FRACTOGRAPHIC STUDY OF FATIGUE CRACK KINETICS IN BODIES AND STRUCTURES

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ABSTRACT

The paper describes procedures for the interpretation of micro-fractographic findings which can reveal the macroscopic characteristics of fatigue crack growth. Fractographic data related to the crack length are transformed into a description of the course in time of the fatigue process. The type of results thus obtained is demonstrated on examples of the fractographic analysis of fatigue failures in aircraft structures.

KEYWORDS

Fatigue crack propagation, quantitative microfractography, fatigue striation spacing, aircraft structures.

INTRODUCTION

A typical examples of large-scale structures which are threatened by fatigue are aircraft structures (Campbell, 1981). Any estimate of their fatigue life and reliability is complicated chiefly by the character of fatigue crack nucleation and growth in real bodies : the fatigue phenomena are statistical in nature (Yokobori, 1981). In the fatigue failure of large-scale structures this statistical character is strongly accentuated, because the course of the individual processes which induce failures of the various components may be substantially affected by their interrelationships : crack systems in large-scale structures are random in respect to time and space (Němec, Drexler, and Klesnil, 1977). In statistically indeterminate aircraft structures, even a simple deterministic loading involves a high degree of uncertainty in assessments of stress state in the individual components. Although we are capable of defining the loading characteristics of the structure as a whole, the individual failure processes are practically indiscernible as far as their stress inputs are concerned; and the outputs of these processes (e.g. in terms of the fatigue crack lengths) are difficult to detect in real time, because many of the important failures are inaccessible for direct examination. All this underlines the role of fractographic investigations : in detailed studies of the fatigue processes leading up to the failure of large-scale structures, such investigations can yield vital data not obtainable by any other means.

QUANTITATIVE FRACTOGRAPHY OF FATIGUE CRACKS

Application of SEM techniques to fatigue fractures enables us to ascertain the dependence of the mean striation spacing, $\bar{s}$, on the crack length, $\underline{a}$, $\bar{s} = \bar{s}(a)$ (see Fig. 1-a). This fractographic information on the course of local microscopic crack growth rates in space must then be transformed either into $v = v(t)$ dependences (i.e. data on the development in time of the macroscopic fatigue crack growth rate) or else into $a = a(t)$ dependences. Both these modes of expressing the macroscopic fatigue crack kinetics are interlinked by the general formula $da = v.dt$, which for the purposes of this transformation is modified to suit the available type of input data, as is shown in Fig. 1-b. Input data based on the striation spacings entail the replacement of continuous time $\underline{t}$ by discrete time intervals, expressed by the number $\underline{N}$ of load cycles; the fundamental equation then assumes the form marked (2) in Fig. 1-b. The data couple (a_1, N_1) in general represents an either previously known or selected boundary condition; the couple (a_x, N_x) is the resultant location of the sougth-for values on the $a = a(N)$ dependence.

The factor denoted $\underline{D}$ in equation (2) was introduced by Nedbal (1979). Briefly, in the $v = D.\bar{s}$ dependence (where $\underline{v}$ is macroscopic crack propagation rate, and $\bar{s}$ is the mean striation spacing), the magnitude of parameter $\underline{D}$ depends on the character of the stochastic interactions between the partial failure processes in microscopic volumes of material. The qualitatively and quantitatively differing micromechanisms of crack tip propagation (governed by heterogeneity of the structure and by the corresponding redistribution, at the microscopic level, of the externally induced stress fields) are reflected in the micromorphology of the newly formed surface. Changes in this micromorphology of the fracture surfaces, and hence in the magnitude of $\underline{D}$, are determined by the type of the structure and depend on the state of stress in the cracked body; in general we may state that $D = D(\Delta K)$. We can exploit the results of material research : an investigation of the $v = v(\Delta K)$ dependence for the macroscopic crack growth rate, and of the fractographic $\bar{s} = \bar{s}(\Delta K)$ plots for the striation spacing, enables us to determine the $D = D(\bar{s})$ dependence which permits reconstruction of the crack kinetics by means of the equation marked (2) in Fig. 1-b. Our knowledge of the $\bar{s} = \bar{s}(\Delta K)$ dependence further allows us to estimate how ΔK (or $\Delta\sigma$) will vary with the crack length or in time, i.e. to describe the redistribution of forces and moments in the damaged structure. Some concrete examples of $D = D(\Delta K)$ dependences are charted in Fig. 2. The line for aluminium alloy ČSN 42 4203 (corresponding to the 2024 alloy) is the outcome of the authors' own experiments, the other two lines were established by analysis and processing of data previously published by

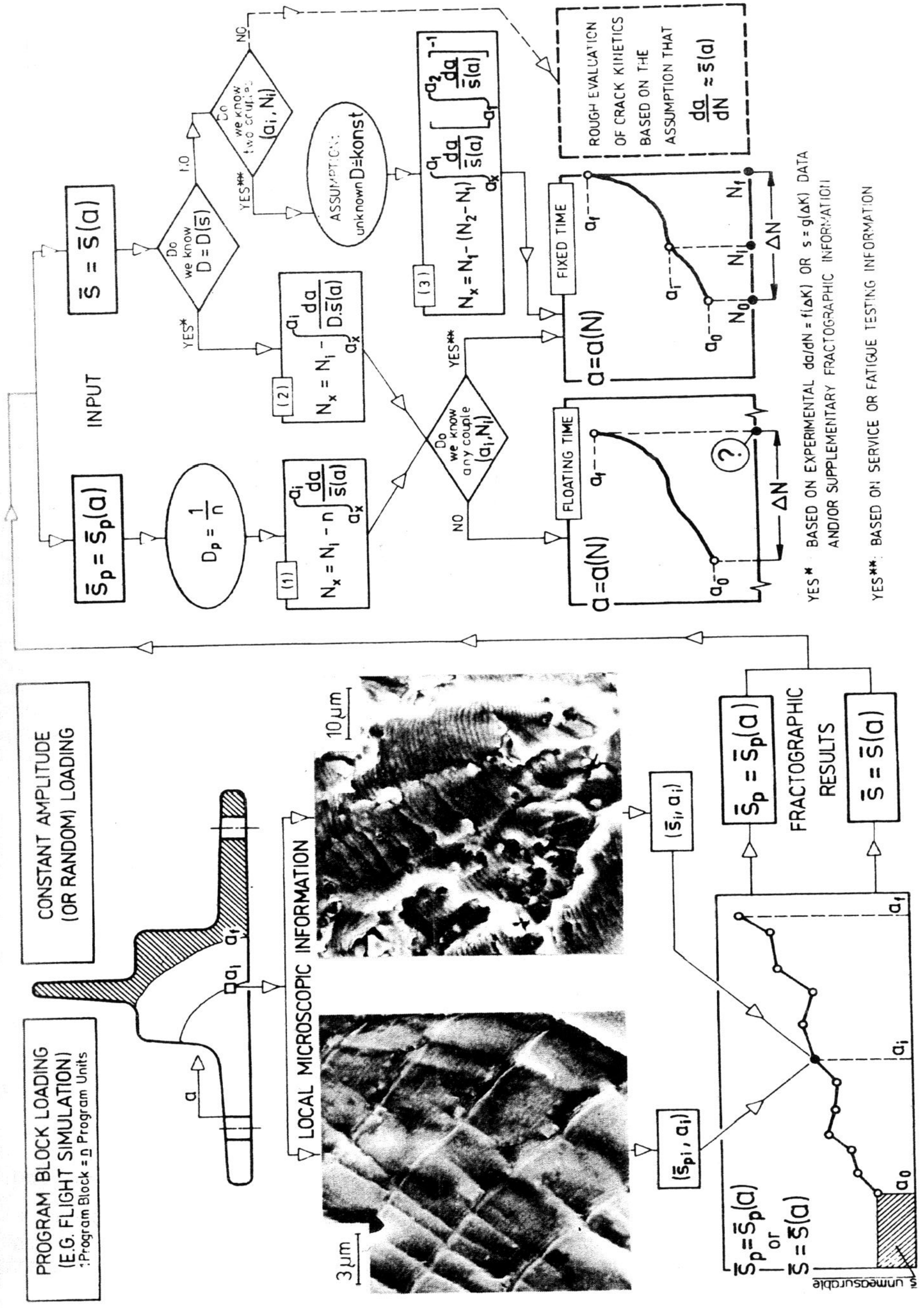

Fig. 1-a. Acquisition of fractographic data.

Fig. 1-b. Crack kinetics reconstruction.

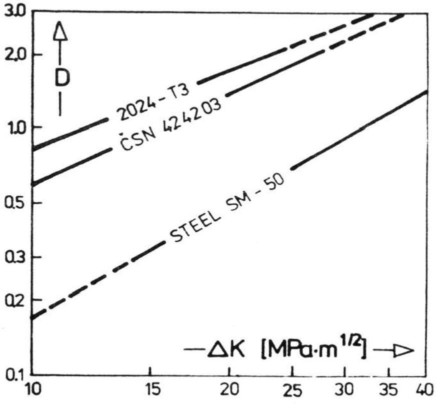

Fig. 2. The D = D(ΔK) plots.

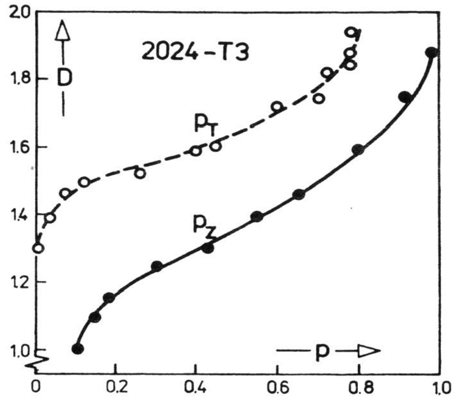

Fig. 3. The D = D(p) plots.

Yokobori and Sato (1976). In certain cases the analysis can be based on the dependence of D on the relative contributions of the various crack propagation micromechanisms, an approach illustrated in Fig. 3 (processed according to Yokobori and Sato, 1976). This involves quantifying not only the $\bar{s} = \bar{s}(a)$ relation, but also the incidence of other microfractographic features, e.g. $p_Z = 1 - p_S$ (where p_S is the area ratio of striation patches), or the area ratio of dimpled fracture p_T. Experimental verification of this procedure (Kunz, Nedbal, and Siegl, 1981) produced close agreement between the fractographic reconstruction and the optically observed a = a(N) dependence. An alternative procedure is to examine the dependence of D on the angle scatter of local microscopic rate vectors, and their deviations from the macroscopic direction of fatigue crack propagation, particularly at lower ΔK (where v is smaller than $\bar{s}$).

Industry continues to call for reconstruction of the kinetics of fatigue failures in bodies and structures. Consequently, further work has been done to check the feasibility of two different solution techniques :

1/ Where no data on D exist, the fractographic reconstruction of fatigue crack kinetics can be tackled by a procedure, proposed by Nedbal (1979), where the lacking D data are replaced by information gained in the course of the failure process. If we know two crack lengths and two appropriate time-related quantities, we can utilize equation (3) in Fig. 1-b, where (a_1, N_1) and (a_2, N_2) denote these two data couples. One couple is usually available in the form of a known number of load cycles, operating hours, or some other time-related variable, at the time when the test or service was discontinued, and the relevant fractographically ascertained total fatigue crack length. The determination of the second data couple is a problem to be solved individually for the investigated structure (Nedbal, 1979). The procedure rests on the implicit assumption that D remains constant throughout the investigated crack, which entails a risk of errors. Still, this procedure permits a sufficiently accurate reconstruction of the a = a(N) dependence, as has been

corroborated experimentally (Nedbal, 1980). One possible type of the final results obtained by this procedure is illustrated in the Case study I.

2/ The problems associated with factor D can be obviated in the case of the structures tested by complex loading programs. A repetition of program blocks which simulate the service loading of the structure produces corresponding repetitive changes in the micromorphology of the fracture surfaces. Such a program block may consist of n basic program units, and terminate with an overload that simulates the effects of a gust. This overload marks the fracture surface with a microscopically detectable crack growth band (gust-line), as seen on the left-hand photograph in Fig. 1-a. The distance between two neighbouring gust-lines defines the crack length increment caused by a known number of program units, n; it thus enables us to determine the mean crack growth rate $\bar{v}_i = (\Delta a)_i / n_i$ accurately, and over $(\Delta a)_i$ intervals small enough for the resultant plot to be considered, for all practical purposes, as continuous. In this case then, we measure the gust-line spacing instead of the striation spacing, and reconstruct the kinetics of crack growth by means of the equation marked (1) in Fig. 1-b. Factor D_P retains its original significance only formally : in this case it assumes a deterministic nature, being directly tied to the number n of program units in the block. The reconstructed a = = a(N) dependences can be reliably located on the time base even if we know only one data couple, (a_i, N_i); this is the "fixed time" result shown in Fig. 1-b. If even this single data couple is unavailable, we still gain a valid description of the macroscopic crack propagation stage, but are unable to ascertain the duration of the initiation stage, as in the "floating time" result in Fig. 1-b. This latter case is fairly rare in practice, because the operating time elapsed before a shut-down or failure of the structure is usually known. The utilization of block loading has further advantages :

a/ Marks of gust-line type allow us to assess the successive changes in the location and shape of the fatigue crack front and to convert a one-dimensional description of crack kinetics, such as a = a(N), into a two-dimensional definition, i.e. into the time dependence of the decrease of the residual cross-sectional area (as is demonstrated in Case study II). This mode of expressing the results of fractographic analyses is closer to the data of vital interest : the residual load-bearing capacity and residual fatigue life of the structure.

b/ Fractographic reconstruction of fatigue failure kinetics is equally applicable to components and structures made of materials in which the propagation of fatigue cracks is not accompanied by the formation of striations.

The use of loading program blocks is only a step away from the marking of fatigue cracks (e.g. Conley, and Sayer, 1977; McGee, and Hsu, 1981; Wilhem, and co-workers, 1981; etc.), which can yield reliable fractographic data of the (a_i, N_i) type. Reconstructions of the kinetics of marked cracks may be based solely on the fractographic identification of these marks, or else the marks may be exploited to improve the accuracy of results obtained by one of the procedures described previously.

CASE STUDIES

By way of illustration we quote the results of fractographic analyses of two aircraft structures which suffered fatigue failures. In both cases, the aim was to reconstruct the kinetics of fatigue processes in the main supporting members of wings, which failed during full-scale fatigue test.

Case study I. A wing was subjected to sawtooth cycles with a constant amplitude; when the test was concluded after 65,293 cycles and the structure was dismantled, four failures were found in the flangeplate of the lower spar. Measurements on the fracture surfaces ascertained the $\bar{s} = \bar{s}(a)$ dependences; the $a = a(N)$ growth lines in Fig. 4 were reconstructed by means of equation (3) in Fig. 1-b. Of the requisite data couples, (a_1,N_1) were determined from the crack growth bands produced on the fracture surfaces by static testing of the structure over $N = 55,440$ cycles; (a_2,N_2) is data couple corresponding to the end of fatigue test. In Fig. 4, the crack growth lines, $a = a(N)$, are supplemented by a "quantil line" for a quantil of 0.001. Quantil lines in effect represent a generalized form of the "boundary lines" for fatigue crack growth which were originally adopted by Drexler (1976). The quantil line in Fig. 4 was computed on the assumption of a log-normal distribution of the number of cycles N corresponding to length a, taking all the investigated cracks to be fully independent of each other

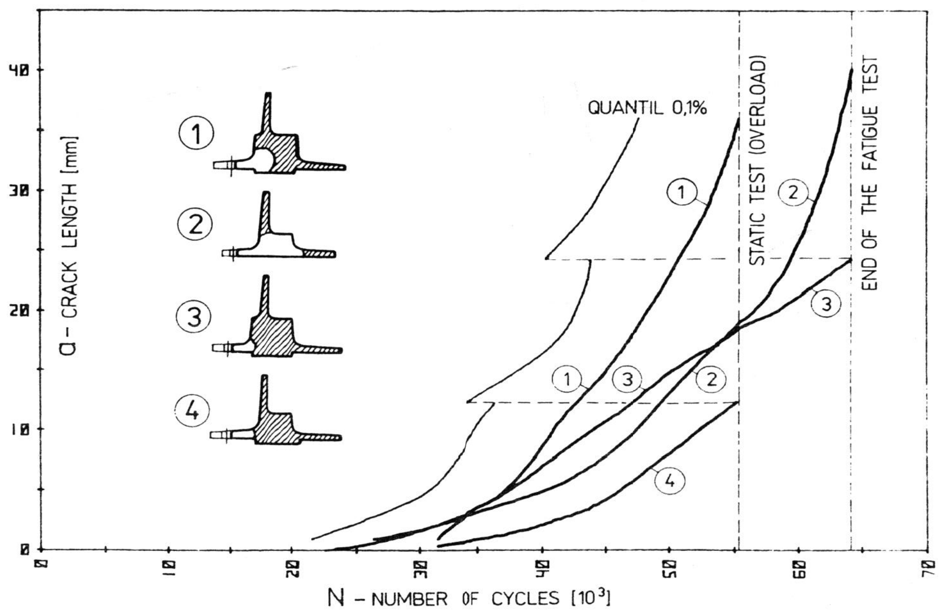

Fig. 4. The $a = a(N)$ plots and a quantil line for fatigue cracks in an aircraft wing structure.

(Kopřiva, 1980). The step-shaped character of quantil line is caused by the changes of the input data number used for computation on different crack lengths. For every crack length $a \in \langle a_{min}, a_{max} \rangle$, this line defines a number N at which there is a probability of 0.001 that a crack of length a will form before this number of cycles has been completed. The quantil lines respect the stochastic character of cracking in large-scale structures, and their credibility grows with the size of the input data set. For extrapolation of the results so as to cover a large set of similar structures, the preferable approach is to study only selected serious failures in several of these structures.

Case study II. The wing of a prototype aircraft was loaded by repeated program blocks, each comprising n program units and terminating in an overload cycle that simulated a gust. In the course of this test, the spar flangeplate fractured at the sections marked 1 and 4 in Fig. 5. After repairs the test continued, to be concluded after 152,840 program units. Subsequent dismantling revealed three more serious failures in the front and rear spars. The fractographic reconstruction of the mean fatigue failure process was based on measurements of the mean gust-line spacing (see the left-hand photograph in Fig. 1-a) in its dependence on the crack length. The calculations utilized equation (1) in Fig. 1-b. This procedure required only one data couple, (a_i,N_i), for locating the growth lines on the common N

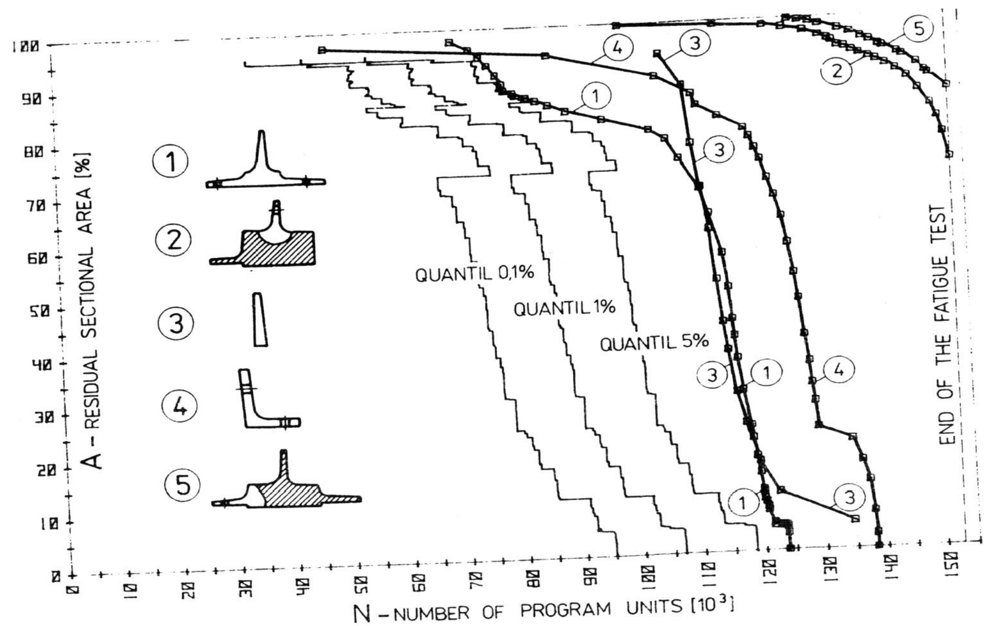

Fig. 5. The $A = A(N)$ plots and quantil lines for fatigue failure in wing spars.

axis, and this couple was established, for each crack, from the number of program units to failure or to the termination of the test. Investigation of the gust-lines enabled us to transform the crack growth lines into the percentual decrements in time of the individual load-bearing cross sections, as they are plotted in Fig. 5. Fig. 5 further presents the quantil lines for quantils of 0.001, 0.01 and 0.05 , again computed on the assumption of a log-normal distribution. A check confirmed that quantil lines founded on the assumption of a Weibull distribution are pronouncedly shifted towards lower N values.

CONCLUSION

This survey has outlined some quantitative fractographic analysis methods which can lead to a broader and deeper understanding of fatigue crack growth. Fractographic reconstructions of the kinetics of fatigue failure can yield data, on failure processes in large-scale structures, which are so far unobtainable by any other means. These data and their adequate statistical processing (e.g. by means of quantil lines) can greatly assist both research into the fatigue life and reliability of these structures, and the practical solution of some of the problems encountered with them in actual service.

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