A NEW NORMALIZED CHARACTERIZING FATIGUE FUNCTION

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ABSTRACT

A normalized (non-dimensional) characterizing fatigue function is proposed and applied to the fatigue and corrosion fatigue behaviour of three steels – an offshore low carbon structural steel, a medium carbon steel and a high-strength spring steel – under different loading conditions, namely of environment, stress state, stress and frequency. This new fatigue function is based on experimental results concerning in-air fatigue-crack and corrosion fatigue-crack growth, and leads to a new graphic presentation of the fatigue behaviour of metals, plotting crack growth rate against normalized fatigue function. The new presentation of fatigue data reveals a linear behaviour of the proposed normalized fatigue function, here called "natural fatigue tendency". This tendency is expressed as a line corresponding to a given stress range at in-air fatigue conditions, or as a narrow linear region corresponding to a given environment in cases of corrosion fatigue. The identification of this natural fatigue tendency gives new possibilities for comparison between the fatigue behaviours of different metals.

INTRODUCTION

It is now well established that the fatigue behaviour of metals can be described by three distinct regimes, namely microstructurally short cracks, physically small cracks and long cracks [1]. Each type of crack requires a different analytical approach to characterize its propagation behaviour.

In terms of the driving stresses, Forsyth [2] distinguishes two basically different forms of cracks: Stage I, a microstructural crack developed by shear stresses, passing into Stage II, as a longer crack developed by tensile stresses. Between these two stages lies a transition zone of what have come to be called "physically small cracks". This zone represents a significant component of the fatigue resistance and cyclic lifetime of metals. The defining limits of this zone are emphasized by Miller as involving two fundamentally different threshold conditions, marking on the one hand a “microstructural dependent state” and on the other a ”mechanical stress-strain dependent state” [3].

In terms of fracture mechanics, two basic short crack models have been adopted to describe the conditions required for both Stage I shear crack growth and Stage II tensile crack growth:

1. The Brown-Hobson model for in-air fatigue [4, 5], modified for corrosion fatigue as the Akid-Murtaza model [6, 7], each presenting two general equations for predicting the crack growth rate for both short and long (including physically small) cracks. (These models have been additionally revised by Angelova-Akid in an attempt to describe the physically small crack growth by a third, separate equation [8]);
2. The Navarro de los Rios model [9], which represents a basic equation for predicting the crack growth rate for both short and long (including physically small) cracks through decreasing crack growth fluctuations,

continuously occurring up to complete failure as the crack grows longer and passes through microstructural barriers of decreasing effectiveness.

An alternative approach to the successive forms of the Brown-Hobson model is proposed by Angelova-Akid [10]. This approach adopts normalized parameters, and describes the metal corrosion fatigue behaviour of different stages of the fatigue process in non-dimensional terms or in unit intervals. Such a presentation includes a normalization of the ordinary corrosion fatigue parameters (as fatigue cycles N, corresponding times t, pit or crack surface lengths a_p or a_c and crack growth rate (da_c/dN)). The new normalized parameters are:

1. $N/N_f = t/t_f$, where N represents the instantaneous number of fatigue cycles, N_f, the final number of fatigue cycles at failure, t and t_f are the corresponding times, and $t = N(1/\nu)$ where ν is the applied test frequency;
2. a_p/a_f, a_c/a_f , adopting the interpretation that the pit and crack sizes a_p and a_c could be expressed as fractions of the final length of the major crack, a_f;
3. $(da/dN)/(da_c/dN)_{max}$, representing the ratio between the pit (da_p/dN) or crack (da_c/dN) growth rate and the maximum crack growth rate $(da_c/dN)_{max}$, in the pitting and non-continuum crack growth region.

These parameters help to reveal the nature of fatigue behaviour in general and let us compare non-dimensionally (in unit intervals) the performance of similar metals from a given class or family when exposed to a wide range of conditions. They make it possible to predict which would score highest in different ways, for example by having the longest lifetime, the greatest resistance to pitting, etc. They also enable us to compare corrosion fatigue behaviours independently of the size effects when different sized specimens are used.

The present paper suggests a further development of the alternative approach of normalized parameters, revealing a tendency of metal fatigue behaviour, called "natural fatigue tendency", expressed in normalized terms as a specific (non-dimensional) characterizing function and illustrated from three steels: a low-carbon roller-quenched tempered steel (the Angelova-Akid normalized parameters model), [10], a medium carbon steel (the Brown-Hobson model), [4, 5] and a high strength spring steel (the Akid-Murtaza model), [6, 7]. The steels are exposed to air and/or an aggressive environment under different frequencies and stress states (uniaxial push-pull and pull-pull, and torsion). The development of pits and short cracks has been carefully monitored by taking replicas from the surfaces of specimens (See Figures 1 ***a***, ***b***, ***c***), most of them of standard hour-glass shape, some with cylindrical twin-section gauge areas as described in [10], p. 413.

MATERIALS AND FATIGUE TEST RESULTS

Low-carbon roller-quenched tempered steel, RQT501. The material selected for this study is a low-carbon roller-quenched tempered steel, RQT501, used for offshore applications. The chemical composition and mechanical properties of this steel are shown in Table 1 and 2, respectively. All tests were carried out under tension-tension loading at a stress ratio R = 0.1 using a servo-electric fatigue rig with a load capacity of 100 kN. Tests were performed in load control at stress levels of 396, 470 and 516 MPa within a 0.6M NaCl environment. A sinusoidal waveform was used at frequencies 0.5 and 1 Hz.

TABLE 1

CHEMICAL COMPOSITION OF RQT501 STEEL (WT%)

C	Mn	Si	S	P	Cr	Mo	Nb	V	Ti	Ni	Cu	Al	CEV
0.12	1.45	0.3	0.003	0.011	0.02	0.01	0.003	0.01	0.004	0.02	0.02	0.04	0.38

TABLE 2

MICROSTRUCTURAL AND MECHANICAL PROPERTIES OF RQT501 STEEL

Average Grain Size	0.2% Proof Stress	Reduction of Area	Elongation	Tensile Strength	Fatigue limit
8.7 μm	508 MPa	77 %	22%	608 MPa	516 MPa

Fatigue tests conducted in this study were based on specimens having a twin-section cylindrical gauge-area configuration. Pit and crack initiation and growth were monitored by surface replication of the specimen at regular intervals and also by direct microscopical observation of the specimen. Pit diameters and crack lengths were measured with the help of an image-analysis system.

Two specific observations from the experimental data are worthy of note:

1. All observed cracks originated from pits.
2. The number of observed cracks varies under different loading conditions as shown in Table 3 and the experimental results for all cracks are represented in Figure 1 ***a***, ***d*** using a traditional way of showing, "crack growth rate against crack length".

TABLE 3

NUMBER OF OBSERVED CRACKS UNDER DIFFERENT LOADING CONDITIONS

Loading Conditions	0.5 Hz 516 MPa	1 Hz 516 MPa	0.5 Hz 470 MPa	1 Hz 470 MPa	0.5 Hz 396 MPa	1 Hz 396 MPa
Number of Cracks	8	10	1	7	1	1

Medium carbon steel and high-strength spring steel, existing results. The experimental work of Hobson represents in-air, push-pull fatigue tests conducted in a medium carbon steel at stress levels of $\Delta\sigma = 638.5$, 815.9 and 998.4 MPa, while Akid and Murtaza employed a high-strength spring steel under fully reversed torsional loading conditions of (i) $\Delta\tau = 915$, 1008 and 1106 MPa in air, and (ii) $\Delta\tau = 404$, 601, 815 and 900 MPa in a 0.6 M NaCl solution. For the two steels pit and short crack initiation and growth have been monitored by surface replication of the standard hour-glass specimens followed by direct microscopical observation; all the sizes of the observed defects, pits and short cracks have been measured by the above mentioned image-analysis system.

Chemical composition as well as average grain size and mechanical properties of the medium carbon steel (Hobson) [3, 4] and high strength spring steel (Akid - Murtaza) [5, 6] are given in Tables 4 and 5 respectively.

TABLE 4

CHEMICAL COMPOSITION (WT%), MICROSTRUCTURAL AND MECHANICAL PARAMETERS OF “HOBSON STEEL”

C	Mn	Si	S	P
0.4	1.0	0.1	0.001	0.005

Average Grain Size	Yield Stress	Ultimate Tensile Strength	% Elongation
97 μm	392 MPa	683 MPa	44

TABLE 5

CHEMICAL COMPOSITION (WT%), MICROSTRUCTURAL AND MECHANICAL PARAMETERS OF "AKID - MURTAZA" STEEL

C	Mn	Si	Cr	Ni	P	Mo	S
0.56	0.81	1.85	0.21	0.15	0.026	0.025	0.024

Average Grain Size	0.2% Proof Stress	Ultimate Tensile Strength	% Elongation	Hardness
30 μm	1440 MPa	1610 MPa	9.3	480 Hv

The data obtained by Brown-Hobson and Akid-Murtaza are shown in terms of "crack growth rate against crack length" respectively in Figures 1 ***b***, ***e*** and 1 ***c***, ***f***.

AN ALTERNATIVE APPROACH FOR DESCRIBING METAL FATIGUE BEHAVIOUR. ANALYSIS AND DISCUSSION

It is now well established that for short fatigue crack results we use standard graphic presentations, plotting pit or crack surface length against cycles, and pit or crack growth rate against pit size or crack length. For long fatigue crack data our presentation plots crack growth rate against crack length, or, for more practical needs, crack growth rate against stress intensity factor range. For the sake of comparison we can present in one graph the data sets of short and long fatigue crack growth, plotting crack growth rate against crack length. But we could also use the long-crack graphic presentation to carry out our comparative analysis of both short and long fatigue crack data, plotting crack growth rate against stress intensity factor range.

We could include short fatigue crack results in the graphic presentation which plots crack growth rate against stress intensity factor range, using an "effective" stress intensity factor range ΔK_{eff} . This would make comparison possible between short and long fatigue crack data, and could also achieve transferability between predictions of fatigue behaviour based on such data. Such presentations of short fatigue crack data (through ΔK_{eff}) can be seen in Figures 1 ***d***, ***e*** and ***f***, containing the experimental results obtained during the fatigue tests conducted in the three chosen steels. However, in order to make an immediate comparison between the fatigue characteristics of different materials and to use a wider range of different-sized specimens, we may prefer to present our data in normalized parameters as follows: normalized defect growth rate, $(da/dN)/(da_c/dN)_{max}$; normalized stress intensity factor range $\Delta K_{eff}/\Delta K_{max}$. Then, using the specific pattern of short fatigue crack data in the presentations shown in Figures 1 ***d***, ***e*** and ***f***, we propose a normalized (non-dimensional) characterizing fatigue function $\Delta K_{(a/N)}$ of the type

$$\Delta K_{(a/N)} = (\Delta K_{eff}/\Delta K_F)[\ (da/dN)/(a_f/N_f)],$$

where $\Delta K_{eff} = \Delta\sigma(\pi a)^{1/2}$, $\Delta K_F = \Delta\sigma_{FL}(\pi a_f)^{1/2}$ and $\Delta\sigma$, $\Delta\sigma_{FL}$ are respectively the applied stress range and the fatigue limit of a given material under fatigue testing. It is also proposed that the function $\Delta K_{(a/N)}$ be included in a presentation plotting crack growth rate against normalized fatigue function $\Delta K_{(a/N)}$.

The new presentation plotting crack growth rate against normalized fatigue function $\Delta K_{(a/N)}$ is shown in Figures 2 ***a***, ***b*** and ***c***. These graphs present the corrosion fatigue data of RQT-501 steel (for all stress ranges and both frequencies), the in-air fatigue data of Hobson steel (separately for each stress range), the in-air fatigue data of Akid-Murtaza steel (separately for each stress range), and the corrosion fatigue data of Akid-Murtaza steel (for all stress ranges and separately for each stress range). They reveal some common features:

1. The four sets of data show an almost linear positioning of the data points for the given stress range, under conditons both of in-air fatigue and of corrosion fatigue.
2. The curves formed by the data points at different stress ranges are almost straight lines, which in the case of in-air fatigue are clearly separated, forning wide bands. In the case of corrosion fatigue they are

almost contiguous, forming narrow bands. We may say that in each case these lines express the "natural fatigue tendency" of the material at the given stress range.
3. In most cases the higher stress range is connected with the higher "natural fatigue tendency" line in the graphs.
4. In the case of RQT-501 steel, the two frequencies are shown to have almost the same influence on corrosion fatigue behaviour; at the lower frequency the line expressing the "natural fatigue tendency" is only very slightly higher.
5. In the case of the Akid-Murtaza steel, the narrow band expressing the "natural fatigue tendency" under conditions of corrosion fatigue is located in the region corresponding to the upper part of the "wide band" formed under conditions of in-air fatigue.

CONCLUSIONS

A new normalized (non-dimensional) characterizing fatigue function $\Delta K_{(a/N)}$ is proposed and illustrated in terms of three steels under different fatigue conditions of environment, stress state, load and frequency. The new function adopts normalized parameters of defect growth rate and effective stress intensity factor range. The function takes part in a new presentation of fatigue data "crack growth rate against normalized fatigue function $\Delta K_{(a/N)}$" and shows a linear behaviour, called "natural fatigue tendency", which can be defined as a line corresponding to a given stress range at in-air fatigue conditions or as a narrow linear region corresponding to a given environment in most cases of corrosion fatigue.

REFERENCES

1. Miller K.J. (1993) *Mater. Sci. Tech.* **9**, 453.
2. Forsyth P.J.E. (1961). *Proc. Crack Propagation Symp.*, pp. 76-94, Cranfield: The College of Aeronautics.
3. Miller K.J. (1993) *Fatigue Fract. Engng Mater. Struct.* **16**, 931.
4. Hobson P.D., Brown M. and de los Rios E.R. (1986) *Short Cracks. ECF Publication 1*, pp. 441-459. Mechanical Engineering Publications, London.
5. Hobson P.D. (1985). PhD Thesis, University of Sheffield, UK.
6. Murtaza G. and Akid R. (1995) *Int. J. Fatigue*. **17** (3), 207.
7. Murtaza G. (1992). PhD Thesis, University of Sheffield, UK.
8. Angelova D. and Akid R. (1998) *Fatigue Fract. Engng Mater. Struct.* **21**, 771.
9. Navarro A. and de los Rios E.R. (1987) *Fatigue Fract. Engng Mater. Struct.* **10**, 169.
10. Angelova D. and Akid R. (1999) *Fatigue Fract. Engng Mater. Struct.* **22**, 409.