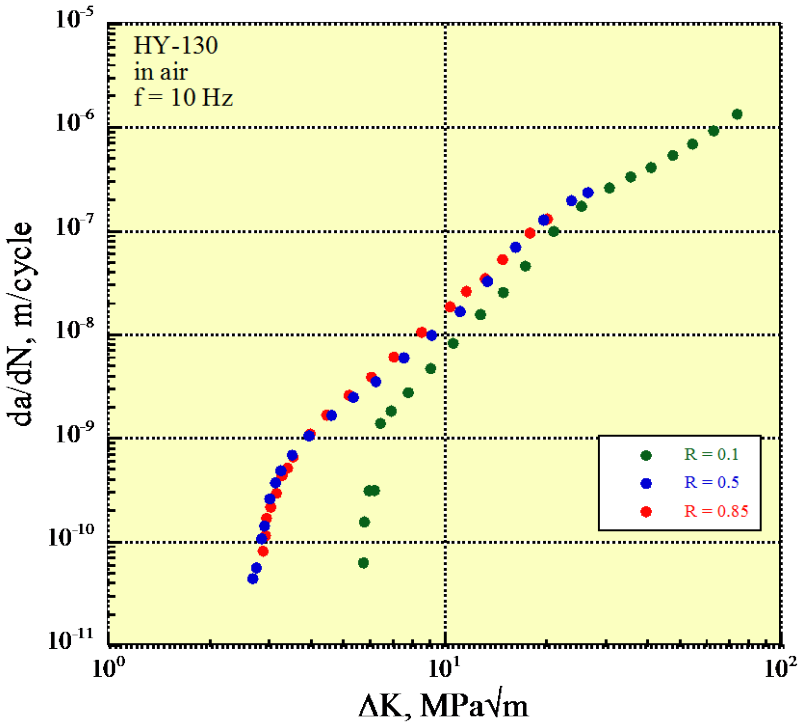


(b)

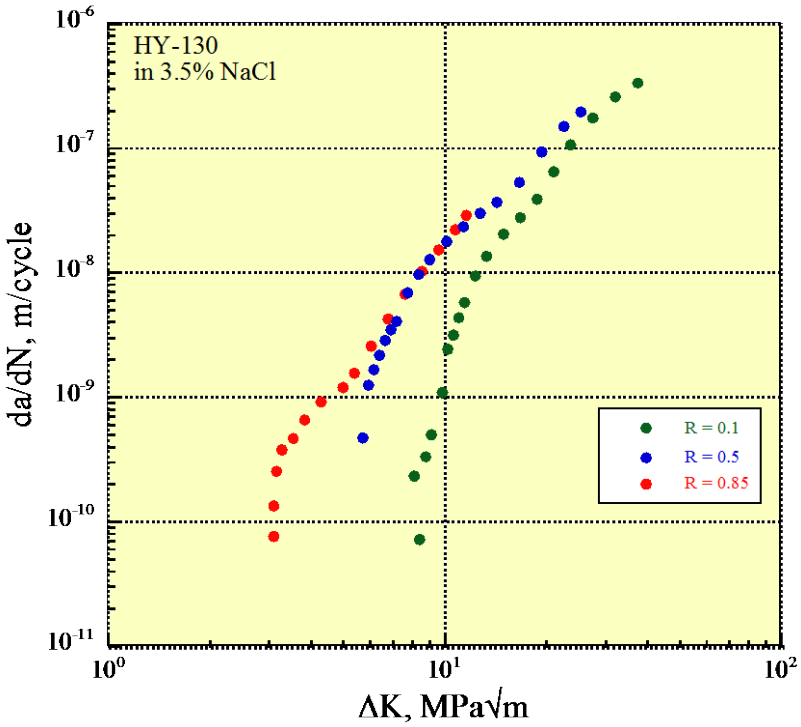
Figure A-3: Effect of environment on fatigue crack growth of HY-80 steel at (a) R = 0.1 and (b) R = 0.85.


HY-130
in vacuum
f = 10 Hz
R = 0.1
R = 0.5
R = 0.85
da/dN, m/cycle
ΔK, MPa√m

(a)


HY-130
in air
f = 10 Hz
R = 0.1
R = 0.5
R = 0.85
da/dN, m/cycle
ΔK, MPa√m

(b)



(c)

Figure A-4: Fatigue crack growth of HY-130 steel in (1) vacuum, (b) ambient air, and (c) 3.5% NaCl.

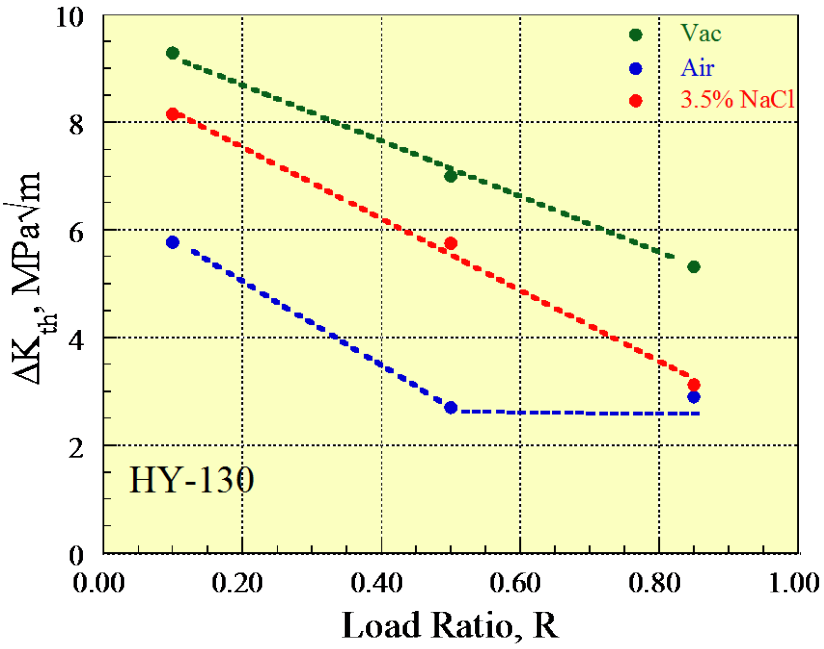
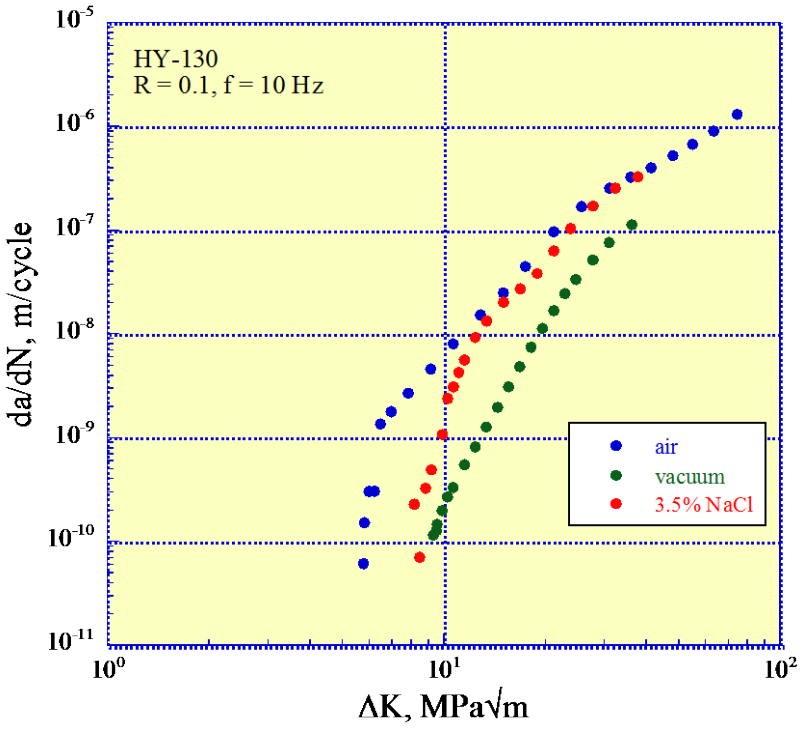
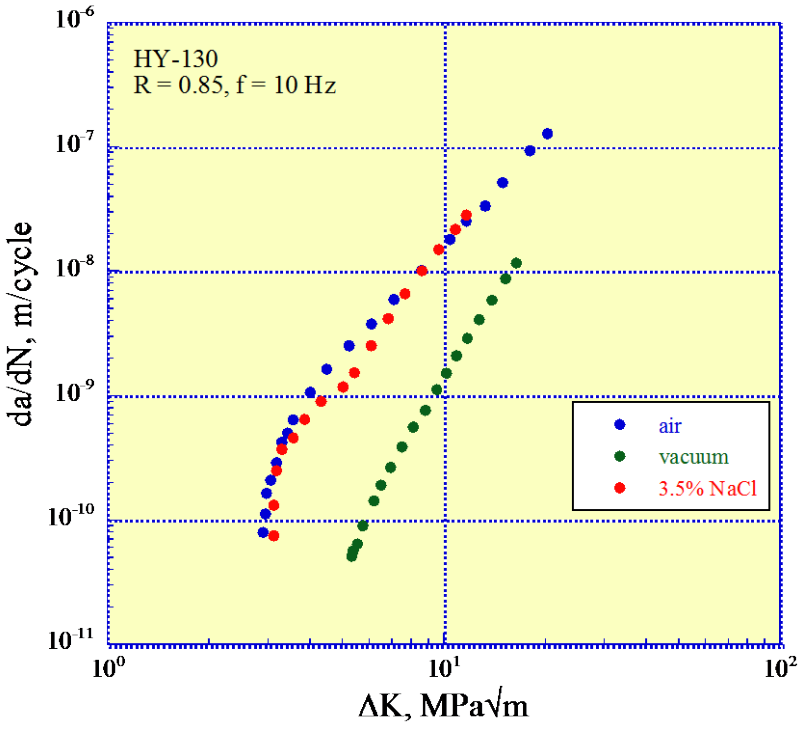


Figure A-5: Effect of load ratio on ΔK_{th} in vacuum, ambient air, and 3.5% NaCl for HY-130 steel.



(a)



(b)

Figure A-6: Effect of environment on fatigue crack growth of HY-130 steel at (a) R = 0.1 and (b) R = 0.85.

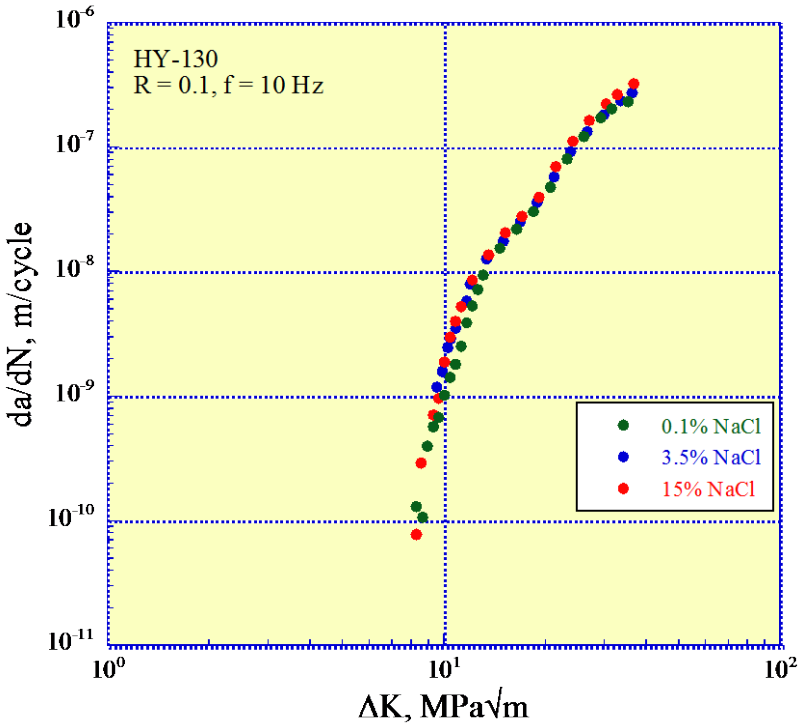


Figure A-7: Effect of [NaCl] concentration on fatigue crack growth of HY-130 steel at R = 0.1.

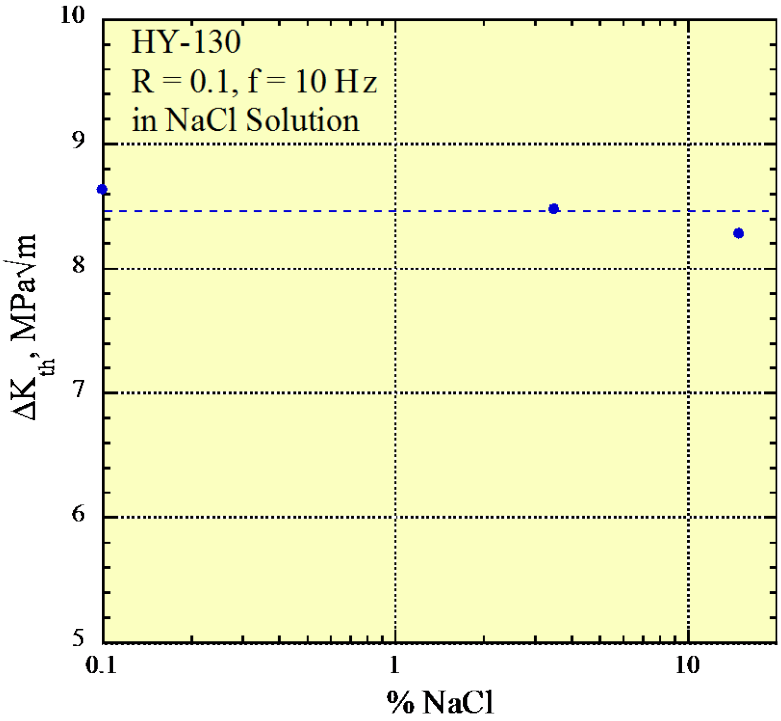


Figure A-8: Effect of [NaCl] concentration on fatigue crack growth threshold, ΔK_{th}, of HY-130 steel at R = 0.1.

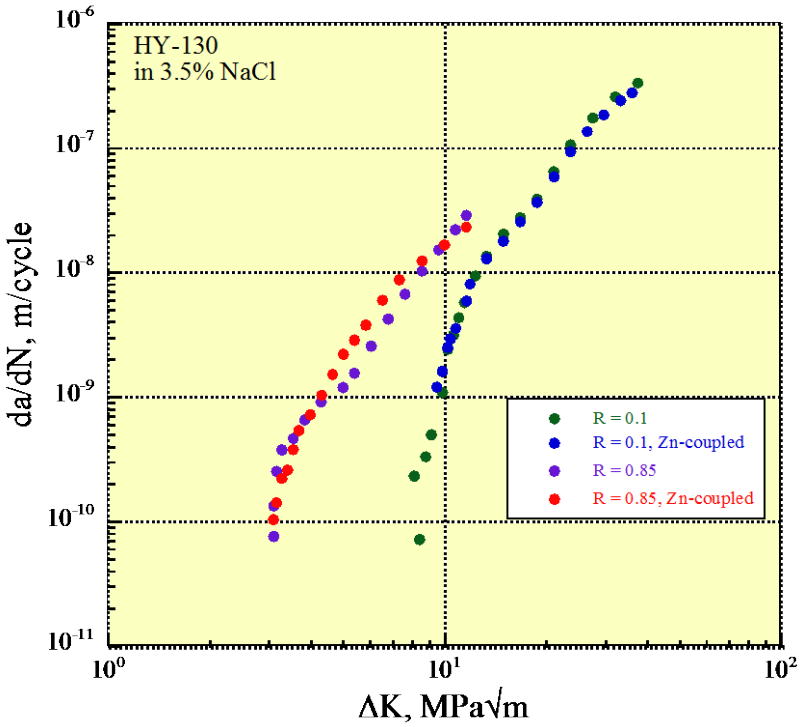
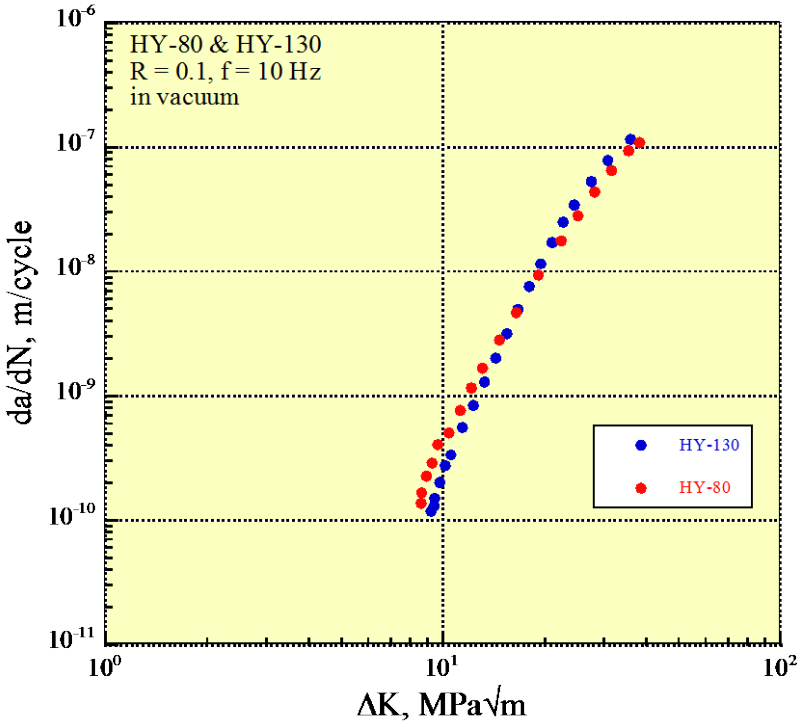
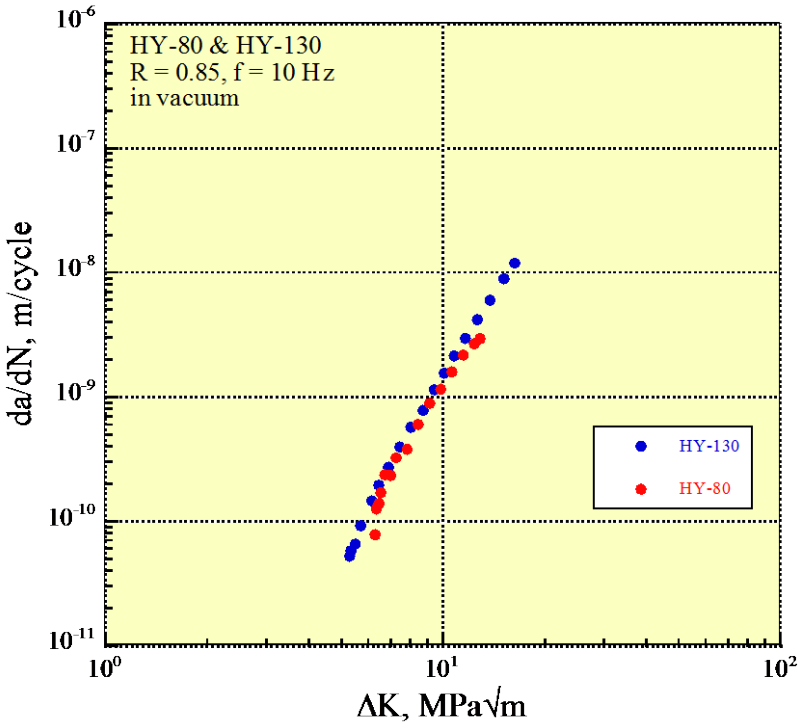


Figure A-9: Effect of Zn-coupling on fatigue crack growth of HY-130 steel in 3.5% NaCl.

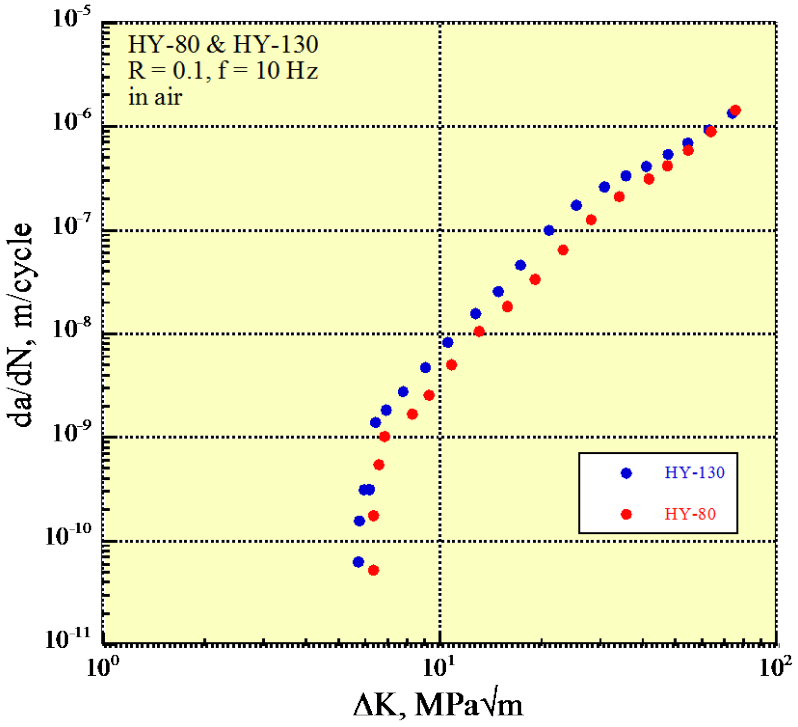


(a)

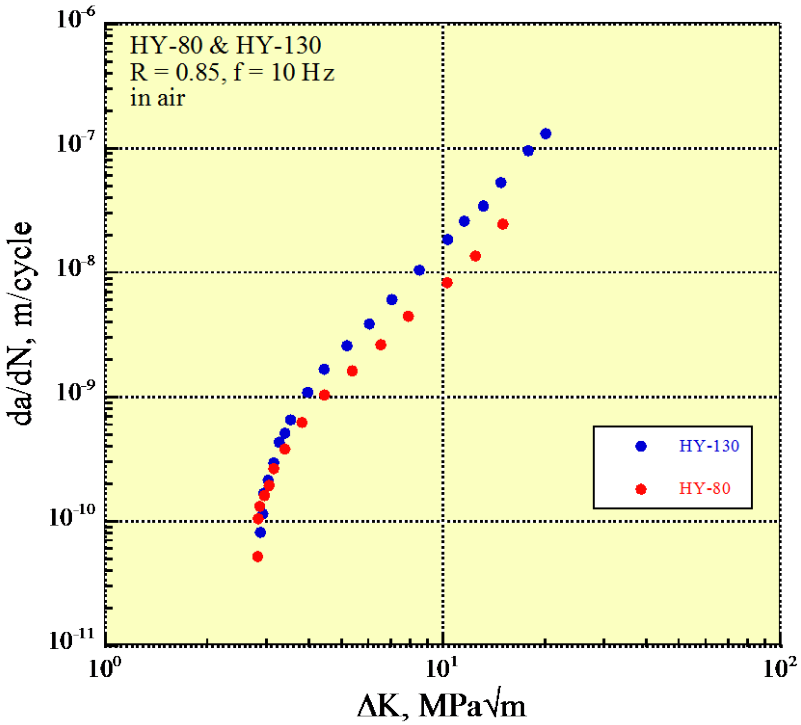


(b)

Figure A-10: Comparison of HY-80 and HY-130 fatigue crack growth in vacuum at (a) R = 0.1 and (b) R = 0.85.

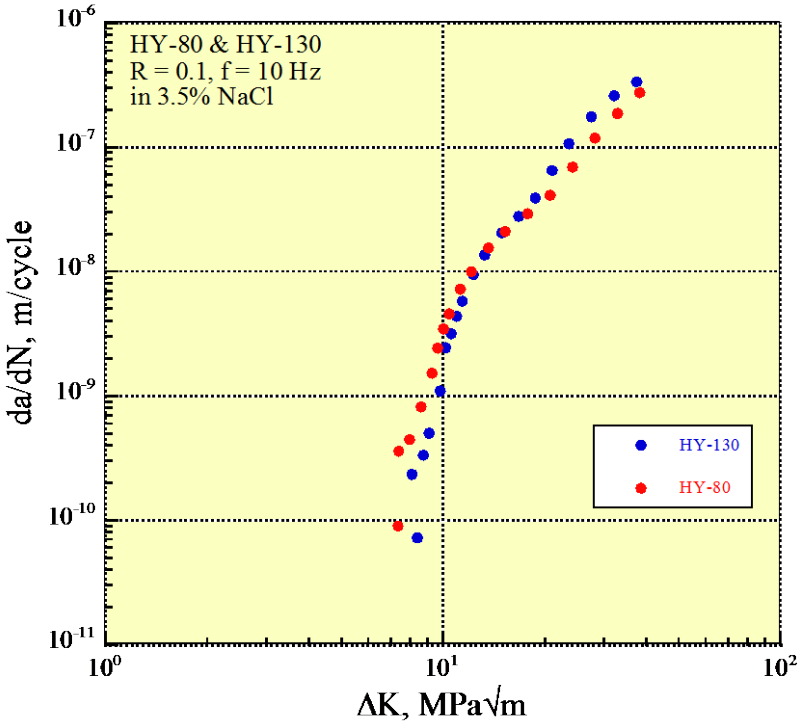


(a)



(b)

Figure A-10: Comparison of HY-80 and HY-130 fatigue crack growth in air at (a) R = 0.1 and (b) R = 0.85.



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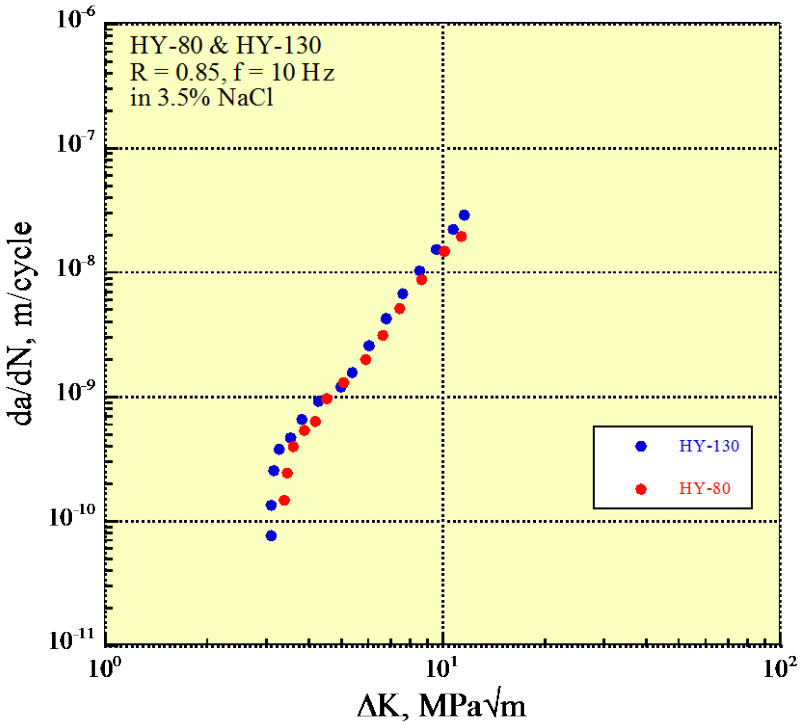

(b)

Figure A-10: Comparison of HY-80 and HY-130 fatigue crack growth in 3.5% NaCl at (a) R = 0.1 and (b) R = 0.85.

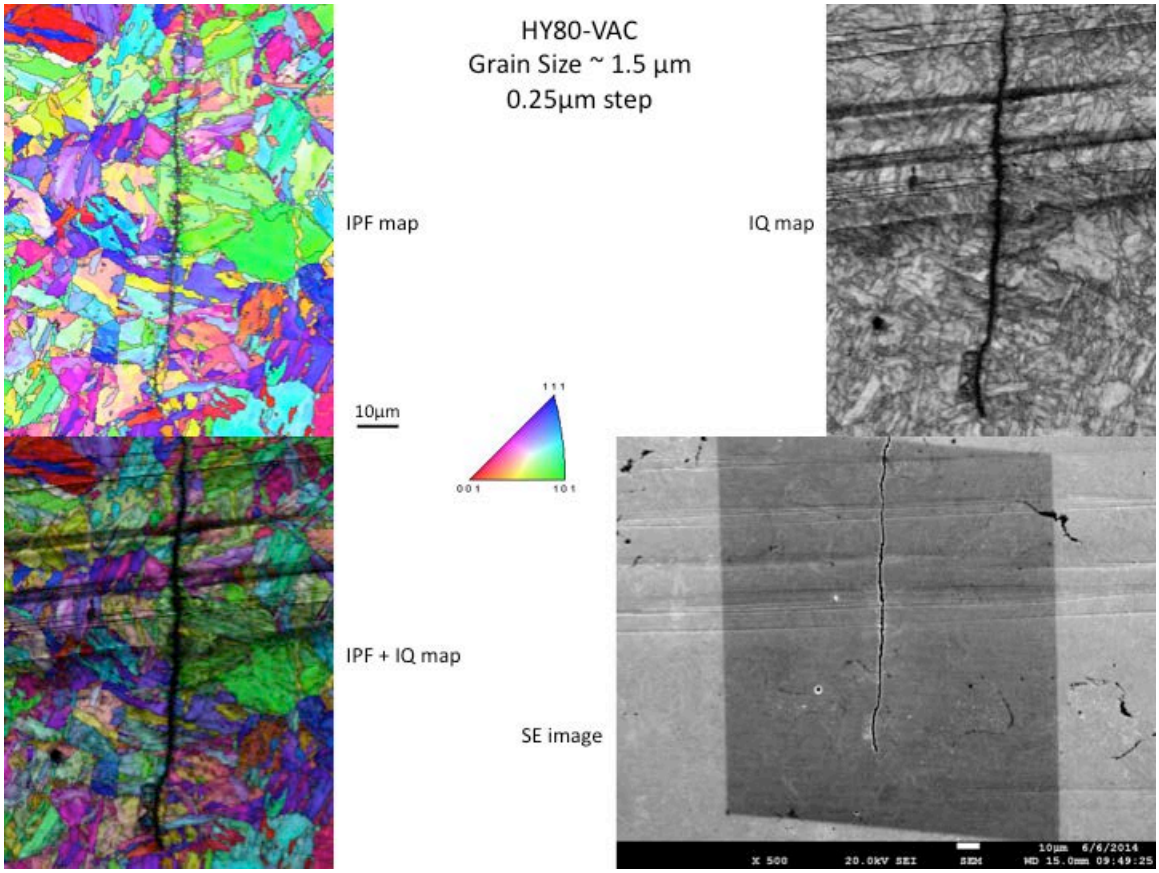

Figure A-11: EBSD and SEM mapping of HY-80 fatigue cracking at R = 0.1 in vacuum.

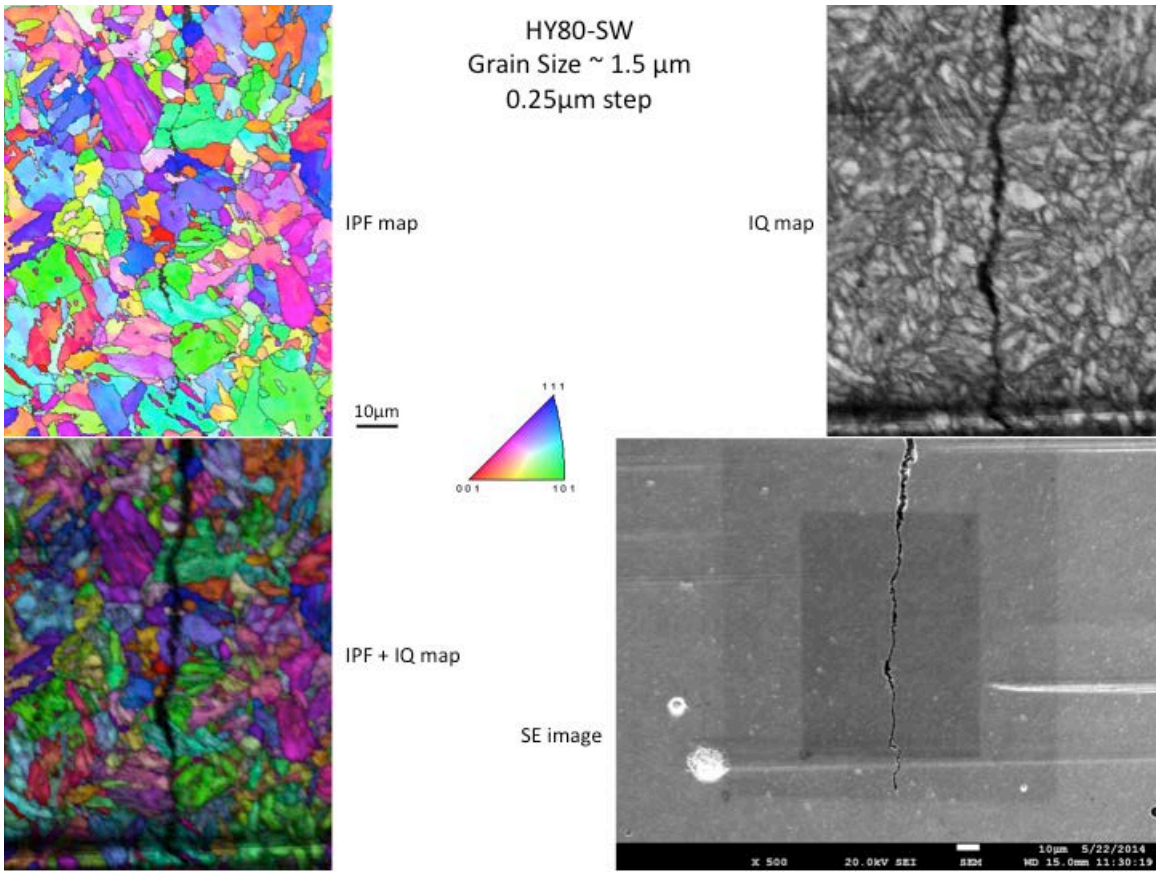

Figure A-12: EBSD and SEM mapping of HY-80 fatigue cracking at R = 0.1 in 3.5% NaCl.

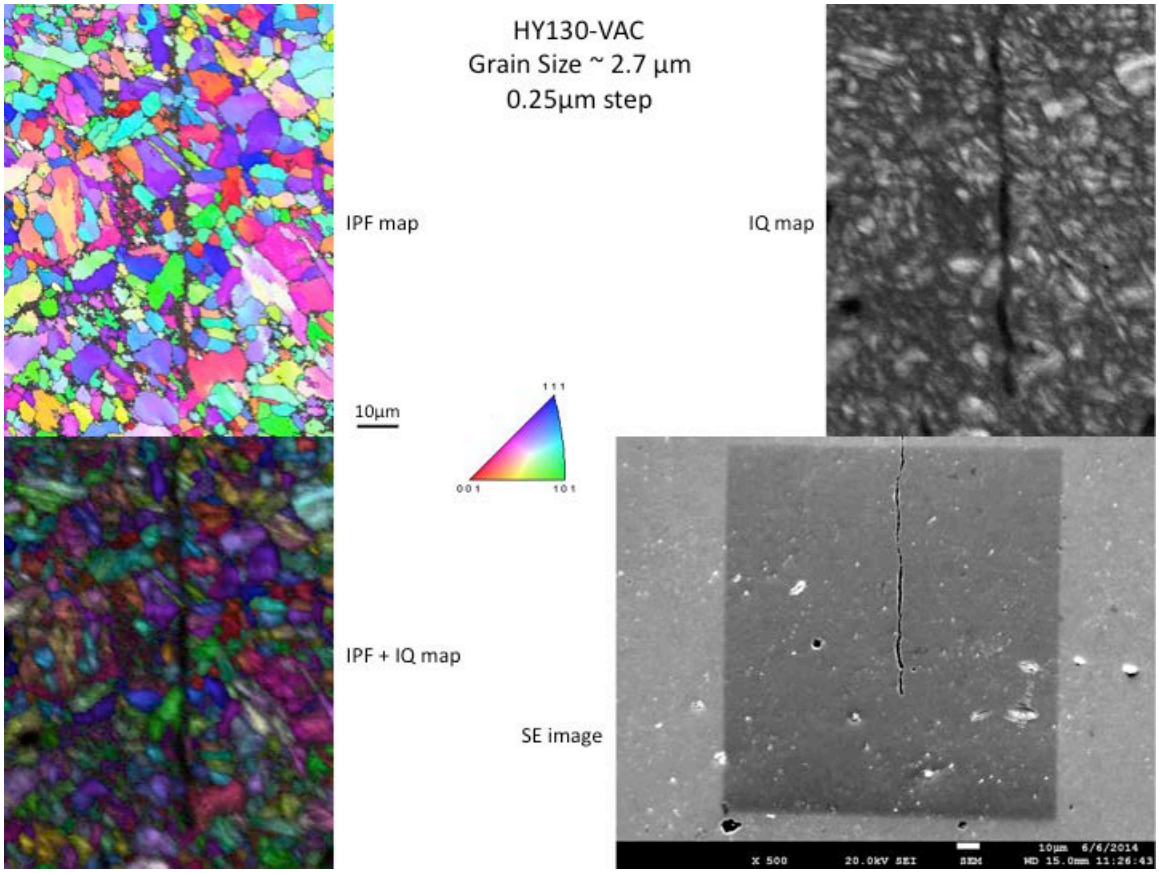

Figure A-13: EBSD and SEM mapping of HY-130 fatigue cracking at R = 0.1 in vacuum.

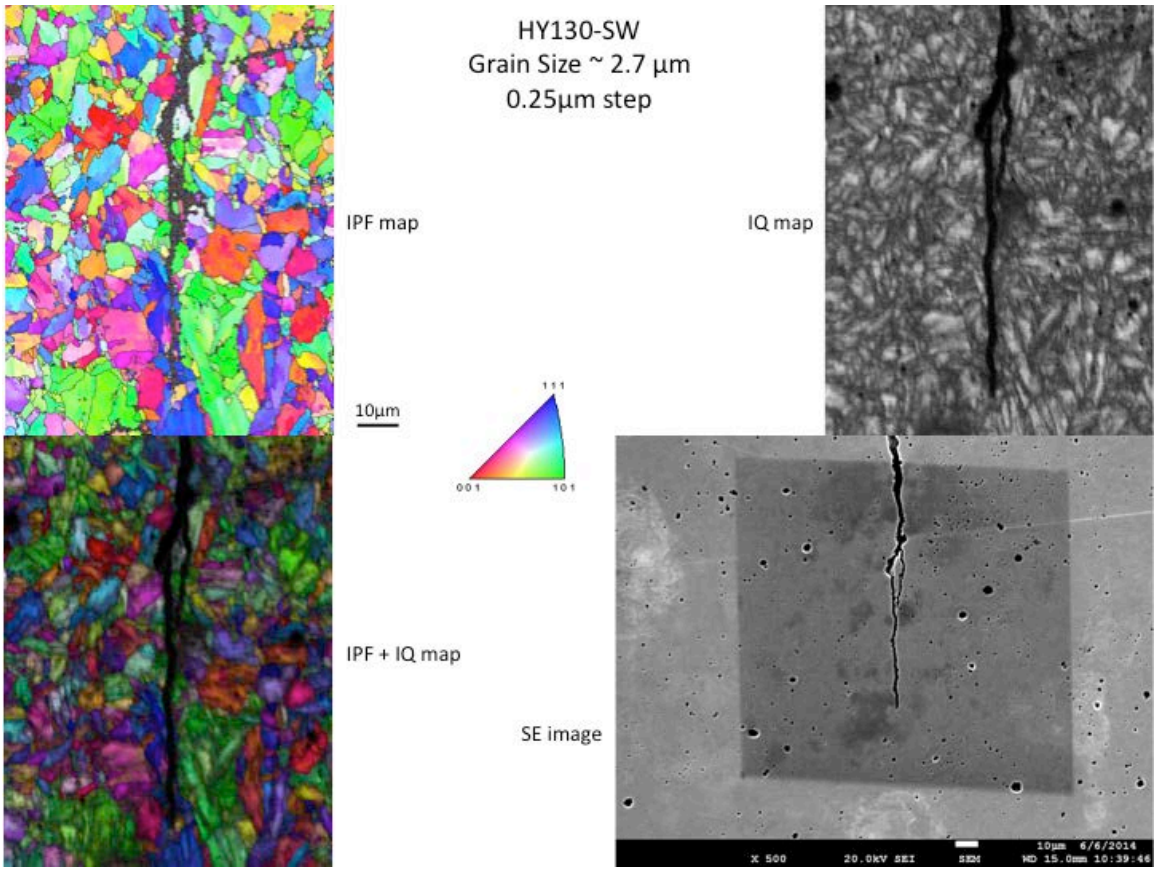

Figure A-14: EBSD and SEM mapping of HY-130 fatigue cracking at R = 0.1 in 3.5% NaCl.