EXPERIMENTAL BACKGROUND FOR THE FATIGUE CRACKS KINETICS SIMULATION

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The paper sets forth the inverse problem of simulating fatigue cracks kinetics, namely, on the basis of the electron microscope analysis of fatigue fractures obtained under harmonic and random loading with variable parameters, to reveal processes inaccessible for direct measurements which take place at the apex of the moving crack, and to construct a kinetics model that fits the processes in question adequately. Experimental foundations for solving this problem have been created. Kinetic effects have been discovered which are testimony to the deep non-linearity of the crack propagation behaviour, which causes a qualitative difference between the nature of the loading amplitude change and the crack propagation rate.

INTRODUCTION

Nowadays, in order to describe the crack propagation one employs regressive models which are an approximation of the empirical data obtained under laboratory conditions as the loading level changed slowly (quasi-statically). However, under service conditions the time variation of the vibrational stresses level is of an irregular nature. Service fractures and, accordingly, the service cracks kinetics differ radically from the laboratory ones (Fig.1a,b). The attempts to use under these conditions various modifications of the regressive models obtained earlier result in the introduction of additional empirical coefficients, which further restricts the prognostic capabilities of such models.

It seems more efficient to develop a model which is based on the interpretation of the processes regulating the crack kinetics and which makes it possible to cover it both under regular and irregular loading on an equal basis. The problem lies in the fact that these processes occur on a micron scale in the inner layers of the material at the apex of a moving crack and are actually inaccessible

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for direct measurements. Nonetheless, they leave traces on the fracture surface and can be decoded on the basis of a macro- and microfractography analysis. To solve this inverse problem of the fatigue cracks kinetics, the Authors have carried out a complete set of investigations. Its first (experimental) part is presented in the given paper.

Basic experiment. Since it is difficult to restore the cracks kinetics directly on the basis of the service fractures because the latter are damaged and there is no detailed load information, a complete set of methods and procedures has been developed and employed which provides a testing effect in the form of random loading with variable parameters, as well as an electron microscope analysis of the fatigue fractures. The object of investigation were the blades of an aviation engine compressor manufactured of the VT3-1 titanium alloy of the uniaxial structure. The crack was not initiated on purpose, but developed naturally in the course of fatigue tests which were performed under harmonic resonance and random pararesonance oscillations of the first bending form of the 270 Hz frequency, i.e., a symmetrical loading cycle was provided. The value of the A envelope of the maximum nominal vibrational stresses (MNVS) was maintained constant for each blade under the harmonic loading, and under the random loading - the mean value $\bar{A}$ of the MNVS envelope and its variation coefficient $v_A = \sigma_A / \bar{A}$, where σ_A is the root-mean-square deviation of the MNVS envelope.

Under harmonic loading the macro- and microrelief of the fracture follows distinctly the load change which reflects the competition of two main trends: 1) increase of the local load on the material at the crack apex when the crack is propagating (due to the cross section reduction), and 2) decrease of the load due to the reduction of the blade oscillations amplitude caused by the diminishing of its proper frequency with the further crack growth and departure from the resonance condition. The first trend is prevalent at the start, and, afterwards, the second trend. This load change is accompanied by an increase and then a decrease of the oblique fracture portion, as well as by smooth quantitative and qualitative changes of the fracture microrelief. As the crack propagates from the destruction seat (on the trailing blade edge) along the blade chord, the striated microrelief (Fig.2a) with the δ increase of the striation pitch (from 0,1 μm to 1,5 μm) is gradually transferred into a mixed striated and dimpled relief (Fig.2b) and then into a dimpled relief (Fig.2c), after that the microrelief is changed in the reverse order. In this case the following behaviour is observed:

1) the maximum scatter of the striations pitch is observed in the mixed striated and dimpled area;

2) with the pitch increase the striations appearance changes qualitatively from the straight and regular striations in case of a small pitch (Fig.2a) to the curved and irregular ones with slippage traces in case of a large pitch (Fig.2d);

3) the maximum portion of the oblique fracture corresponds to the dimpled microrelief;

4) all intermediate states of the microrelief are implemented successively and continuously (without visible borders) during the transition from the striated relief to the dimpled one and back;

5) the qualitative change of the fracture microrelief (transition from striations to dimples) is not accompanied by a similar change of the macro-relief - the fracture remains sufficiently uniform and macro-brittle (without traces of the macro-plastic deformation);

6) damage to the straight fracture parts caused by the contact of the crack shores is of a local nature (the oblique fracture parts are virtually obliterated by the mutual antisymmetrical displacement of the crack shores); the maximum damage is observed in the areas near the destruction seat; the damage degree is increases with the growth of the loading level.

Random-loading fractures which coincide qualitatively with the service ones differ radically from the fractures obtained under harmonic loading (Fig.1; the fracture in Fig.1c has been obtained for $v_A = 0{,}4$; the corresponding MNVS oscillogram and the probability density of their envelope are given in Fig.3). The destruction seat is located in the place of the maximum normal stresses action, i.e. on the trough near the trailing edge. The fracture consists of three sections. The initial light-coloured section (marked with arrow 1 in Fig.1c) is covered with fatigue striations of a varying pitch (Fig.4a,b) which reflect the loading irregularity. The final dark-coloured section (marked with arrow 3 in Fig.1c) has a dimpled microrelief. The dimples are deep with thin partitions, which is typical of static fracture of plastic materials. However, unlike it, 1) there happen to be sections with small striations among the dimples (Fig.4c), and 2) there are no traces of the macro-plastic deformation, that is, the microplastic relief does not conform to the macro-brittle nature of the fracture.

The intermediate fracture section between the first and the last transition to the dimpled relief occupies 95 % of the fracture surface and consists of fatigue bands. The light bands possess a mixed microbrittle and striated relief, the dark ones have a dimpled relief. The look of the dimples differs from the one in the final fracture section. They are less developed with broad partitions, which is characteristic of the static destruction of the high-strength low-plastic materials. The striations also differ from the initial fracture section: they are less relief, and their pitch which is much more stable along the whole length of the band increases sharply towards its end. The striations pitch change in the light-coloured band marked by arrow 2 in Fig.1c is shown in Fig.4d. The rate of the striations pitch increase $\partial\delta/\partial l$ during the transition from the striated to the dimpled relief at the band output is by a factor of 10^2 greater than the analogous rate under harmonic loading. Transitions from dimples to striations (DS-transitions) and from striations to dimples (SD-transitions) differ in kind from the similar transitions under harmonic loading. Here there is no mixed relief area with an anomalous scatter of the striations pitch which blurs the border between striations and dimples, and here frequently occur discontinuities of the microrelief state - dimples are replaced by shallow striations. As a result, the distinctly outlined lines of the SD- and DS-transitions are produced which form the fatigue bands typical of service fractures. Each light band with striations and dark one with dimples passes from one free blade surface to the other (including the oblique fracture sections) transverse to the direction of the crack propagation. In this manner a sufficiently regular macro- and microrelief is formed on the intermediate fracture section which does not conform to the stochasticity of the loading process.

Damages to the straight fracture sections (caused by the mutual contact of the crack shores) under random loading are smaller than under harmonic loading, despite the much greater compressive overloads in the negative part of the cycle. Minimum damage is observed in the fatigue bands with a dimpled microrelief. There is no fracture damage on the final fracture section which is characterised by the maximum compressive overloads and the most plastic microrelief.

Allowing for the connection between the fracture microrelief and the crack propagation velocity V (with an increase of V the microbrittle relief is replaced by a striated one with a growing striations pitch, and then it changes over to a dimpled relief), established earlier in a number of papers, the patterns of the fractures microrelief change indicated in the present paper signify that the cracks kinetics under quasi-static and under fast random time variation of the K_e envelope of the stresses intensity coefficient are of a radically different kind. In the first case, V changes continuously in conformity with the K_e increase or decrease, i.e., the kinetics patterns are totally inverse. In the second case, for the qualitatively constant (v_A = const) fast fluctuations of the K_e envelope, whose mean level grows slowly with the crack development, the kinetics of the latter, both in the inner and in the near-surface layers of the material, changes in kind passing consecutively through three stages. The first and the third kinetics stages (corresponding to the initial fracture section covered with striations of a varying pitch, and to the final section of a dimpled microrelief) are similar to the corresponding stages under the quasi-static increase of K_e. The most extended intermediate section of the fracture which is not available under the quasi-static change of K_e and which is covered with fatigue bands, typical for service fractures, corresponds to the spasmodic (rupture) kinetics stage. At this stage the time variation of V is fundamentally different from the random variation of K_e and occurs in turn on two different scales: a slow change within the fatigue bands and a fast change near the fatigue lines. The dark sections with a dimpled microrelief are bands of the intensive propagation of cracks (BIPC), and the light-coloured sections with a striated and a microbrittle relief are bands of the cracks propagation arrest (BCPA). The DS-transitions correspond to a sharp slowing-down of the crack growth, and the SD-transitions correspond to acceleration, these transitions forming borders between the BIPC and BCPA.

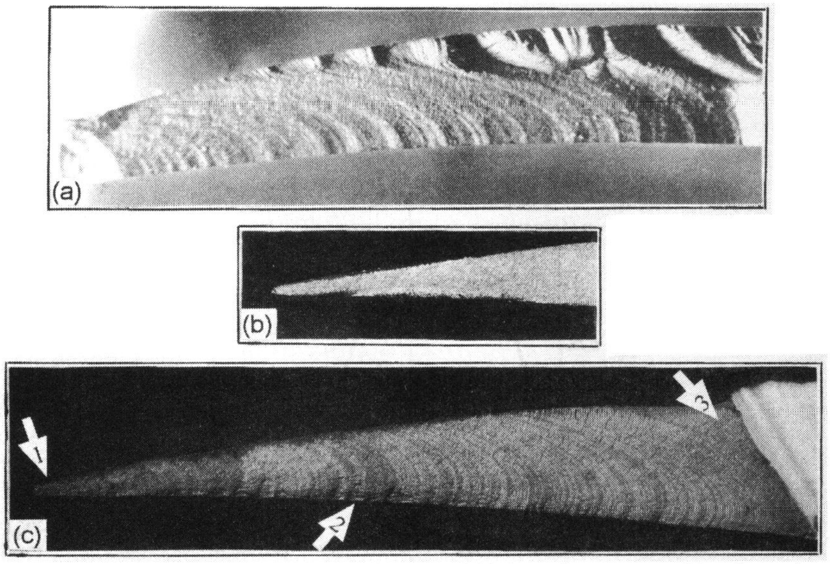

Fig. 1 A service (a) and laboratory fatigue fractures of blades under a constant (b) and a random (c) loading amplitudes.

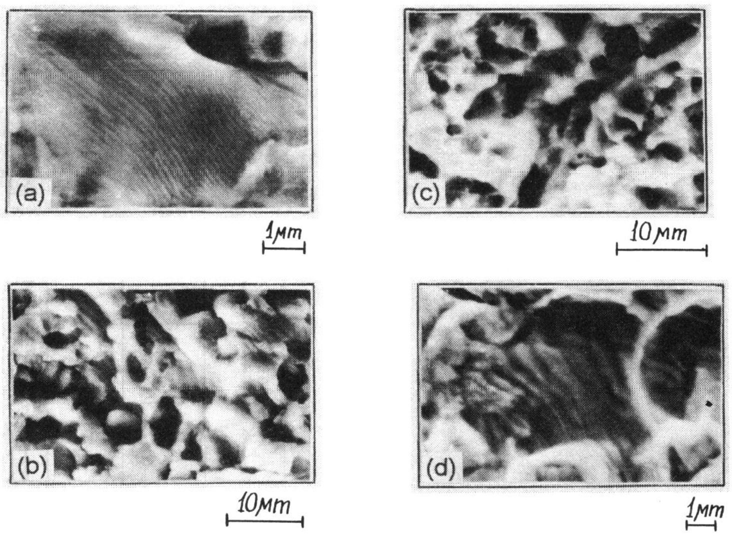

Fig. 2 Microfractograms corresponding to various fracture sections under harmonic loading.

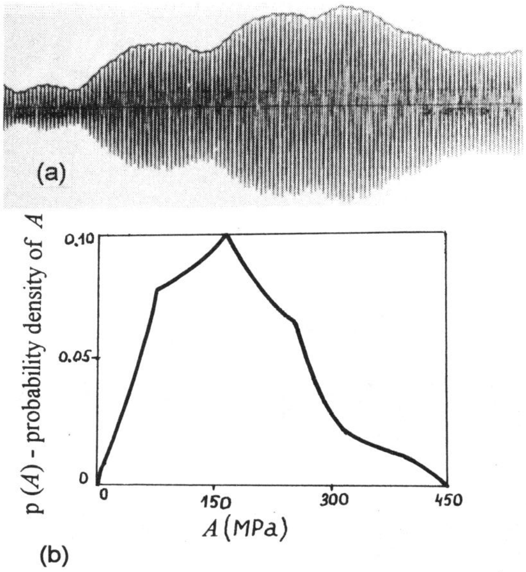

Fig. 3 The MNVS oscillogram and their envelope (a) and the probability density of the envelope (b).

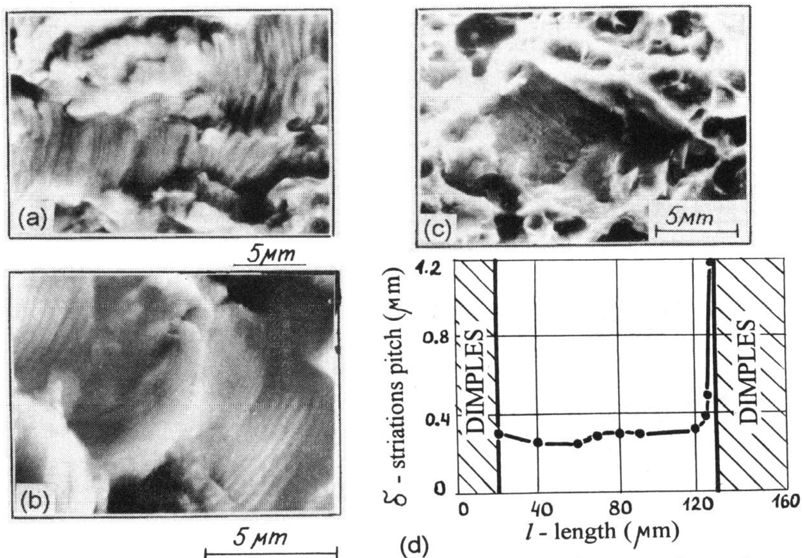

Fig. 4 Microfractograms corresponding to the initial (a,b) and final (c) fracture sections under random loading and change of the striations pitch in the fatigue band (d).