THE ΔK_{th} BEHAVIOUR OF THREE STAINLESS STEELS IN DIFFERENT ENVIRONMENTS

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ABSTRACT

The fatigue threshold values, ΔK_{th}, were measured for three stainless steels (KCR 171, CA 15 and 304) in different environments, generally at R = 0.1. In white water, ΔK_{th} for KCR 171 and CA 15 was lower than in air, probably as a result of increased hydrogen embrittlement effects. In silicone oil, ΔK_{th} for KCR 171 and CA 15 was higher than in air, at least partially as a result of an increase in plastic zone size and in crack closure effects.

KEYWORDS

Fatigue thresholds; influence of environment; R-ratio; crack closure; corrosion-fatigue; hydrogen embrittlement; stainless steels.

INTRODUCTION

The influence of the environment on the threshold value of the cyclic stress intensity factor, ΔK_{th}, is very variable. Depending on the material and environment, an aggressive environment can decrease (Vosikovsky, 1976; Haagensen, 1977), not influence (Mautz and Weiss, 1976; Baïlon and others, 1983) or increase (Stewart, 1980; Ritchie and others, 1980; Baïlon and others, 1983) ΔK_{th}. An inert environment generally (Beevers, 1977; Baïlon and others, 1983) but not always (Stewart, 1980; Ritchie and others, 1980) increases ΔK_{th}. This seemingly confusing behaviour occurs since the environment can influence not only the fracture and plastic properties of the material at the crack tip but also the crack tip morphology (Radon, 1970) and crack closure. A change in the $(\Delta K_{eff})_{th}/\Delta K_{th}$ ratio can thus result, where $(\Delta K_{eff})_{th}$ represents the portion of ΔK_{th} effectively acting on the material immediately ahead of the crack tip. Accordingly, ΔK_{th} can be decomposed thus:

$$\Delta K_{th} = (\Delta K_{eff})_{th} + \Delta K'_{th} \qquad (1)$$

where $(\Delta K_{eff})_{th}$ should be determined by the fracture and plastic properties of the crack tip material. As such, it is a material property that can be influenced by the environment. The $\Delta K'_{th}$ component represents the influence on the threshold of effects which cause the effective ΔK to differ from the applied ΔK. Crack closure, changes in crack tip morphology (e.g., crack branching) and the presence of residual stresses ahead of the crack tip can all contribute to $\Delta K'_{th}$. Of these, the crack closure contribution can be relatively easily measured. Assuming the other contributions to be negligible or unchanged by the environment and therefore treatable as a component of $(\Delta K_{eff})_{th}$, equation (1) can be more conveniently written to include K_{op}, the stress intensity at which the crack tip becomes open:

$$\Delta K_{th} = (\Delta K_{eff})_{th} + (K_{op} - K_{min}) \tag{2}$$

The usual method of measuring K_{op} is by recording load-crack mouth opening displacement (CMOD) hysteresis loops and evaluating the change in compliance. The possibility of a change in crack tip morphology can be evaluated by detailed fractography. Residual stress effects can be kept to a minimum by correct testing and sample preparation procedures.

The present paper considers, for three stainless steels, the influence of environment on ΔK_{th} and on the near-threshold fractography as well as the influence of environment, ΔK and R on the near-threshold K_{op}.

EXPERIMENTAL PROCEDURE

The materials studied were KCR 171 a 24% Cr, 8% Ni, 1% Mo austenitic-ferritic stainless steel containing approximately 55% of austenite, CA 15, a 12% Cr, 0.5% Mo martensitic stainless steel containing less than 10% of delta ferrite and metastable austenitic 304 stainless steel. All tests were performed at room temperature, 20 Hz and generally at R = 0.1. Tests were carried out in air of ≈ 35% relative humidity, white water (an acidified $NaCl$-Na_2SO_4-$Na_2S_2O_3$ pulp and paper industry solution of composition given by Ait Bassidi and others (1983)) and Dow Corning 550F silicone oil. A servohydraulic machine interfaced for automatic test control and data acquisition was employed. The crack lengths were measured optically using a travelling microscope with resolution better than 0.01 mm. Hysteresis loops of load versus CMOD in the near-threshold region were recorded digitally at reduced frequencies of 0.1 or 1 Hz. For the K_{op} determination, the best fit straight line was first calculated for the portion of the K versus CMOD curve for which elastic behaviour was obtained for the fully opened crack. The deviation of the experimental points from this line were then plotted as K vs CMOD deviation and K_{op} taken as the point at which the crack closure portion could first be separated from the elastic portion for the fully opened crack. The low crack propagation rates and the ΔK_{th} values were measured by employing a load-shedding procedure, with decreasing shedding steps of 10%, 5% and 3%.

RESULTS

ΔK_{th} and K_{op} values

Figure 1 presents typical da/dN versus ΔK results. The threshold values, ΔK_{th}, for the different materials and environments are presented in Table I. For KCR 171, a series of measurements were performed in air at R = 0.1 for K_{max} values of 23.8 to 61.6 MPa√m and at R = 0.2 for K_{max} values of 23.8 to 40.7 MPa√m. At R = 0.1, K_{op} remained essentially constant at 8.1 MPa√m with a standard deviation of 0.22 MPa√m. At R = 0.2, the constant K_{op} was 7.9 MPa√m with a standard deviation of 0.13 MPa√m. A series of K_{op} measurements

were also performed at R = 0.5 in air and following the introduction of white water, silicone oil and silicone oil contaminated with 2% of viscous paint stripper so as to transform it into an aggressive environment of similar viscosity. These changes in environment were performed at a K_{max} of 14 MPa√m for which K_{op} in air was 7.8 MPa√m. The introduction of white water or of contaminated silicone oil had no influence on the load-CMOD hysteresis loops and K_{op}. The introduction of inert silicone oil resulted in a very rapid increase in K_{op} over the first ≈ 20 cycles and then a more gradual increase. After 1000 cycles K_{op} became constant at 8.5 MPa√m. Gradually increasing K_{max} to 30 MPa√m and, when necessary to detect crack closure, decreasing K_{min} during the recording of a hysteresis loop resulted in an essentially constant K_{op} of 9.6 MPa√m. On a second sample, silicone oil was introduced at R = 0.5 at a K_{max} value of 17.9 MPa√m for which no crack closure effects were noticed in air. Silicone oil introduction again resulted in crack closure with K_{op} becoming constant at 9.9 MPa√m after 3000 cycles.

TABLE I: ΔK_{th} values in MPa√m

MATERIAL	R	AIR	WHITE WATER	SILICONE OIL
KCR 171	0.1	7.2	6.1	9.2
KCR 171	0.5	5.0	-	6.5
CA 15	0.1	9.3	8.8	-
304	0.1	6.9	6.4	7.9

Values of K_{op} were determined for tests in air at R = 0.1 to 0.4 for CA 15. The value of K_{op} remained essentially constant at 6.3 MPa√m with a standard deviation of 0.15 MPa√m as K_{max} was increased from 10.3 to 17.9 MPa√m. For higher K_{max} values up to 24.4 MPa√m, K_{op} decreased slightly to ≈ 5.5 MPa√m. As well, R-ratios of 0.1-0.4 appeared to have no significant influence on K_{op}. Bignonnet and others (1982) have also observed little or no influence of K_{max} or R on K_{op} near ΔK_{th} for a number of other materials.

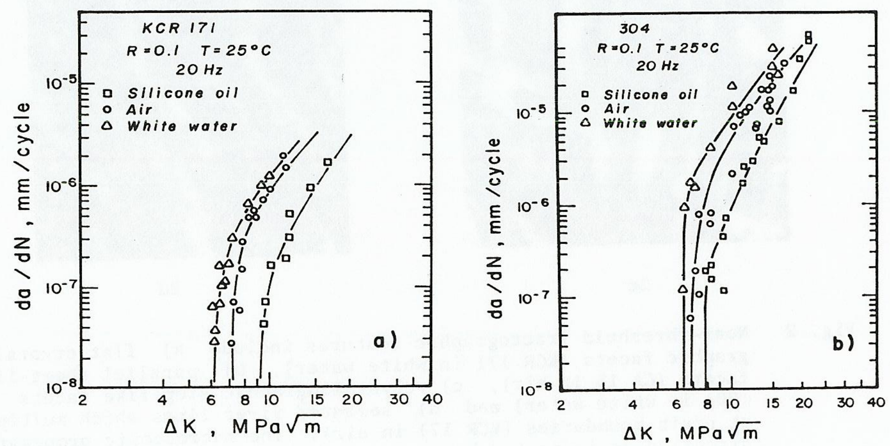

Fig. 1 Near-threshold crack growth rate curves for a) KCR 171 and b) 304 steels.

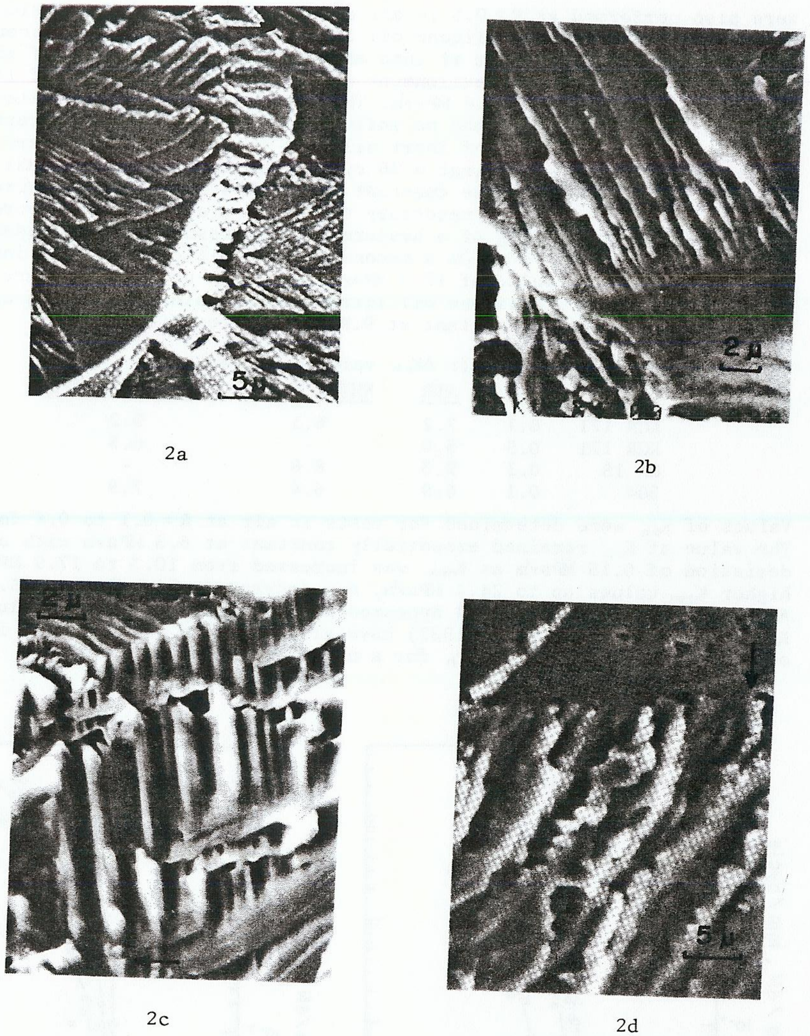

Fig. 2 Near-threshold fractographic features include a) flat crystallographic facets (KCR 171 in white water), b) parallel sheet-like facets (CA 15 in air), c) crystallographic step-like facets (304 in white water) and d) serrated river lines which multiply at grain boundaries (KCR 171 in air). The macroscopic propagation direction is indicated by an arrow.

Fractographic and plastic zone size observations

For all three materials and for both phases of KCR 171 and CA 15, the near-threshold fractography consisted of fine crystallographic facets (Fig. 2). Features observed included flat, rather smooth facets (Fig. 2a), parallel sheet-like facets separated by fine cracks (Fig. 2b), crystallographic steps (Fig. 2c) and river lines which often increased in number on crossing grain boundaries. These river lines often were crystallographically serrated (Fig. 2d) and at times formed fan-shaped patterns, very similar to those observed during transgranular stress corrosion cracking (tscc) (Mukai and others, 1978; Dickson and others, 1980). The other features mentioned can also be observed on tscc fracture surfaces. The near-threshold fractography of the 304 steel (Fig. 3) was observed to be particularly similar to that typical of tscc of the 300 series stainless steels. The crystallographic facets produced in silicone oil tended to suggest a less brittle fracture mode; however, closer examination indicated that the only difference was that edges and corners which acted as asperities had generally been rounded by crack closure (Fig. 4a). Etch-pit shapes (Ait Bassidi and others, 1983) showed that the fracture planes in the KCR 171 ferrite were {100}.

Silicone oil introduction after testing in air resulted in the occurrence, on the portion of the fracture surface previously produced and which was quite close to the crack front when this oil was introduced, of quasi-macroscopic regions almost completely flattened (Fig. 4b) by crack closure. The crystallographic aspects were still discernible, however, in the more pronounced microscopic depressions. The introduction of this inert environment during a test in air resulted in a rapid increase in plastic zone size, similar to other observations (Davidson and Lankford, 1977; Baïlon and others, 1983). This rapid increase was clearly observed with the travelling microscope employed for crack length measurements. A doubling in surface plastic zone size was estimated microscopically after the test.

DISCUSSION

Threshold values

The R = 0.1 ΔK_{th} values in white water for KCR 171, CA 15 and 304 steels are approximately 15%, 5% and 7% lower, respectively, than those in air. For KCR 171, no change in K_{op} was detected for a change from air to white water; however, the measurements in white water were carried out only for a few thousand cycles, which was probably insufficient for an increased effect of corrosion-product induced crack closure to occur. As well, the increase in K_{op} due to fretting oxide crack closure can be more pronounced at than near ΔK_{th} (Bignonnet and others, 1983). The indication clearly is that the decrease in ΔK_{th} in white water is associated with a decrease in $(\Delta K_{eff})_{th}$ probably as a result of an (or a more severe) embrittlement compared to testing in air. If increased corrosion-product induced crack closure occurs in white water, for which environment the fracture surfaces were, prior to cleaning in inhibited HCl solution, more strongly covered with corrosion product, the true decrease in $(\Delta K_{eff})_{th}$ may actually be greater than suggested by the decrease in ΔK_{th}. The corrosion-fatigue effects at higher ΔK values obtained during tests in white water on KCR 171 and CA 15 have been explained (Ait Bassidi and others, 1983, 1984) by hydrogen embrittlement of the ferritic phase and hydrogen embrittlement is also the likely explanation for the observed decrease of ΔK_{th} and $(\Delta K_{eff})_{th}$ in white water. In this respect, it is interesting to note that a similar decrease of ΔK_{th} in white water occurred for the metastable austenitic 304 steel.

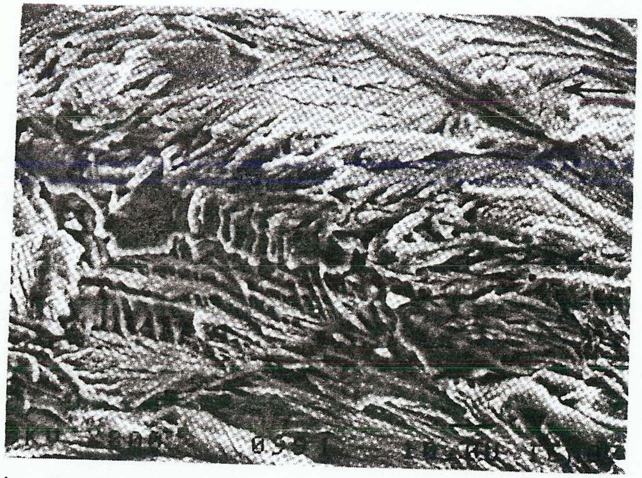

Fig. 3 Near-threshold fracture surface produced on 304 stainless steel in air

4a

4b

Fig. 4 Near-threshold fracture surfaced produced in KCR 171 a) in silicone oil showing crystallographic facets with rounded edges b) in air and subsequently flattened after a change in environment to silicone oil.

For KCR 171, ΔK_{th} was $\approx$ 30% higher in silicone oil than in air for both R = 0.1 and 0.5. For 304 stainless steel at R = 0.1, ΔK_{th} was $\approx$ 15% higher in silicone oil than in air. For KCR 171, the value of K_{op} increased initially rapidly and then gradually after a change from air to silicone oil near ΔK_{th} and stabilized after approximately 3000 cycles. The initial increase appeared to correspond well to the rapid increase in plastic zone. A subsequent gradual increase of this zone would have been very difficult to detect optically. Taking K_{op} for KCR 171 as 7.8 MPa$\sqrt{m}$ in air and 9.6 MPa$\sqrt{m}$ in silicone oil, the increase in K_{op} explains 80% and 20% of the increase in ΔK_{th} for testing in silicone oil at R = 0.1 and 0.5, respectively. Testing in silicone oil also produced fractographic evidence at both R-ratios for more crack closure than in air. An important portion of the increase in ΔK_{th} in silicone oil thus results from the increase in plasticity-induced crack closure effects, although as noted by Baïlon and others (1983) roughness-induced crack closure generally occurs in combination with plasticity-induced or with oxide-induced crack closure. The portion of the increased ΔK_{th} in silicone oil not explained by the increased closure may be associated with the occurrence of some hydrogen embrittlement in air, as suggested by occasional observations of brittle striations above the ΔK_{th} region (Ait Bassidi and others, 1983, 1984). For the 304 steel, no measurements were performed of ΔK_{th} in white water or of the change in K_{op} associated with a change in environment. For this austenitic steel, the effect of hydrogen embrittlement at ΔK_{th} in air may be small and the smaller increase in ΔK_{th} in silicone oil may be essentially associated with increased crack closure.

Fractographic aspects

The fractographic aspects of flattened or rounded asperities (Fig. 4a), obtained principally in silicone oil, indicate a combination of plasticity-induced and roughness-induced crack closure, in agreement with the increase in plastic zone size and resulting increase in K_{op} associated with a change to this inert environment. No other fractographic differences were detected for the different environments, suggesting similar crack tip morphologies. Strong hydrodynamic wedging effects in silicone oil also were not indicated since the surface flattening was not uniform.

As noted by Dickson and others (1981), the crystallographic facets obtained near ΔK_{th} are very similar to those obtained during tscc. These characteristic cleavage-type facets are produced near ΔK_{th} even in such inert environments as silicone oil and vacuum. The explanation proposed is that both types of cracking are produced by small, discontinuous, cleavage-type crack bursts, as experimentally observed for tscc of Admiralty metal (Pugh, 1981), although near ΔK_{th} this cleavage is not necessarily environmentally-assisted.

CONCLUSIONS

It can therefore be concluded that testing in white water at R = 0.1 results in a decrease of ΔK_{th} and $(\Delta K_{eff})_{th}$ compared to testing in air for KCR 171, CA 15 and 304 stainless steels. Testing in silicone oil, results in an increase in ΔK_{th}, which is at least partially associated with an increase in plastic zone size, in plasticity-induced crack closure and in K_{op}.

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REFERENCES

Ait Bassidi, M., J. Masounave, J.P. Baïlon and J.I. Dickson (1983). Fractographic study of corrosion-fatigue crack propagation in a duplex stainless steel. In G.C. Sih and J.W. Provan (Eds.), *Defects, Fracture and Fatigue*. Martinus Nijhoff, The Hague, pp. 359-371.

Ait Bassidi, M., J. Masounave, J.I. Dickson and J.P. Baïlon (1984). Corrosion-fatigue of duplex KCR 171 stainless steel in white water. *Can. Metall. Q.*, in press.

Baïlon, J.P., M. El Boujdaini and J.I. Dickson, (1983). Environmental effects on ΔK_{th} in 70-30 α-brass and 2024 T-351 Al alloy. In TMS-AIME Symposium, *Fatigue Crack Growth Threshold Concepts*, in press.

Bignonnet, A., A. Dias and H.P. Lieurade (1982). Contribution à l'étude des mécanismes de fissuration par fatigue. *Mém. Et. Sci. Rév. Mét.*, 9, 510.

Bignonnet, A., D. Loison, R. Namdar-Irani, B. Bouchet, J.H. Kwon and J. Petit (1983). Environmental and frequency effects on near-threshold fatigue crack propagation in structural steel. In TMS-AIME Symposium, *Fatigue Crack Growth Threshold Concepts*, in press.

Beevers, C.J. (1977). Fatigue crack growth characteristics at low stress intensities of metals and alloys. *Met. Sci.* 11, 362-367.

Davidson, D.L. and J. Lankford (1977). The influence of water vapour on fatigue crack plasticity in low carbon steel. In D.M.R. Taplin (Ed.), *Fracture 1977*, Pergamon Press, vol. 2, pp. 897-904.

Dickson, J.I., A.J. Russell and D. Tromans (1980), Stress-corrosion crack propagation in annealed and cold-worked 310 and 316 austenitic stainless steels in boiling (154°C) aqueous $MgCl_2$ solution", *Can. Metall. Q.*, 19, 161-167.

Dickson, J.I., J.P. Baïlon and J. Masounave (1981). A review on the threshold stress intensity range crack propagation. *Can. Metall. Q.*, 20, 317-329.

Haagensen, P.J. (1977). Fatigue crack growth in steel in air and sea water under constant amplitude and random loading. In D.M.R. Taplin (Ed.), *Fracture 1977*, Pergamon Press, vol. II, p. 905-909.

Mautz, J. and Weiss, V. (1976). Mean stress and environmental effects on near-threshold fatigue crack growth. *Cracks and Fracture. ASTM-STP 601*, p. 154-168.

Mukai, Y., M. Watanabe and M. Murata (1978). Fractographic observation of stress-corrosion cracking of AISI 304 stainless steel in boiling 42 percent magnesium chloride solution. In B.M. Strauss and W.H. Cullen (Eds.), *Fractography in Failure Analysis, ASTM STP 645*, pp. 164-175.

Pugh, E.N. (1981). On the propagation of transgranular stress-corrosion cracks. *Proceedings of NATO Advanced Research Institute Conference on Atomistics of Fracture*.

Radon, J.C. (1979). Influence of environment on threshold in fatigue crack growth. *Met. Sci.*, 18, 411-419.

Ritchie, R.O., C.M. Moss and S. Suresh (1980). Near-threshold fatigue crack growth in 2¼ Cr-1Mo pressure vessel steel in air and hydrogen. *J. Engng. Mater. Tech.*, *H102*, 293-299.

Stewart, A.T. (1980). The influence of environment and stress ratio on fatigue crack growth at near-threshold stress intensities in low alloy steel. *Engng Fract. Mech.*, 13, 463-478.

Vosikovsky, O. (1976). Fatigue crack growth in an X65 line pipe steel in sour crude oil. *Corrosion* 32, 472-475.