A NEW METHOD FOR FATIGUE TESTING AND DATA PRESENTATION: AN ILLUSTRATION ON SOME METALLIC CERAMIC AND POLYMER MATERIALS

D. G. Angelova

The University of Chemical Technology and Metallurgy, Sofia, Bulgaria

ABSTRACT *In this study a new method for fatigue testing and data presentation has been proposed, which is based on a reduced number of data readings during a fatigue test. This method represents the experimental results obtained at a given stress range linearly and shows possibilities for shortening testing times and making fatigue analyses and predictions more precise. The paper describes how the method works for representing fatigue in a high-strength spring steel. Some preparatory work has been done towards showing the applicability of the proposed method to different kinds of* Al_2O_3 *ceramic and a PC polymer.*

INTRODUCTION

Since the Paris equation appeared in the early 1960's many attempts have been made to present fatigue phenomenon by simple models. Some, for example those of Forman [1] and Walker [2], have been proposed to account for the load ratio dependence of fatigue crack growth rate and the distinction of crack growth behaviour in the near-threshold and final-failure regimes from that in the intermediate one. Summarizing, if **R**-ratio effects are taken into consideration, an accurate description of the whole fatigue behaviour of a given material needs about ten empirical constants after Dowling [3].

Other models, especially those of short fatigue crack propagation of Brown-Hobson [5] and Navarro-de los Rios [4], have been introduced to represent crack growth rates through the decreasing crack growth falls at the fatigue thresholds, Miller [6]. Some later modifications of these models describe accurately: corrosion fatigue behaviour, Akid-Murtaza [7]; a physically small crack growth regime separately from a short crack growth regime by a new equation, Angelova-Akid [8]; fatigue crack coalescence, Brown *et al.* [9]. Lately a new alternative approach has been introduced revealing a specific tendency of metal fatigue behaviour, expressed analytically as a relation between the crack growth rate and a non-dimensional characterizing fatigue function, and graphically as an almost straight line. The non-dimensional characterizing function is firstly mentioned by Angelova [10] and called “natural fatigue tendency”. A further study [11] reveals the energy dimension of the proposed new function and widens the range of its applications to many more steels and non-ferrous alloys as well as to a bigger variety of different testing conditions.

PREDICTIONS OF NATURAL FATIGUE TENDENCY FOR SOME METALLIC, CERAMIC AND POLYMER MATERIALS

In the previous studies on fatigue in metallic materials [11] a non-dimensional characterizing fatigue function was proposed as

$$\Delta W_{(a/N)} = k\frac{da}{dN}\Delta K\,, \quad k = \frac{N_f}{a_f}\frac{1}{\Delta K_{FL}}\left(\frac{cycle}{m^{3/2}Pa}\right), \tag{1}$$

where k is a normalizing constant; da/dN is the crack growth rate, ΔK is the stress intensity factor range; $\Delta K_{FL} = F\Delta\sigma_{FL}\sqrt{\pi a_f}$ =constant is the maximum value of the stress intensity factor range at fatigue limit when $a \equiv a_f$, $\Delta\sigma_{FL}$ is the stress range at fatigue limit, F is the finite size correction factor, and a_f and N_f are respectively the final length of the major crack and the number of cycles at failure. The physical sense of the function $\Delta W_{(a/N)}$ is of a certain portion of normalized potential energy decrease of ΔW per second or cycle, necessary for a corresponding crack growth of Δa. This function is employed for characterizing fatigue phenomenon in materials through a new presentation “$\log da/dN$ – $\log \Delta W_{(a/N)}$” revealing an almost straight line for fatigue tendency at a given stress range [10, 11]. The present study confirms this in Fig. 1, ***a b c*** by a family of lines ***Q*** (or $\Delta W_{(a/N)}$-lines), each of them corresponding to one of the applied different stress ranges. In a case where there is not data enough for calculating the constant k from (1) and/or ΔK, we still can transform the presentations of fatigue data in the literature “da/dN against ΔK or a” in $\Delta W_{(a/N)}$-terms, if we use one of the following functions [11]

$$\Delta W^{*}_{(a/N)} = \frac{\Delta W_{(a/N)}}{k} = \frac{da}{dN}\Delta K\,, \; \Delta W^{**}_{(a/N)} = \frac{\Delta W_{(a/N)}}{kF\sqrt{\pi}\Delta\sigma} = \frac{da}{dN}\sqrt{a}\,. \tag{2}$$

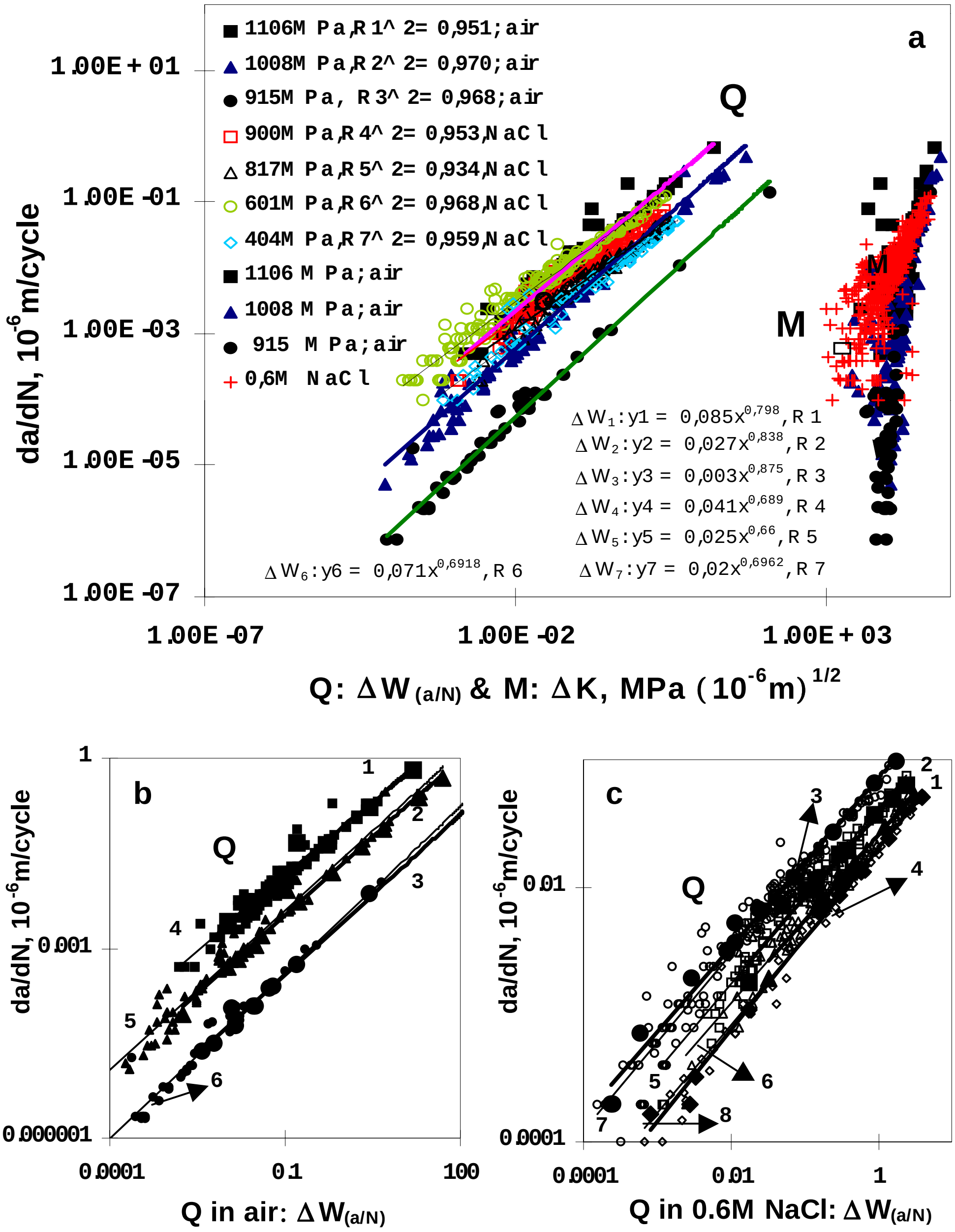

Figure 1: Fatigue in a high-strength spring steel – ***a,*** multitudes ***Q*** ($\Delta W_{(a/N)}$ - presentation) and ***M*** (ΔK - presentation) include all data from [7]; ***b*** & ***c,*** bigger symbols and thick lines 1, 2, 3 in ***b*** & ***c*** and 4 in ***c*** show a reduced number of readings and measurements only for the main cracks, while thin lines 4 in ***b*** and 5, 6, 7, 8 in ***b*** & ***c*** include all data for all crack.

An application of these functions is shown in Fig. 2, ***a b***.

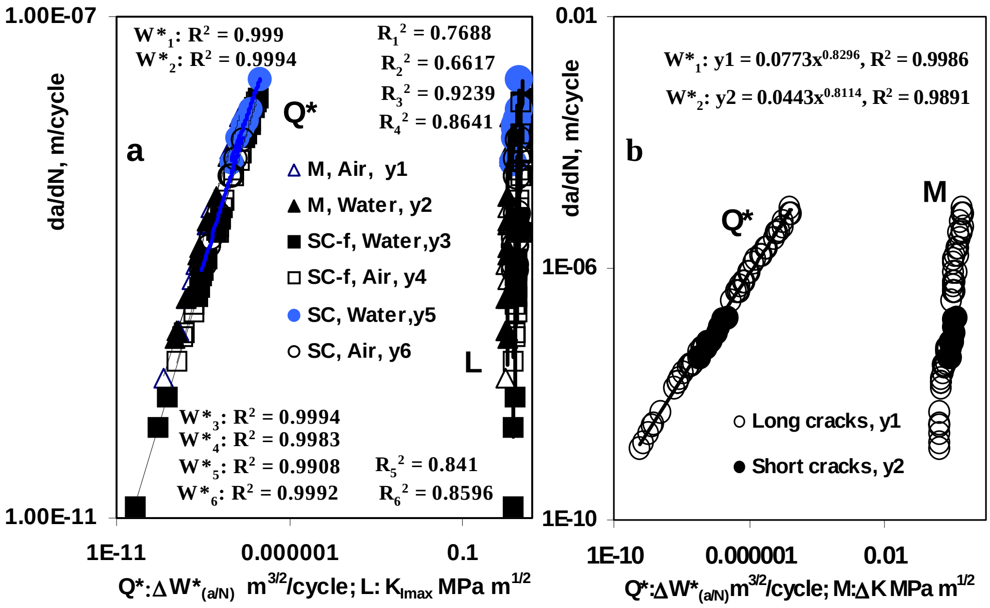

Figure 2: Fatigue in ceramics, ***a*** and a PC polymer, ***b*** shown by ***Q*, L, M***

In Fig. 2 it can be seen again that each line (here, $\Delta W*_{(a/N)}$-line) belonging to the families ***Q**** corresponds to a given stress range. What is more, all lines in ***Q*** and ***Q**** show a high correlation coefficient R^2 given in Figs. 1 and 2. Consequently, because of the revealed specific linear presentation of the fatigue behaviour of a given material or its linear fatigue tendency at a given stress range, we can reduce significantly the readings made in each test and hence, its frequent intermittence. This makes it possible not only to shorten fatigue testing times, but to make the step between the different combinations of loading conditions (in terms of sets of fatigue-loading parameters: stress ranges, frequencies, **R**-ratios, temperatures, mediums) smaller, and thus to make the analyses and predictions more precise.

A new method will be proposed in this study leading to an eventual reduction in the number of readings during different fatigue tests applied to a high-strength spring steel, and a specific data presentation. Also an attempt will be made to apply the function $\log(da/dN) = f\left(\log\Delta W*_{(a/N)}\right)$ to fatigue in ceramics and polymers expressing linearly their fatigue tendency at a given stress range, as a first step towards using the new method for these classes of materials.

MATERIALS AND TEST PROCEDURE

The materials selected for the present investigation are representatives of three basic classes, of metallic ceramic and polymer materials.

High-strength spring steel, existing results. The experimental work of Murtaza [7] has employed a high-strength spring steel for pit and short crack examination under fully reversed torsional loading of (i) $\Delta\tau$ = 915, 1008 and 1106 *MPa* in air, and (ii) $\Delta\tau$ = 404, 601, 815 and 900 *MPa* within 0.6M *NaCl* solution. The chemical composition and microstructural and mechanical properties of this steel are as follows: *C 0.56, Mn 0.81, Si 1.85, Cr 0.21, Ni 0.15, P 0.026, Mo 0.025, S 0.024*, average grain size (30 μm), 0.2% proof stress (1440 *MPa*), ultimate tensile strength (1610 *MPa*), % elongation (9.3), hardness (480 *HV*).

Ceramics from the system Al_2O_3, existing results. Three different kinds of Al_2O_3 ceramic with microstructures controlled by sintering additives (MgO, SiO_2+CaO) and particle size have been fabricated by Kido *et al.* [12] – fine equi-axed grains (Material M, MgO added), coarse columnar grains (Material SC, SiO_2+CaO added) and fine columnar grains (Material SC-f, SiO_2+CaO added) – and exposed to fatigue in air and water at room temperature. Tests have been conducted under a symmetric four–point bending using pre-cracked specimens for long crack observations.

PC polymer, existing results. A PC polymer has been exposed to fatigue at room temperature. Two groups of specimens have been used for fatigue tests carried out by Takemori [13]: smooth specimens showing discontinuous growth associated with the short part-through surface crack, and compact specimens containing long through-thickness cracks.

The results from all fatigue tests described in the above-mentioned papers are shown as originally presented by their authors as one of the multitudes ***L*** or ***M*** in Figs 1 and 2. In these figures the original graphic presentation of ***L*** and ***M*** is: $\log da/dN - \log K_{\max}$ or $\log da/dN - \log \Delta K$; and where the Paris law can fit the data, the corresponding multitude is expressed by a family of lines ***L*** (Figs. 2, ***a***). When there is no such relation, the corresponding multitude is marked as ***M*** (Fig. 1 and 2, ***b***).

RESULTS AND DISCUSSION

As already mentioned above, for some steels and nonferrous alloys it has been proved that they show almost linear behaviour under fatigue conditions, if we use one of the functions $\log(da/dN) = f\left(\log\Delta W_{(a/N)}\right)$, $\log(da/dN) = f\left(\log\Delta W *_{(a/N)}\right)$ or $\log(da/dN) = f\left(\log\Delta W **_{(a/N)}\right)$ from (1) and (2). (See their presentation in Fig. 1 of this study and in [11], the latter illustrating the linear plotting of the three mentioned functions on 9 metallic materials under different cyclic conditions within a variety of environments, at room and elevated temperatures, at different stress states ranges ratios and frequencies, at constant-amplitude and random-amplitude loading, having tested smooth and notched specimens, examining short and long fatigue cracks.) Using all this experience of the revealed linear fatigue tendency in [11], now we will try to reduce the readings during different fatigue tests applied to the chosen high-strength spring steel as follows.

All fatigue data of this steel are shown in Fig. 1, ***a*** through: (i) their original presentation taken from Murtaza work [7], where the data plot a multitude of points ***M*** $\left(\log da/dN,\ \log\Delta K\right)$; and (ii) the presentation "$\log da/dN - \log\Delta W_{(a/N)}$" expressed as a family of $\Delta W_{(a/N)}$-lines ***Q***. Figure 1, ***a*** includes two sets of data for two environments, air and 0.6M NaCl-solution, and for all stress ranges tested in [7]. To make some reduction in these data we use just a *small number of readings for instantaneous crack length and number of cycles, between 9 and 14, belonging only to the main crack* at a given stress range. In Fig. 1, ***b*** the *reduced in-air data* of the main cracks are shown through the following $\Delta W_{(a/N)}$-lines: **1** (obtained under the stress range $\Delta\tau = 1106 MPa$ and including 12 readings-measurements corresponding to 12 intermittences of the test); **2** (obtained under $\Delta\tau = 1008 MPa$ at 12 readings and 12 intermittences of the test); **3** (obtained under $\Delta\tau = 915 MPa$ at 11 readings and 11 intermittences). In the same figure *all original data* are again shown as $\Delta W_{(a/N)}$-lines: **4** at $\Delta\tau = 1008 MPa$ including 100 measurements for 4 cracks (among them 30 readings-measurements only for the main crack, which correspond to 30 intermittences of the test); **5** at $\Delta\tau = 1008 MPa$ including 90 measurements for 5 cracks (at 40 readings only for the main crack and 40 intermittences of the test); **6** at $\Delta\tau = 915 MPa$ including 50 measurements for 4 cracks (at 25 readings only for the main crack and 25 intermittences). Analogously, in Fig. 1, ***c*** the *reduced in-0.6M NaCl data* belonging just to the main cracks are shown as $\Delta W_{(a/N)}$-lines **1**, **2**, **3**, **4,** obtained respectively under $\Delta\tau \in [900, 817, 601, 404] MPa$ and fitting 10, 11, 14, 9 readings and so many intermittences of the corresponding tests. In the same figure *all original data* are again shown as $\Delta W_{(a/N)}$-lines **5**, **6**, **7**, **8,** respectively at $\Delta\tau \in [900,817,601,404]MPa$, where: **5** is plotted from 115 measurements for 8 cracks (at 20 readings-measurements only for the main crack and so many intermittences of the test); **6**, from 110 measurements for 6 cracks (at 20 readings only for the main crack and 20 intermittences of the test); **7**, from 203 measurements for 5 cracks (at 39 readings only for the main crack and 39 intermittences), **8**, from 75 measurements for 3 cracks (at 26 readings only for the main crack and 26 intermittences). It is clearly seen in Fig. 1, ***b*** and ***c*** that employing the $\Delta W_{(a/N)}$- presentation, each line plotted by using *fewer readings* derived only from the main cracks almost repeats the corresponding line including *all original data*.

Now it is useful to apply the functions (1) and (2) to some ceramics and polymers in an attempt to describe linearly their fatigue behaviour, which of course is different from that of metallic materials. In Fig. 2, ***a*** the presentation $\log(da/dN) = f\left(\log \Delta W^{*}_{(a/N)}\right)$ is shown for three ceramics from [12] tested in air and water, through a family of $\Delta W^{*}_{(a/N)}$-lines, ***Q****. The original data plotted by Kido *et al.* as $\log da/dN - \log K_{\max}$ are fitted in lines too, which form a family ***L,*** but show lesser correlation coefficients R^2 than the corresponding R^2 of ***Q****. Analogously, in Fig. 2, ***b*** fatigue in a PC polymer [13] is represented by $\log(da/dN) = f\left(\log \Delta W^{*}_{(a/N)}\right)$ expressing a family of $\Delta W^{*}_{(a/N)}$-lines, ***Q****, while the original presentation of Takemori "$\log da/dN - \log \Delta K$" is a multitude of points ***M***.

So for the ceramics and polymers from [12, 13] the linear fatigue tendency is clearly revealed, and we can apply the "*reduced*" $\Delta W_{(a/N)}$-presentation in order to save testing time (similarly to the examined spring steel) and to make fatigue analyses and predictions more precise.

CONCLUSIONS

A new method of fatigue testing and data presentation is proposed, that significantly reduces the numerous readings and measurements in each fatigue test, makes the step between the different fatigue-loading combinations (in terms of *stress range*, *frequency*, **R**-*ratio*, *temperature, environment*) smaller, and thus makes the analyses and predictions of fatigue behaviour more precise at shortened testing times. This method is based on a previously introduced specific $\Delta W_{(a/N)}$ - presentation for metallic materials or "$\log da/dN - \log \Delta W_{(a/N)}$", which is expressed as a straight line called "linear fatigue tendency" for a given stress range. The newly proposed method is illustrated on a high-strength spring steel, where the number of readings during each test is decreased by (50-70)% and the number of measurements by (80-90)% compared to those originally made.

For the first time it is proved that a version of the $\Delta W_{(a/N)}$-presentation or "$\log da/dN - \log \Delta W^*_{(a/N)}$" (where $\Delta W_{(a/N)}$ and $\Delta W^*_{(a/N)}$ differ by a constant) applied to some ceramics and polymers shows a clearly revealed linear fatigue tendency at a given stress range for short and long cracks. This makes possible an eventual application of the new method of fatigue testing and data presentation to ceramic and polymer materials after more tests of its applicability to other representatives of both classes.

REFERENCES

1. Forman R.G., Kearney V.E. and Engle R.M. (1967) *Journal of Basic Engineering* **89**, 459-464.
2. Walker K. (1970) In: *Effects of Environment and Complex Load History for Fatigue Life*, Philadelphia:ASTM Special Technical Publication 462.
3. Dowling N.E. (1999) In: *Mechanical Behaviour of Materials*, pp. 510.
4. Navarro A. and de los Rios E.R. (1987) *Fatigue Fract. Engng Mater. Struct.* **10**, 169-186.
5. Hobson P.D., Brown M. and de los Rios E.R. (1986) In: *ECF Publication 1.* Mechanical Engineering Publications, London, 441-459.
6. Miller K.J. (1993) *Mater. Sci. Tech.* **9**, 453-462.
7. Murtaza G. and Akid R. (1995) *Int. J. Fatigue.* **17** (3), 207-214.
8. Angelova D. and Akid R. (1998) *Fatigue Fract. Engng Mater. Struct.* **21**, 771-779.
9. Gao N., Brown M.W. and Miller K.J. (1995) *Fatigue Fract. Engng Mater. Struct.* **18**, 1407-1441.
10. Angelova D. (2000) *ECF 13 "Fracture Mechanics: Applications and Challenges"*, San Sebastian, Spain, Abstracts Volume, pp. 128.
11. Angelova D. (2002) *Interhational Journal of Fracture*, forthcoming.
12. Kido M., Katayama J., Tsuchibushi Y. and Inoda N. (1998) *ECF-12 "Fracture from Defects"*, Sheffield, UK, pp. 61-66.
13. Takemori M. T. (1984) *Annual Review of Materials Science* **14**,171-204.