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Development and early growth of fatigue cracks from corrosion damage in high strength stainless steel

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Abstract

This paper investigates the influence of localised corrosion flaws caused by pitting and crevice corrosion in 15-5PH high strength stainless steel on the development and early growth of fatigue cracks. Fatigue specimens fitted with a crevice former were exposed to a 5%NaCl solution in a salt spray cabinet to produce a single flaw in the middle of the specimen and then tested in fatigue. The development and early growth of fatigue cracks were recorded using a range of techniques. After failure the shape and size of corrosion flaws where cracks initiated were measured and their largest K_t values determined by finite element analysis. Considerable variability in life response to defect K_t was found. Comparison of experimental crack growth data with fracture mechanics predictions showed evidence of a significant number of cycles occupied in transforming defects into cracks in some initiating flaws.

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1. Introduction

Passive metals such as stainless steels suffer from localised corrosion when in contact with corrosive environments like chloride solutions. When coupled with fatigue, localised corrosion damage acts as a stress raiser and moves the endurance of the metal from crack initiation domination to a life consumed by crack propagation. The difference between endurance in fatigue crack initiation and in fatigue crack propagation becomes more extreme as material strength increases.

Fatigue cracks in stainless steels have been shown to initiate at corrosion pits and in 12% Cr high strength martensitic alloys the initiation time represents most of the fatigue life [1]. Shalaby et al. [2] found that initiation in these steels was environmentally controlled in chloride solutions and occurred at pits, sites of dissolved non-metallic inclusions and areas of etched grain boundary formed during the fatigue tests. In 316L austenitic stainless steel, initiation was related to the formation of both pitting and intergranular corrosion [3]. Grain boundaries were shown to be attacked preferentially within the pits, forming stress raising notches that then became crack initiation sites. As the crack propagated, it transformed from the initial intergranular form to a transgranular mode. Studies on artificial

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pits have been used to investigate the role of pit shape on initiation [4]. In 2024-T3 aluminium alloy pit depth was shown to be the critical parameter determining life. For 7075-T6 aluminium alloy, besides pit depth, the time and location of crack initiation was dependent on pit surface area and surrounding pit proximity [5].

Another cause of surface damage that raises the stress locally and can act as an initiation site is crevice corrosion. There are several mechanisms for crevice corrosion [6] but it is most widely thought to occur where there is insufficient access of oxygen to the metal surface to maintain the protective passive film. This may arise within a joint or beneath a seal or surface deposit and metal loss occurs preferentially in the occluded region [7,8]. Both pitting and crevice corrosion can occur on stainless steels in the presence of chlorides and similar acidic conditions exist in the electrolyte in each case [9]. However, the critical temperature for crevice corrosion to occur is generally lower than for pitting and in many practical conditions crevice corrosion represents the more likely source of corrosion damage [6].

Although localised corrosion damage is known to be the initiation site for fatigue cracks, factors controlling the transformation of flaws into cracks are not yet understood. This paper describes a study of the influence of localised corrosion flaws caused by pitting and crevice corrosion in 15-5PH high strength stainless steel on the development and early growth of fatigue cracks.

2. Experimental methods & test material

The chemical composition of 15-5 precipitation hardening (PH) stainless steel is given in Table 1. Static strength and ductility properties are given in Table 2.

Table 1. Chemical composition of 15-5PH stainless steel [10]

C	Si	Mn	Cr	Ni	Mo	Cu	P	S	Nb
0.043	0.37	0.54	15.23	4.30	0.20	3.28	0.027	0.001	0.32

Table 2. Static strength and ductility properties of 15-5PH (H1025) L [10]

Rp 0.2%	UTS	Elongation, E	Reduction of area, RA
MPa	MPa	%	%
1275	1392	18	59

The fatigue test specimens were 6 mm thick dog-bone specimens, 160 mm long with a minimum width of 12 mm. Crevice corrosion damage was introduced into the sample minimum section by attaching to it a 3 mm diameter crevice former made of Perspex, as illustrated in Fig. 1. Samples were corroded in a salt spray cabinet until a single crevice defect was produced located under the former in the centre of the specimen. Between 1300 and 1800 hours were required for this to occur.



Fig. 1. Crevice former together with fatigue specimen

Flaw sizes were measured either by taking a replica of the sample surface and observing it with an optical microscope or by directly measuring the defect with a confocal laser scanning microscope. Details of the defect shape, width and depth were recorded. Defect depth was defined as the distance between the focal plane of the

surface of the specimen and the focal plane of the deepest point. Each fatigue specimen was then fitted with a cell surrounding the defect containing a 3.5% NaCl solution to keep the corrosion damage active during the fatigue test. A total of 6 samples were tested. Samples were tested in fatigue with a maximum stress of 350 MPa, an R ratio of 0.1 and a frequency of 3 Hz. One sample was tested with a maximum stress of 970 MPa. Crack initiation and growth was monitored as a function of fatigue cycles either by replicas taken regularly during the test or with a digital camera. For some specimens fatigue cracks did not initiate from the crevice flaw but from other corrosion damage and monitoring of the crack development process was only partially complete.

After failure, the fracture surface of each specimen was observed with a scanning electron microscope and the width and depth of the defect within the corroded area from which the crack had developed was measured. These overall dimensions were used to calculate the stress concentration factor of each initiating flaw using finite element analysis. Each crevice was modelled as a semi-ellipse of semi-major axis a and semi-minor b (a being half of the width and b the maximum depth of the actual damage measured on the fracture surface). The analysis did not represent the local irregularities observed on a microscopic scale within the defect, but the gross shape only.

3. Results

3.1. Development of corrosion damage

A typical example of a corrosion defect developed under the crevice former is shown in Fig. 2. The bottom surface of the defect was very irregular and contained local areas (circled) which were of significantly greater depth than the rest of the defect. The width of the defect was approximately 3 mm, the maximum depth locally varied greatly but was typically 0.1-0.7 mm. Corrosion flaws also developed independently on the samples at sites remote from the crevice former.

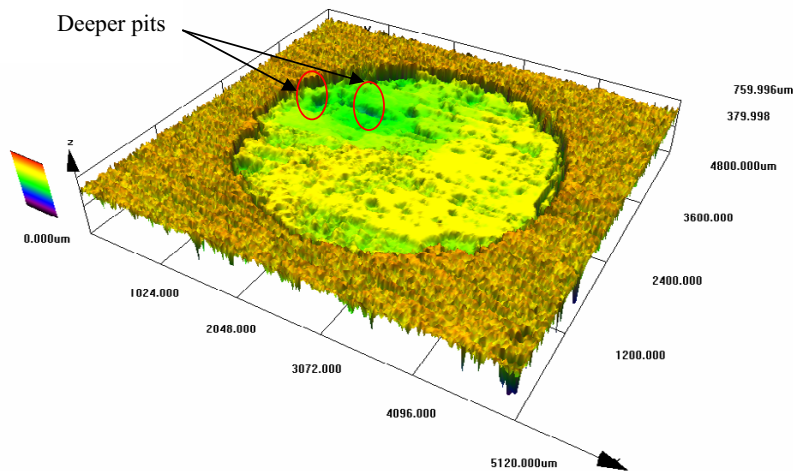


Fig. 2. 3D image of the crevice corrosion damage in specimen 2

3.2. Fatigue testing

For specimens 6, 2, 21 and 24, the failure crack initiated from the large crevice corrosion flaw, and complete monitoring of the crack development process was possible. The site of crack development within the flaw was never across the largest diameter, but was a chord of the roughly circular defect displaced from the diameter. The width of the defect measured on the fracture surface was therefore always less than 3 mm and for these samples was 2.0-2.9

mm depending on the location of the initiation. An example of this crack initiation behaviour is shown in Fig. 3 for the crack initiating at the crevice corrosion of sample 21, where the crack is located at a position almost at the furthest extremity from the centreline of the defect. Regarding specimen 17 and 20, the failure crack initiated from smaller crevice corrosion flaws which had widths at initiation varying from 0.2-0.3mm.

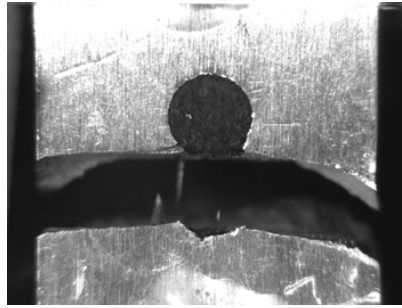


Fig. 3. Picture of a crack developing away from the maximum width of the defect in sample 21

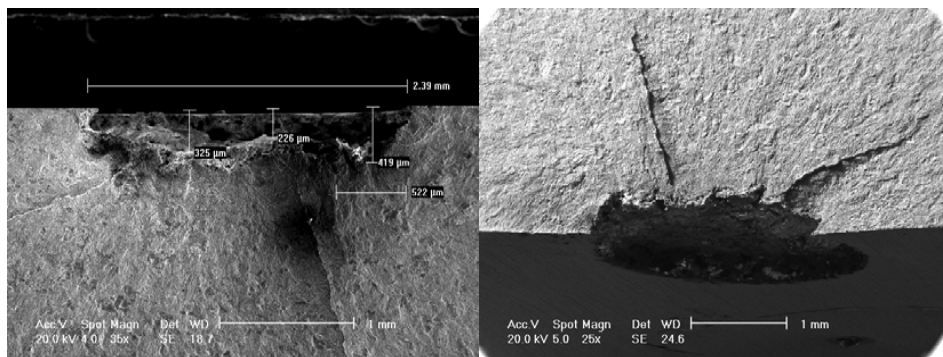


Fig. 4. Specimen 21 - Flaw where the fatigue crack initiated on fatigue fracture surface

After sample failure it was possible to accurately measure the depths and widths of the flaws in which the fatigue crack had initiated. An example of the initiating flaw from sample 21 is shown in Fig. 3. The two pictures show different views of the same sample. It can be seen that the flaw is less than the 3 mm width of the crevice former and the depth varies significantly across the width but at its deepest point approaches 500 μm .

Table 3. Dimensions of initiating flaws, total fatigue life and calculated K_t values

Specimen	Width $2a$ [mm]	Depth b [mm]	Life Total cycles to failure	FE calculated K_t
17	0.200	0.174	8196	2.29
6	2.000	0.320	167806	1.55
2	2.880	0.276	158485	1.30
20	0.330	0.110	211383	1.78
21	2.400	0.470	208679	1.50
24	2.600	0.720	91572	1.72

Defect sizes measured from the fracture surface post failure and total fatigue lives measured on all the samples are shown in Table 3. Excluding sample 17, tested at a different stress, lives varied from 9.1×10^4 to 2.1×10^5 cycles- approximately a factor of 3. Pristine samples of 15-5 PH have a fatigue strength- σ_{max} - at this $R=0.1$ of 1050MPa. [11]. This give a stress concentration in fatigue $K_f = 1050/350$ of 3. This compared with values for K_t calculated using FE from the gross shapes of the defects as shown in Table 3 of between 1.3 and 1.78- appreciably less than 3 and suggesting that the fine root radius in the pit like excursions at the bottom of the crevice corrosion defect were enhancing the nominal K_t values.

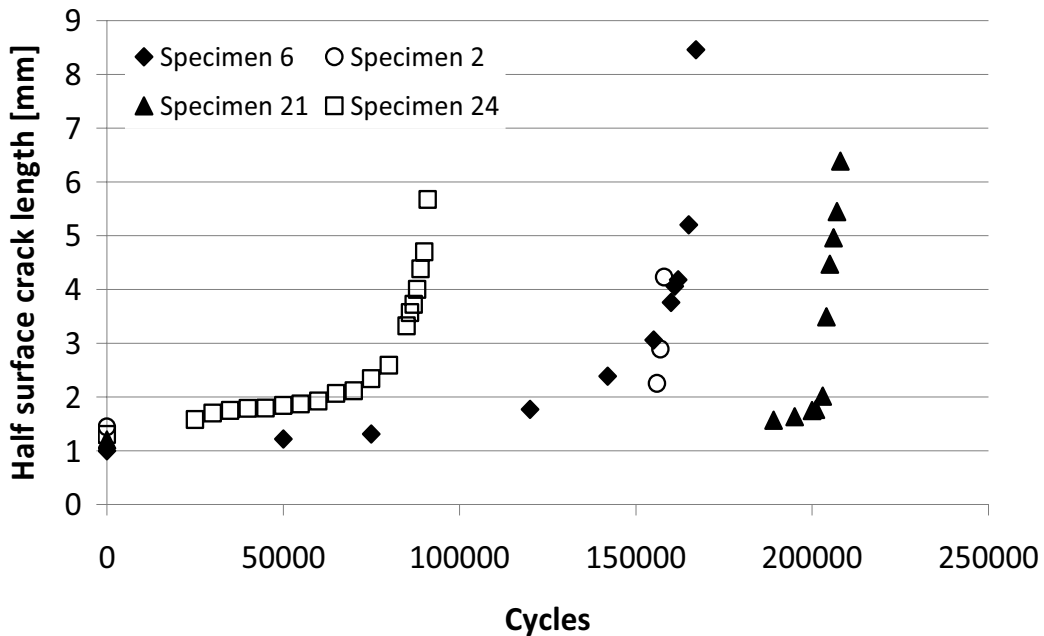


Fig. 5. Surface crack development from defects for samples 2, 6, 21 and 24

Fig. 5 shows a plot of surface crack development as measured from the centre of the flaw for these samples. The point of intersection of the data with the crack length axis is the defect half width.

Fig. 5 shows significant variability in the early crack growth behaviour from the corrosion defects, but growth rates at surface crack lengths greater than about 1.5- 2 mm all look similar. Based on the data in Fig. 5, Table 4 can be constructed and shows the lives to attain 0.2 mm, 0.8 mm and failure crack length for the 4 samples.

Table 4. Surface defect half width (a) and cycles to achieve 0.2 mm, 0.8 mm and failure length

Specimen	Half crack surface length a	Cycles to 0.2 mm from defect edge	Cycles to 0.8 mm from defect edge	Total life	Crack growth life 0.8 mm to failure
6	0.77 mm	50000	120000	167806	47806
2	0.81 mm	80000	156000	158485	2485
21	0.81 mm	100000	203000	208679	5679
24	0.82 mm	18000	70000	91572	21572

The cycles to achieve 0.2 mm crack growth are between 26% and 51% of the total life, and life to 0.8 mm fatigue crack growth is between 72%-98% of total life. Crack growth after 0.8 mm is always less than 30% of total life and in two of the samples is less than 2% of total life- a significant variability in crack growth life under nominally identical conditions.

The calculated value of the K_t for each of the defects in the samples tested varies with both the defect depth, but also with the aspect ratio $2a/b$. Fig. 6 shows how the K_t varies with the geometry factor $2a/b$ of the flaw, being largely invariant, once $2a/b$ becomes greater than about 6.

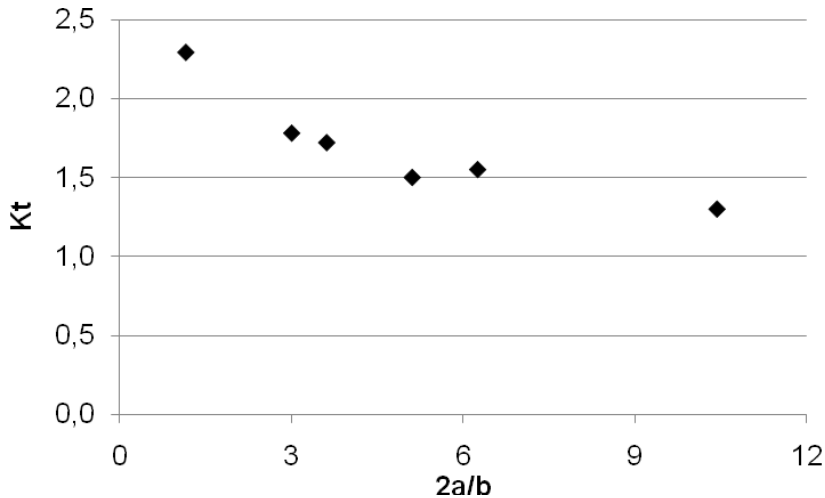


Fig. 6. Stress concentration factor K_t as a function of the shape of the corrosion flaw

4. Discussion

For the specimens in which the crack initiated at the crevice corrosion flaw, it appeared that the fatigue crack did not necessarily initiate at the deepest point, as shown in Table 5. In addition, when the fatigue crack initiated from a circular crevice corrosion flaw, the fatigue crack did not initiate at the maximum width of the flaw, which was 3 mm. These observations are consistent with the conclusions of Jones and Hoepfner [5] who showed that corrosion flaw surface area was as important as its depth in the location of the fatigue crack initiation. The value of stress concentration factor is also related to the shape of the corrosion flaw at the point where the fatigue crack initiated. Fig. 6 illustrates that the smaller the ratio $2a/b$, the larger the K_t .

Table 5. Comparison of the maximum flaw depth measured before fatigue testing and where the fatigue crack initiated

Specimen	Maximum depth measured before fatigue testing	Maximum depth at which fatigue crack initiated
17	156 μm	174 μm
6	250 μm	320 μm
2	338 μm	276 μm
21	631 μm	470 μm
24	1023 μm	720 μm

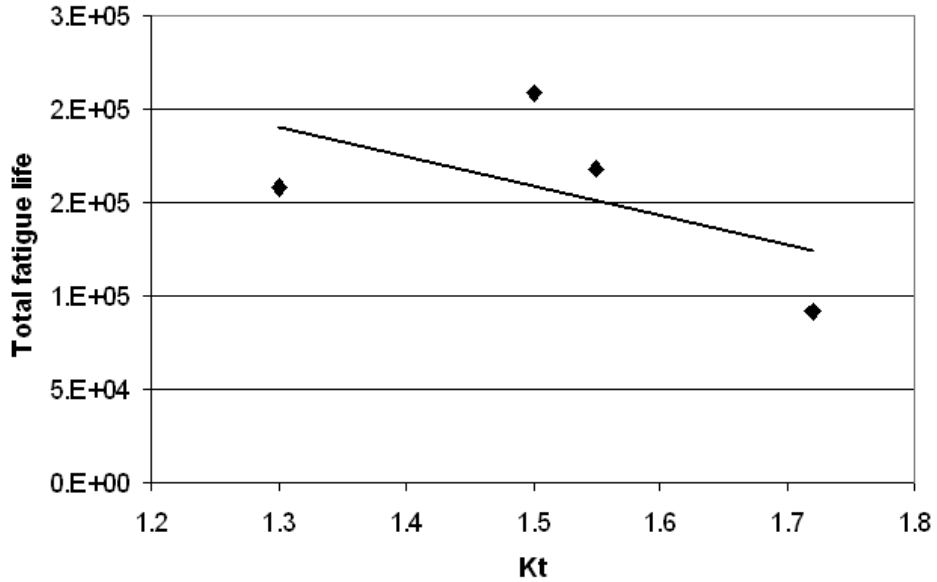


Fig. 7. Total fatigue life vs. Kt

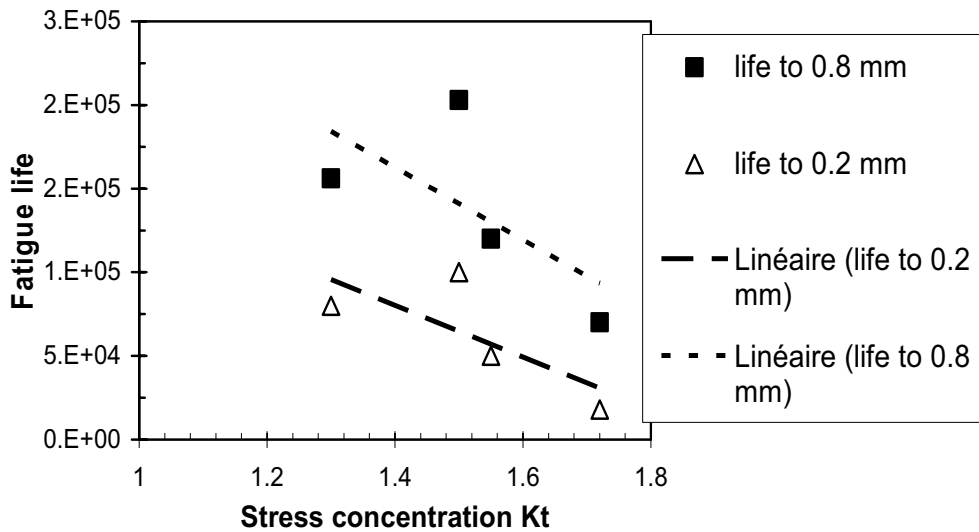


Fig. 8. Fatigue life vs. Kt for lifes to 0.8mm and 0.2mm crack extensions

The process of fatigue consists of initiation and crack growth, and it might be expected that Kt will influence the process of initiation and early growth near the boundary of the defect, but not at the longer crack lengths. To explore the influence of Kt, the value of defect Kt for the individual sample defects was plotted against cycles to achieve failure, as shown in Fig. 7 and cycles to achieve 0.2 mm and 0.8 mm crack extensions, this is shown in Fig. 8. The

lines are best fit lines to the data using a least squares fit. It can be seen that there is a rather poor correlation of total life with Kt (Fig. 7), which improves if rather than total life, life to 0.8 mm crack extension and life to 0.2 mm crack extension are considered. This suggests that early crack growth and /or initiation behaviour is indeed being influenced by Kt .

Another means of establishing the extent of any differences between initiation behaviour and crack propagation behaviour is to calculate fatigue crack growth lives using the corrosion defects as a starting crack rather than a defect. Discrepancies between calculated and experimentally measured crack growth behaviour may indicate the extent of any initiation stage in which defects are transformed to cracks.

The AFGROW crack growth package [12] was used to model the growth of an elliptical surface defect using the geometries of $2a/b$ in Table 3 for samples 2,6,21, and 24, as starter dimensions. The crack growth data for 15-5 PH at a similar strength level to that used in this work was used as the input material data.

A comparison of calculated and experimental total lives is shown in Fig. 9. It can be seen that the agreement is excellent for the sample with shortest life (and largest Kt , but becomes increasingly inaccurate and conservative at longer lives. This implies that life is almost all crack growth for the shortest life and the longest life contains at least 50% of the life as cycles to transform the corrosion defect into a crack. A comparison of the experimental crack growth behaviour of this sample 21, with the calculated fracture mechanics prediction is shown in Fig. 10.

This confirms that the major difference between the short predicted life and the experimental life in this sample is a substantially increased number of cycles to transform the defect to a growing crack. Samples 2 and 6 also had significant initiation cycles prior to crack growth, whereas in specimen 24 the initiation stage was vestigial.

The differences between the cycles required to initiate the growing crack in these and the other samples must be related to geometrical differences in their detailed morphology which are as yet undefined, despite the similarities in their gross shapes. Further work is proceeding to identify more exactly the morphological origins of these differences in life.

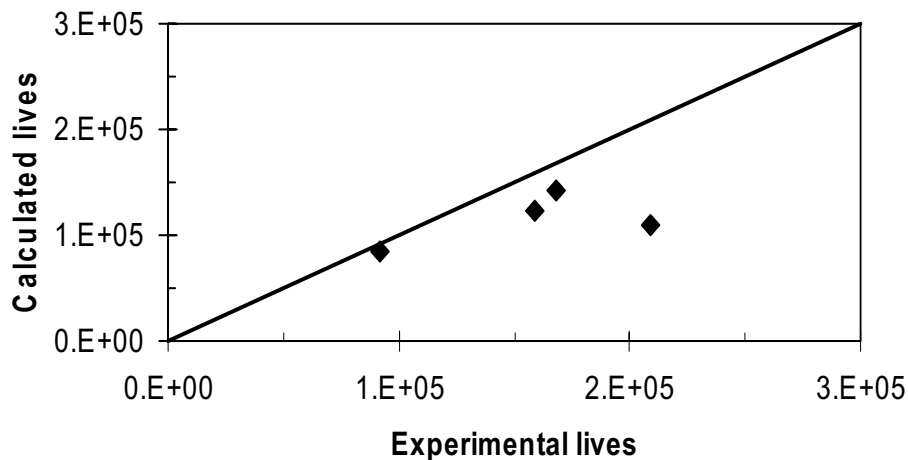


Fig. 9. Comparison of calculated and experimental crack growth lives for samples 2,6,21 and 24

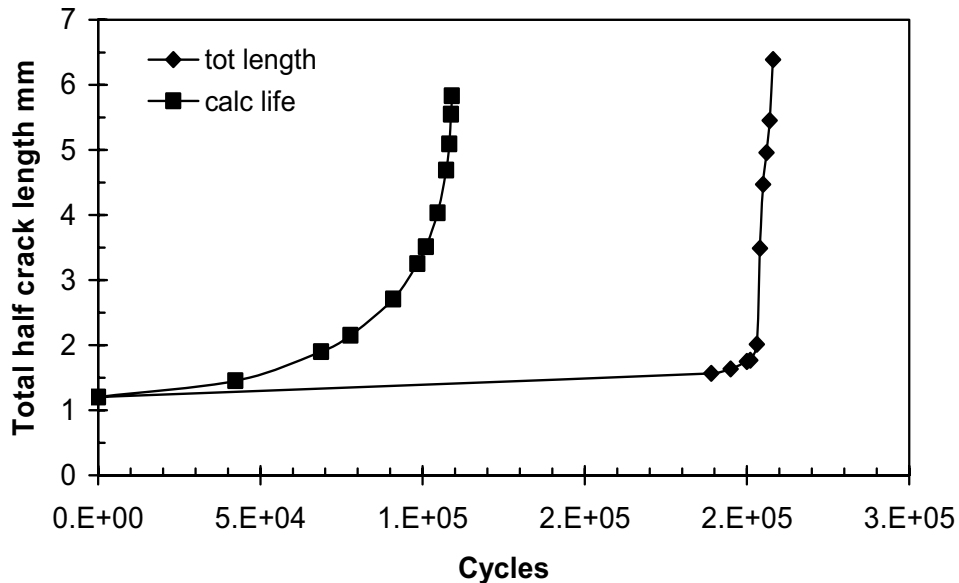


Fig. 10. Crack length Vs cycles measured experimentally and calculated using AFGROW

5. Conclusions

1. 15-5 PH stainless steel is susceptible to crevice corrosion attack, readily creating surface corrosion defects which reduced the fatigue strength markedly from that of pristine samples.
2. The calculated Kt values of the defects ranged from 1.3- 1.78 depending on their depth and aspect ratio. . This is significantly less than the experimentally derived Kt value of a factor of 3, obtained by comparison with pristine sample fatigue strengths. Fatigue lives could be approximately related to the value of calculated defect Kt for lives to crack lengths of 0.2 and 0.8 mm.
3. Measurements of the crack development from the corrosion defects showed significant variation in the early crack growth behaviour. Comparison with calculated fatigue crack growth crack length cycles curves showed that some defects had significant initiation stages whereas others did not, and this was the source of the variability.

Acknowledgements

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References

- [1] R. Ebara, "Corrosion fatigue crack initiation in 12% chromium stainless steel", Mater. Sci. Eng. A **468-470** (2007), pp 109-113
- [2] H.M. Shalaby, J.A. Begley and D.D. MacDonald, "Phenomenological aspects of fatigue crack initiation and propagation in type 403 stainless steel in simulated steam cycle environments", Corrosion **52** (1996), pp 262-274

- [3] J. Xie, A.T. Alpas and D.O. Northwood, "A mechanism for the crack initiation of corrosion fatigue of 316L stainless steel in Hank's solution", *Mater. Charact.* **48** (2002), pp 271-277
- [4] S.I. Rokhlin, J.-Y. Kim, H. Nagy and B. Zoofan, "Effect of pitting corrosion on fatigue crack initiation and fatigue life", *Eng. Fract. Mech.* **62** (1999), pp 425-444
- [5] K. Jones and D.W. Hoepfner, "Pit-to-crack transition in pre-corroded 7075-T6 aluminium alloy under cyclic loading", *Corr. Sci.* **47** (2005), pp 2185-2198
- [6] N.J. Laycock, J. Stewart and R.C. Newman, "The initiation of crevice corrosion in stainless steels", *Corr. Sci.* **39** (1997), pp 1791-1809
- [7] J.W. Oldfield and W.H. Sutton, "Crevice corrosion of stainless steels. I- A mathematical model", *Brit. Corr. J.* **13** (1978), pp 13-22
- [8] J.W. Oldfield and W.H. Sutton, "Crevice corrosion of stainless steel. II- Experimental studies", *Brit. Corr. J.* **13** (1978), pp 104-111
- [9] A. Turnbull, "Review of the electrochemical conditions in cracks with particular reference to corrosion fatigue of structural steels in sea water", *Rev. Coatings Corr.* **5** (1982), pp 43-171
- [10] "Inspection Certificate of 15-5PH", Acciaierie Valbruna for AK steel S.R.L
- [11] Military Handbook - www.knovel.com
- [12] www.afgrow.net