Pergamon

Engineering Failure Analysis, Vol. 3, No. 3, pp. 227-230, 1996

1350-6307/96 $15.00 + 0.00

PII:S1350-6307(96)00009-X

THE EFFECT OF CRACK BLUNTING IN LIQUID METAL ENVIRONMENTS ON K_{IEAC} DETERMINED BY THE RISING LOAD TEST

P. J. L. FERNANDES

Metallurgical and Corrosion Services, MATTEK, CSIR, Private Bag X28, Auckland Park, 2006, South Africa

and

D. R. H. JONES

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, U.K.

(*Received* 13 *March* 1996)

K_{IEAC} is the threshold stress intensity below which environmentally assisted crack growth does not occur. This parameter is equivalent to K_{ISCC} for stress corrosion cracking, or K_{ILME} for crack growth in molten metal environments. Two techniques frequently employed in the determination of K_{IEAC} are the constant load and constant displacement tests. Although these tests have been used extensively in the past [1], they require substantially long testing times before reliable K_{IEAC} values can be obtained. By using environments significantly more aggressive than those encountered in practice, the testing times can be reduced. However, this approach introduces considerable difficulties and uncertainties in the interpretation of data.

In order to overcome the limitations of the constant load and constant displacement tests, McIntyre and Priest [2] proposed the use of an accelerated testing method, now commonly referred to as the rising load K_{ISCC} test. This technique is essentially identical to the procedure used for K_{IC} fracture toughness testing [3], except that slower loading rates are used. A monotonically increasing load is applied to a pre-cracked fracture mechanics type specimen exposed to the environment of interest. The stress intensity for crack initiation is calculated from the initiation load, as determined from the point of deviation from the linear load–displacement record, and the corresponding crack length (Fig. 1). This stress intensity value is assumed to be equivalent to K_{IEAC}.

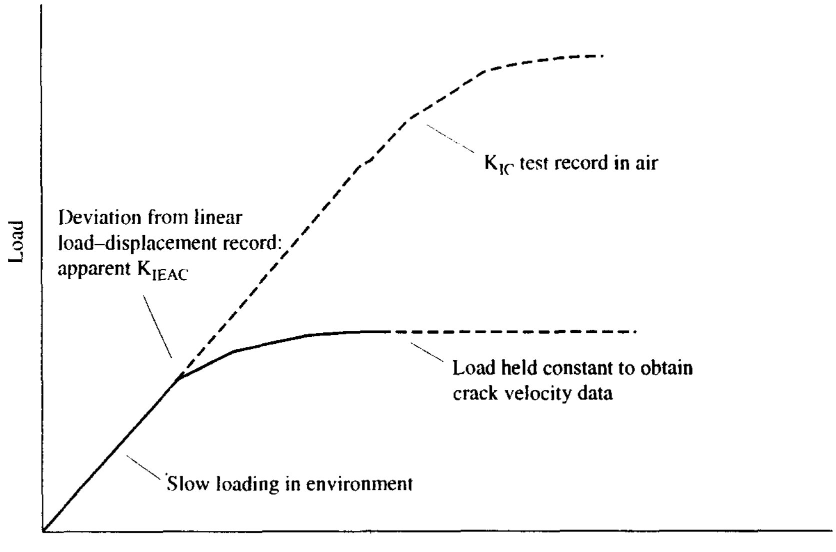

Fig. 1. Schematic of the rising load K_{ISCC} test method [11].

The rising load K_{IEAC} test has been used successfully on a number of material–environment combinations [4–9]. The technique has also been shown to be applicable under elastic–plastic fracture mechanics conditions [6–9]. A further advantage is that both K_{IEAC} and crack growth rate data can be determined from a single test.

A current limitation to the use of the rising load K_{IEAC} technique is the determination of the loading rate necessary to obtain reliable and accurate values of K_{IEAC}. Hirano *et al.* [5] and Mayville *et al.* [10] have shown that K_{IEAC} varies with loading rate or the rate of increase of stress intensity (dK/dt). As dK/dt decreases, K_{IEAC} decreases, and at low dK/dt values K_{IEAC} becomes constant (Fig. 2). Furthermore, it appears that at very low values of dK/dt the apparent K_{IEAC} may again increase [10]. This is shown schematically with a dotted line in Fig. 2. Mayville *et al.* [11] have proposed a procedure to determine the required loading rate base from crack growth data in inert environments and in the environment of interest, the latter being obtained by alternative test procedures.

The increase in apparent K_{IEAC} at low loading rates has been attributed to the formation of a protective film at the crack tip [10]. Under conditions of low loading rates, the rate of film formation (e.g. oxidation) can exceed the rate of crack growth and thus lead to the formation of a protective layer which essentially shields the crack tip from the environment. The formation of such a protective film at the crack tip under stress corrosion conditions has been well documented [12].

Wheeler *et al.* [13] have reported similar results in the case of crack growth in the aluminium–molten mercury system. By changing the loading conditions from fixed displacement to fixed or increasing load, a decelerating crack (under fixed displacement) was changed to an accelerating crack (under fixed or increasing load). If the stress intensity, and hence crack growth rate, at which the loading conditions were changed was high, the crack would accelerate under fixed or increasing load conditions. However, if the change in loading conditions was made at lower stress intensities, and therefore at lower crack growth rates, the crack would initially accelerate, but would then decelerate and eventually arrest. This behaviour is shown schematically in Fig. 3. Wheeler *et al.* [13] showed that these observations were due to crack tip oxidation effects which compete with the crack growth process. At low crack growth rates, crack tip oxidation is sufficiently rapid to suppress crack growth. At higher crack growth rates, however, insufficient time is available for oxidation to take place, and, therefore, crack growth dominates.

A further cause for the increase in the apparent K_{IEAC} at very low loading rates which has not been addressed to date is the occurrence of crack blunting at low crack growth rates in certain material–environment systems. The present authors have carried out extensive crack

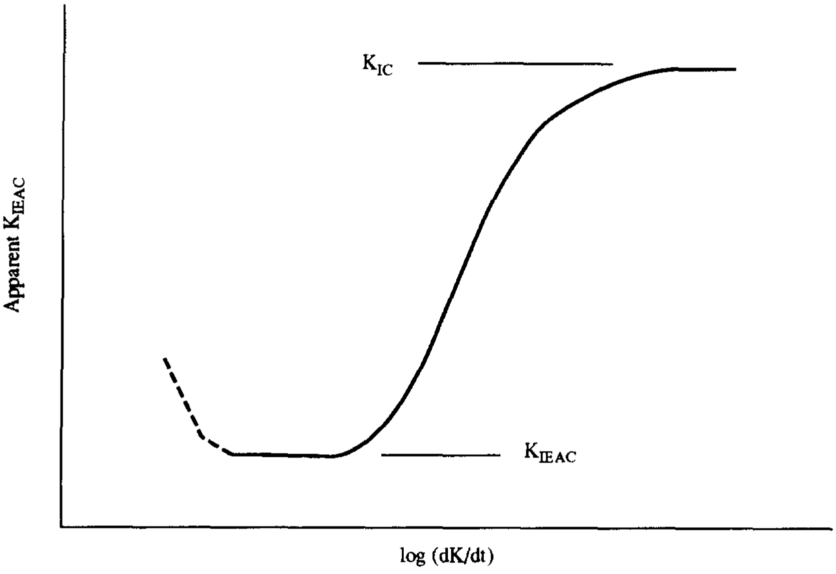

Fig. 2. Effect of loading rate on apparent K_{IEAC} [11].

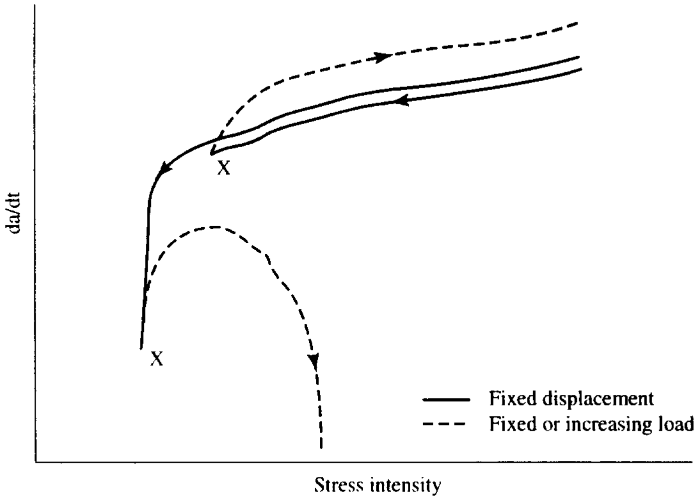

Fig. 3. Schematic of crack growth behaviour in the aluminium-mercury system [13]. The points at which the loading conditions are changed are marked with an "X".

growth tests on 63/37 brass in a molten gallium environment where liquid metal induced embrittlement of the solid metal occurs. Fatigue tests performed under various conditions of load ratio, cyclic frequency, load wave form and temperature have shown that at low crack growth rates, or where the crack tip is exposed to the liquid metal for long periods, dissolution of the solid metal into the liquid metal takes place at the crack tip [14, 15]. This results in blunting of the crack tip, which, in turn, leads to an increase in the apparent stress intensity required for subsequent crack initiation. Preliminary rising load K_{IEAC} tests performed on the same material-environment system suggest that blunting also occurs under monotonically loading conditions, provided the loading rate is sufficiently slow [16].

It should be noted that crack tip blunting due to the dissolution of the solid metal into the liquid environment has also been observed in environments other than molten metals. Radon *et al.* [17] have shown that crack blunting occurs in mild steel tested in aqueous sodium chloride solutions at low crack growth rates. Similar results were reported by Austen *et al.* [18] for martensitic steels tested in acidified water and acidified aqueous sodium chloride solutions.

The Technical Committee 10 ("Environmentally Assisted Cracking") of the European Structural Integrity Society (ESIS) has recently prepared a document entitled *Recommendations for Stress Corrosion Testing using Pre-cracked Specimens* (ESIS P4-92D), in which an attempt is made to specify a test procedure based on the rising load K_{ISCC} test [19]. It is hoped that such a procedure will allow the determination of both K_{IEAC} and crack growth data within an acceptable period. The question remains, however, as to the selection of an appropriate loading rate. In this regard, cognisance should be taken of the exact processes (e.g. oxidation, dissolution, etc.) taking place at the crack tip, since these could significantly affect the validity and reliability of results.

REFERENCES

1. A. Turnbull, *Br. Corr. J.* **27**(4), 271–289 (1992).
2. P. McIntyre and A. H. Priest, British Steel Corporation Report MG/31/72 (1972).
3. ASTM Standard E399, *Standard Test Method for Plane-strain Fracture Toughness of Metallic Materials* (1990).
4. W. G. Clark and J. D. Landes, *Stress Corrosion—New Approaches*, ASTM STP 610, American Society for Testing and Materials, Philadelphia, PA (1976).
5. K. Hirano, S. Ishizaki, H. Kobayashi and H. Nakazawa, *J. Testing Eval.* **13**(2), 162–168 (1985).
6. T. Kawakubo and M. Hishida, *J. Engng Mater. Tech*, **107**(7), 240–245 (1985).
7. G. Abramson, J. T. Evans and R. N. Parkins, *Metall. Trans. A* **16**(1), 101–108 (1985).
8. D. R. Anderson and J. P. Gudas, *Environmentally-sensitive Fracture: Evaluation and Comparison of Test Methods*, ASTM STP 821 (edited by S. W. Dean, E. N. Pugh and G. M. Ugiansky), pp. 98–113, American Society for Testing and Materials, Philadelphia, PA (1984).

9. W. Dietzel, K. H. Schwalbe and D. Wu, *Fatigue Fracture Engng Mater. Struct.* **12**(6), 495–510 (1989).
10. R. A. Mayville, T. J. Warren and P. D. Hilton, *Trans. ASM* **109**(7), 188–193 (1987).
11. R. A. Mayville, T. J. Warren and P. D. Hilton, *J. Testing Eval.* **17**(4), 203–211 (1989).
12. J. C. Scully, *Corros. Sci.* **20**, 997–1016 (1980).
13. D. A. Wheeler, R. G. Hoagland and J. P. Hirth, *Corros. Sci.* **45**, 207–212 (1989).
14. P. J. L. Fernandes and D. R. H. Jones, *Int. J. Fatigue* **17**(7), 501–505 (1995).
15. P. J. L. Fernandes and D. R. H. Jones, *Corros. Sci.* **38**, 745–754 (1996).
16. P. J. L. Fernandes, PhD Thesis, University of Cambridge (1994).
17. J. C. Radon, C. M. Branco and L. E. Culver, *Int. J. Fracture* **12**, 467–469 (1976).
18. I. M. Austen, R. Brook and J. M. West, *J. Fracture* **12**(2), 253–263 (1976).
19. W. Dietzel, 7th *International Conference on Mechanical Behaviour of Materials*, The Hague, pp. 313–314 (1995).