BASIC MECHANISMS OF FATIGUE CRACK KINETICS IN METALS

N. V Tumanov* and S. A. Cherkasova*

The authors put forward a new conception of the fatigue damage and fracture as processes • of fragmented (misoriented) medium development by action of extremely large localized plastic deformation and • of delamination along the critical kinetics (FCK) are described on the basis of this conception. The key parameters have been revealed, which influence FCK and characterize strain hardening of misoriented medium in front of the crack.

INTRODUCTION

As a result of experimental study of fatigue crack kinetics (FCK) performed over the last 35 years in coordinates (ΔK,V) (ΔK is range of stress intensity factor K, V is crack growth rate), basic FCK peculiarities for quasi-static ΔK variation have been established: three steps of crack growth, each being described by the relationship of type:

$$V = C\Delta K^{m} \qquad (1)$$

with their own values of parameters C and m determined from experimental data (Fig. 1). It has been ascertained by numerous fractographic tests that a specific natural microrelief of fracture prevails at each step: quasi-cleavage, striations, and dimples, respectively.

Notwithstanding considerable progress that has been made in FCK study due to eq.(1) application, a number of important practical tasks remain to be solved. The key problem is FCK for fast ΔK variation, typical under service conditions, when «anomalous» (i.e. not described by qu.(1)) crack behavior is realized. In this case, eq.(1) is modified using various additional coefficients and hypotheses *ad hoc*: the coefficients correct the argument or the function in formula (1),and the hypotheses substantiate this operation. This approach is obviously inefficient, since the field of these coefficients application is extremely limited, the hypotheses are problematical, and correction of eq.(1) is to be made after each K variation.

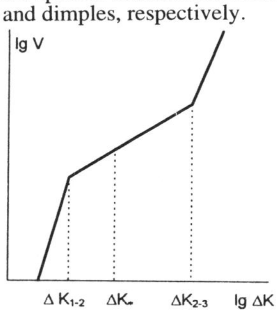

Fig.1. The ***V-ΔK*** diagram.

This situation is quite natural if one takes into account how inadequate the linear-elastic parameter ΔK is to processes governing crack kinetics and occurring before its front in the region of localized developed plastic deformation. However, if one consider ΔK as a value connected with the level of mechanical energy which entered the material at the crack front (CF) during cycling, then the experimental data (a three-step nature of the V-ΔK diagram and of the fracture microrelief, FCK irreversibility under fast ΔK variation) actually signify that this material is an active nonlinear medium which changes its properties with the increase of the input energy level. It is the object of the present paper to reveal the physical nature of the indicated changes, to establish their connection with the FCK mechanisms, and to create a foundation for developing basic phenomenological models which mike it possible to describe all stages of crack growth under constant and variable amplitude loading on an equal basis.

PHYSICAL MODEL

*Central Institute of Aviation Motors (CIAM), Moscow, Russia.

High degree of similarity of FCK characteristics, true of mono- and multiphase metals and alloys with various crystal lattice and production heredity, can be understood in the context of the dislocation structure universal evolution concept under large plastic deformation [1]. Fragmented (misoriented) structure (FS) is the last to develop in the evolution series of dislocation structures. It provides plastic distortion through rotation and shear of the adjacent crystal areas (fragments). With the ε strain growth, the mean size of $\bar{d}$ fragments is reduced, and the mean misorientation $\bar{\theta}$ between them is increased. At the final stage of the fragmentation development, super-fragments are formed which correspond to the rotation and shear of meso- and macroareas fragmented uniformly. Critical FS preceding fracture originates along the critical misorientation boundaries (CMB) where strain incompatibility-induced internal stresses exceed theoretical strength. As a result, microcracks and microvoids develop, whose growth causes complete fracture.

Realization of the above processes under fatiguing is conditioned by extreme locality of highly plastic areas concentrated in the boundaries and junctions of the suitably oriented grains as well as in the persistent slip bands (PSB) or at the CF. In consequence, these areas are subjected to the action of squeezing produced by the surrounding material, i.e. they constitute original Bridgman's chambers [2], in which material has a very large strain capacity (because squeezing, which hampers the microcracks and microvoids growth, increases the range from initial FS up to the critical one on the ε scale). In this case, the horizontal component of the distributed squeezing load, which counterbalances a similar component acting from the inner layers side, wedges the crack out (Fig.2) and prevents closure of microcracks [3], short cracks [4], and long cracks [5] even under symmetrical cycling (stress ratio R= -1). The plastic range expansion with ΔK growth causes increase of squeezing, which, in turn, elevates the material strain capacity at CF and enhances the artificial wedge effect securing the fracture micro relief against damage. In this fashion, conditions are created for forming still more developed FS at CF and, at the same time, for decoding its marks on the fracture surface. The latter is essential since analysis of the fracture surface relief and of the near-surface dislocation structure is of fundamental importance for FCK mechanisms reconstruction as processes of the critical misoriented medium development and fracture under cycling loading. Within the framework of this approach, we shall briefly study fatigue stages, paying main attention to stage II (dominant crack growth).

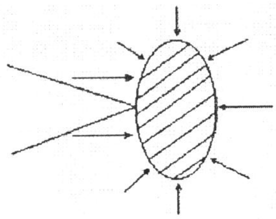

Fig. 2. Schematic drawing of wedging effect.

Fatigue stage I (until the dominant crack formation)

During stage I FS is localized near the free surface inside PSBs [3, 6] or at the grain boundaries [7]. Generally, the CMBs coincide with the maximum resolved shear stress directions and are located • between PSBs and matrix, between extrusion and intrusion [3,8]; • in the junctions of PSBs and grain boundaries [8.9]; •between grains [7, 9. 10. 11]. Dominant crack is formed as a results of microcracks growth and linking along the CMBs. After that formation and growth of surface micro-cracks cease, and further on fatigue processes are localized at the dominant crack tip [12. 13].

Fatigue stage II (dominant crack growth)

Stage II comprises 3 FCK steps corresponding to 3 sections of the V-ΔK diagram (Fig.1)

1 The first FCK step ($\Delta K_{th} < \Delta K < \Delta K_{1-2}$) At the fracture surface in the propagating dominant crack front vicinity, fatigue processes similar to those taking place on the free surface during fatigue stage I are repeated many times. Consequently, the crack kinetics is of intermittent nature [14]. Each crack length $\Delta\ell$ increment is characterized by •a lengthy period (during N_ℓ cycles) of CMBs forming at the fracture surface near the CF

and •fast delamination (during $N_C$cycles) along the CMBs (often as far as a next structural barrier [15]). As $N\ell >> N_c$, the average crack growth rate

$$V = \Delta\ell/(N\ell + N_c) \qquad (2)$$

is determined by the value of $N\ell$ and $V << V_c$, where $V_c = \Delta\ell/N_c$ is the crack jump rate (fracture surface formation rate). In this case at the fracture surface there remain PSBs which have not reached critical misorientation and microcracks which have not linked with the dominant crack (Fig.3), and the fracture surface microrelief is of quasi-cleavage nature, similar to fatigue stage I.

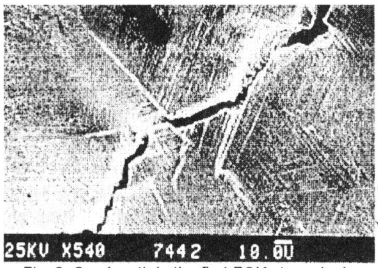

Fig. 3. Crack path in the first FCK step: single crystal Ni-alloy.

The above sequence of deformation and fracture processes (CMBs forming and delamination along them) near the free surface and fracture surface effective during fatigue stage I and also during the first step of stage II will be called the first FCK mechanism. Its realization at the dominant crack tip has the following features: • equal possibility of critical misorientation near both crack faces gives rise to the crack branching and to considerable deviation from the original direction (near the free surface); • increase of squeezing in the inner regions causes $N\ell$ growth and, consequently, V reduction as compared to stage I [13, 16]. Since with the ΔK growth the $N\ell$ period of quasi-brittle jumps preparation is reduced and their $\Delta\ell$ length is increased, V quickly grows according to eq.(2). Then the sharp reduction $\partial V/\partial\Delta K$ for $\Delta K = \Delta K_{1-2}$ completing the first FCK step signifies qualitative change of the FCK mechanisms.

2 <u>The second FCK step</u> $(\Delta K_{1-2} < \Delta K2 < \Delta K_{2-3})$. Instead of the near-surface fragmentation mechanism, a more power-consuming bulk fragmentation mechanism covering the whole area in the CF vicinity becomes determining. In this case, straight or slightly curved perfect boundaries of very high misorientation (around several dozens degrees), the so-called knife boundaries (KBs) [1], are formed in the highly gradient stress field in front of CF because of dislocations self-organization against the uniform FS background. These high-angled internal misorientation surfaces of deformation origin passing through the grains and phases boundaries and providing plastic rotation and shear of meso- and macroareas adjacent to CF are oriented parallel to the principal directions of the local stress-strain state in front of CF [1]: they are perpendicular to each other and parallel to the direction of the maximum principal deformation (Fig.4.). The key role is played by KB of type I lying along CF (Fig.5a). It appears in the tension

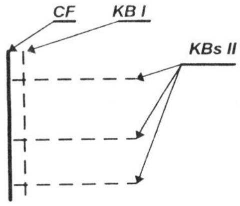

Fig. 4. The KBs in front of CF.

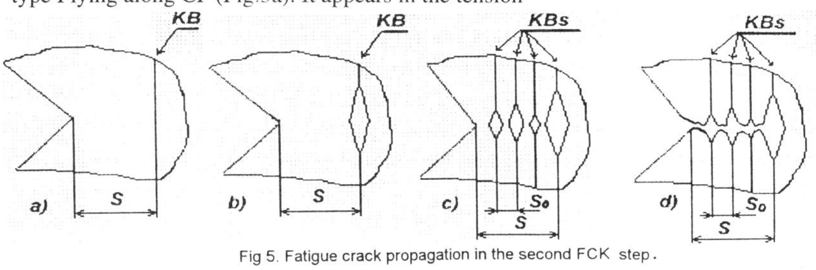

Fig 5. Fatigue crack propagation in the second FCK step.

half cycle at a distance S from CF in the place where the uniform FS achieves the ultimate state (under conditions involved) with the minimum average size of fragments $\bar{d}_{min}$ and maximum average misorientation $\bar{\theta}_{max}$ (it will be explained below why this happens at a distance from CF). Critical misorientation and delamination take place along KB. As a result, the slit-like cavity is formed at a distance S from CF (Fig 5b). Secondary KBs and delaminations parallel to the primary ones (Fig.5c) appear in the partition between the cavity and CF when this partition is deformed later. Since the partition squeezing prevents the delamination cracks from opening in the direction perpendicular to KB, the KN formation process is repeated every time in the partitions created anew until the distance between them becomes less than a certain critical value of S_O determined by parameters $\bar{d}_{min}$ and $\bar{\theta}_{max}$ of the uniform FS (in the first approximation one can adopt $S_o = \bar{d}_{min} / \bar{\theta}_{max}$). After that fragmentation inside the partitions becomes impossible, and they are deformed thinning into numerous internal necks (Fig.5c). Coalescence of cavities in the tension half cycle finishes the main partition fracture, and CF moves by S-value (Fig. 5d). In the next compression half cycle, highly gradient recovery (increase of $\bar{d}$ and reduction of $\bar{\theta}$) of the ultimate FS located at the new CF, i.e. at the former KB is accomplished. Therefore, the FS development front in the subsequent tension half cycle is positioned at a distance S from CF, which is increased with the recovery intensity growth (for example, when $|K_{min} - K_{max}|$ is increased in the compression half cycle [17], where K_{max} and K_{min} are maximum and minimum values of K). When uniform fragmentation on the FS development front attains its ultimate state, KB is formed there, and then the above sequence of deformation and fracture processes in repeated (it will be called the second FCK mechanism). As a result a periodic relief (fatigue striations), whose period (striations spacing) is equal to distance S from CF to basic KB, is formed on the fracture surface, and secondary striations with average spacing S_O are formed at the apex of main striations.

In addition to the fracture microrelief change, the second FCK mechanism is revealed through qualitative changes • of dislocation structure parameters near the fracture surface (sharp increase of misorientation [8] and lattice distortion, [18, 19], appearance of dislocation bands with a bandwidth equal to the striation spacing [20, 21]), and • of FCK macrocharacteristics (derivative discontinuity of $V(\Delta K)$ function, considerably more steady crack growth, the fracture surface reorientation in the direction perpendicular to the loading axis). All these changes are due to KBs appearance transversally to the crack path. This causes increase of mean FS misorientation at the fracture surface and formation of dislocation bands there, which are the marks of alternately occurring KBs. Delaminations along KBs preceding every crack increment dramatically increase the fracture process energy capacity as compared to the first FCK step when the dominant crack propagated along the CMBs. Length of the crack increment is reduced (because $\Delta\ell = S$), $N\ell$ is decreased (because FS near KB is close to critical) and N_C is increased due to considerable energy capacity of the partition fracture process). Starting with some value of $\Delta K^* > \Delta K_{1-2}$ (Fig. 1), the partition is ruptured in each cycle for $K=K_{max}$. Hence, in eq.(2) $(N\ell + N_c) = 1$ and V=S. Then it can be admitted that the intensity of energy emitted in the course of partition fracture is, to a first approximation, proportional to K^2_{max}, and intensity of consumed energy - to S/S_O (the smaller S_O, the bigger is the number of delaminations accompanying the partition fracture of S width). From the energy balance condition we obtain $S/S_o \sim K^2_{max}$ of $V \sim (d_{min}/\theta_{max})K^2_{max}$. It follows that in addition to K_{max}, FCK is determined by the ultimate value of parameter $\varphi = \bar{p}\bar{\theta}$ where $\bar{p} = \bar{d}^{-1}$ is the average density of fragments boundaries. The dislocations immobilization by the fragments boundaries grows with the increase of $\bar{\varphi}$, that is, $\bar{\varphi}$ characterizes strain hardening in the course of uniform fragmentation, and $\overline{\varphi}_{max} = \overline{p}_{max}\,\overline{\theta}_{max}$ characterizes the ultimate level of this hardening realized under conditions involved in front of CF. In this way, $V \sim K^2_{max}/\overline{\varphi}_{max}$ where $\overline{\varphi}_{max} \sim S_o^{-1}$. The bigger $\overline{\varphi}_{max}$, •the closer to CF the main KB is formed (and, correspondingly, the smaller V is), and •the more secondary KBs are formed and the more energy is emitted during delamination along each KB, expanding the internal surface of slit-like cavities.

3 The third FCK step ($\Delta K > \Delta K_{2-3}$) The decisive mechanism of the crack growth is the development of microvoids forming in the fragments junctions of the critical uniform FS in front of CF, which ends with the void coalescence and formation of a dimpled microrelief on the fracture surface. Thereby, energy accumulated in the uniform fragmentation process is emitted. As has been mentioned before, in the internal regions this energy is greater than near the free surface. As a consequence, CF is twisted, and narrow partitions remain between the CF edgings and the free surface. Since now uniform void medium is arranged in front of CF, the partitions fracture takes place in conformity with the continuum concepts, that is, in the plane of maximum shear stresses and with the shear lip formation [5].

Despite certain common features, the fracture mechanism at the third FCK step is radically different from the ductile total fracture. The void formation in front of CF strongly expands this area and, correspondingly, sharply increases the squeezing exerted by the surrounding material. As a result, • the crack wedging is enhanced, which preserves the fracture surface (at the third FCK step it has no traces of damage even for R= -1 [5], which, evidently, gave grounds for the single load rupture concept), and • behind the loosened-up void layer an extremely deeply developed uniform FS is formed with the value of $\overline{\varphi}_{max}$ exceeding its maximum value at the second FCK step. this overhardened layer, hidden inside the material, localizes fracture and prevents development of macroplasticity [5, 22]. (It is visualized when V is rapidly reduced in a certain range, which causes the crack to enter this layer and to decelerate abruptly. After passing the layer, the crack leaves on the fracture surface a crack arrest band (CAB) with striated microrelief (Fig. 6) [5, 23, 24]). The fracture mechanism described herein (development and coalescence of microvoids in the thin layer between CF and the overhardened uniformly fragmented medium) will be defined as the third FCK mechanism.

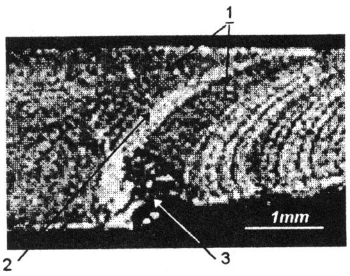

Fig 6. The CABs in the third FCK step: 1-dimples, 2-striations, 3-shear lip; f = 250 Hz, R = -1; Ti alloy VT3-1.

With ΔK increase, $\overline{\varphi}_{max}$ grows in the overhardened layer, which gives rise to augmentation of the density of critical junctions and, correspondingly, of microvoids. As a result, the fracture energy capacity decreases with the increase of the mechanical energy accumulated in front of CF. In this respect the third FCK mechanism (mechanism of fracture acceleration with ΔK growth) differs fundamentally from the second one (mechanism of fracture inhibition with ΔK growth), which brings about abrupt increase of $\partial V/\partial \Delta K$ when passing from the second FCK step to the third.

CONCLUDING REMARKS

1 As follows from the above, the FCK regularities are invariant to the crack length and to loading system and are caused by the common peculiarities of fragmented medium

development. Since the bulk fragmentation in front of CF starts in the boundaries and junctions of the suitably oriented grains and covers with the growth of deformation increasingly more areas, the transition to the second FCK step and to striated microrelief forming follow the same basic pattern.

2 The relationship of type $V \sim K^2_{max}/\overline{\varphi}_{max}$ provides a basis for FCK simulation under variable amplitude loading, when $\overline{\varphi}_{max}$ increases under tension overloading and decreases under compression overloading, which causes the corresponding change of V. The analogous relationship (with others indices) can be used for the first FCK step, because there are crack accelerations and arrests under overloading there too [25.26].

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