# A MODEL OF FATIGUE CRACK PROPAGATION BY STRIATION MECHANISM

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## ABSTRACT

A quantitative model of fatigue crack propagation by striation mechanism has been proposed. The model is based on the data of fracture surface stereofractographic analysis for aluminium alloy AMцC sheet specimens with a crack tested in axial cyclic tension. The model comprises the derivation of a quantitative relationship between the crack propagation rate and the stress intensity factor range and a three-dimensional scheme.

## KEYWORDS

Striation, stereofractography, fatigue crack, fracture surface.

## INTRODUCTION

A study of the laws of striation formation as a purely fatigue fracture mechanism atracts special attention of investigators since it gives a clue to understanding the processes of fatigue crack growth (FCG).

The model of striation formation by crack tip plastic blunting of Laird and Smith (1963, 1967) belongs to the most well-known models of FCG by striation mechanism. Similar concepts were also used by McMillan and Pelloux (1967) and Schijve (1967) in the creation of models which differ from the mentioned one in that the groove is formed at the end of a striation rather than at its beginning owing to the crack tip closure at unloading. The model of Tomkins and Biggs (1969) involves fracture by tearing along with plastic blunting: the whole striation together with the groove is formed within the load half-cycle. In the experimental model of Tomkins (1980) attention is also paid to the formation of traces arranged regularly in between the striations. Their appearance resembles normal small striations, though they differ from the latter by the discontinuity of the front, less rigorous regularity and the absence of correlation between their spacing and the FCG rate. Tomkins

(1980) as well as Laird (1967) relates the traces to the slip line relief on the fracture surface and, in particular, on the striation body as a result of intense plastic deformation. Some models assume the action of crystallographic shear mechanisms (Broek, 1974; Pelloux, 1969) with the striations forming by several sequential occurrences of shear in slip planes. Krasowsky and Stepanenko (1879) built a significant geometric model of the cycle-by-cycle FCG basing on the data of stereofractographic analysis of nickel fracture surfaces, in which special attention is paid to the role of a compression half-cycle where the material is prepared for subsequent fracture. However, this model, as well as most other ones, lacks a specific mathematical expression.

## MATERIALS AND METHOD OF INVESTIGATION

An aluminium - based alloy was chosen for investigations since it belongs to the class of materials which are widely used in engineering and in which fatigue striations are the predominant and sometimes the only mechanism of fracture in a specific range of the stress intensity factor (SIF) amplitude The author analysed fracture surfaces of 10 mm thick sheet specimens with a surface semi-elliptical crack made of the AMцC alloy of the Al-Mn system and tested in low-cycle fatigue by axial tension. Mechanical testing at a frequency of 30 cycles/min with the stress ratio in a cycle R=0 was carried out by Kaplinsky A.L. according to the method described by Strizhalo et al. (1984).

Stereofractographic analysis was made by the method described by Kramarenko (1985). Stereo pairs of fracture surface microrelief were obtained in a scanning electron microscop"Stereoscan S4-10", the microrelief stereometric model was constructed using a precision stereocomparator "Stecometer E". Figure 1 illustrates an example of selecting the reference points for matching the microrelief stereometric models. Fracture surfaces of two corresponding areas of the fractured specimen are shown here with hill "1" in Fig.1a to depression "1" in Fig.1b matching.

## RESULTS AND DISCUSSION

The striation morphology changed depending on the SIF amplitude. Shallow, not quite regular striations were observed at low SIF amplitude values. With an increase in the latter, the striations assumed regular and clear out appearance. A further increase in the SIF led to the formation of blocks of striations. Here fatique crack growth macrorates are related to the spacing of blocks rather than to that of single striations. This observation was also made for materials of other classes (Blochwitz, 1991; Kramarenko, 1987; Krasowsky and Kramarenko, 1989).

As an example, Fig.2 shows the results of a stereometric matching of two corresponding areas of fracture surfaces exhibiting striations. The data presented here and in what follows refer to the high-rate FCG region where the geometric parameters of striations varied dynamically that allows the laws of their shape evolution to be illustrated clearly enough. One of the sections of the specimen two halves is shown in the upper part of Fig.2 and in the lower part their profiles are brought together artificially. In their section the striations are shaped as a scalene triangle. The signs of fracture by shear are prevalent on the short side, and by tearing on the long side of the striation.

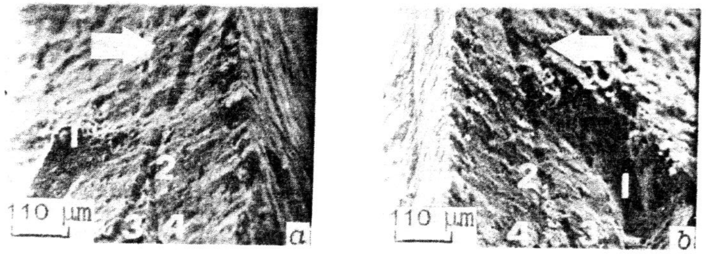

Fig.1 Matching areas of the fractured AMцC alloy sheet specimen tested in low-cycle fatigue. Arrows indicate the main FCG direction. Figures mark corresponding to each other elements on the fracture surfaces of the specimen halves. In Fig.1a the specimen side surface is seen on the right, and in Fig.1b it is on the left.

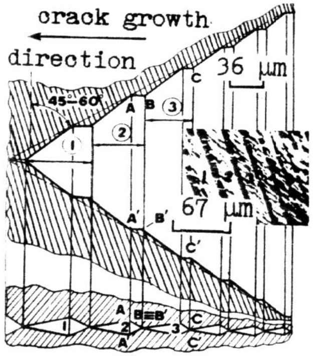

Fig.2 The profile of the stereometric mating of the corresponding areas of fracture surfaces exhibiting striations for a sheet specimen of the AMцC alloy. In the upper part of the graph the specimen halves are positioned in such a way as if the loading had been terminated after one of the cycles and the specimen had been left in the grips of the testing machine. The grips axis is parallel to the Figure vertical. Numbers 1, 2, 3 denote the corresponding striations.

The profile of the fracture surfaces mating in the lower part of Fig.2 and the Figures representing the models of McMillan and Pelloux (1967), Schijve (1967) are actually identical, but this is only the coincidence of the experimental data. But as far as their interpretation is concerned, the fractographic analysis of the striation formation features, when the crack having grown-through the sheet thickness reaches the specimen edge opposite the concentrator, suggests a different version. In the idea of the authors mentioned above, the formation of a short part of striation is associated with pressing of the material at the moment of crack faces closure in the part of a cycle corresponding to unloading, i.e. at the final stage of a cycle rather than at the initial one.

Figures 3a and 3b show the central area of the fracture surface. The last striation, before the crack reaches the side surface, (point A) is formed when the semi-elliptical crack tip almost touches the side surface. The distance between them is less than 12 µm. Yet its shape differs but little from the preceding ones. The photograph in Fig.3c is taken somewhat lower than the fracture centre. Here this striation is the last but one on the right, and the striation which was formed after the crack became a through one is the last on the right. As is seen, the shape of the latter is not distorted either. If the idea of the authors mentioned were right, the fracture relief would have a slightly different appearance. The slope of the striation short side formed within the last load cycle would differ from that of other striations. This difference should necessarily occur also in the case when after the completion of the last load cycle there is some part of the material left ahead of the crack tip whose thickness is less than the width of the long side of the next striation should have been. However, in practice the situation is different (Fig.3). In Fig.3c between figures 1 and 2 a short side of a "truncated" striation is shown which was formed at the moment when the crack reached the specimen side surface. Its slope differs but little from the slope of the preceding striation short side and from that of the same striation but somewhat lower along its front.

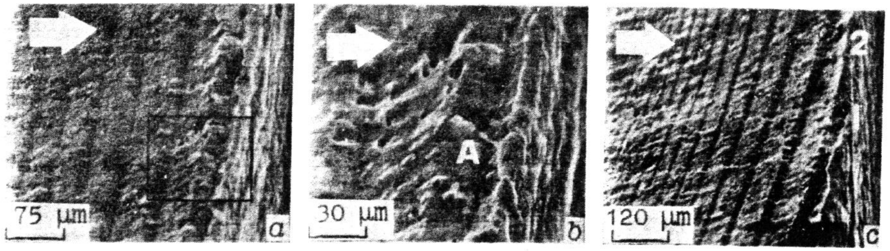

Fig.3 Striations in the vicinity of the side surface opposite to the concentrator (here it is on the right) for a sheet AMцC specimen. The FCG direction in the photographs is from left to right. *b* is the site enframed in Fig.3a.

Taking into account the above considerations, as well as the results of analysing the relation between the tear and shear signs on the striation short and long sides, the FCG process by striation mechanism can be visualized as is shown schematically in Fig.4.

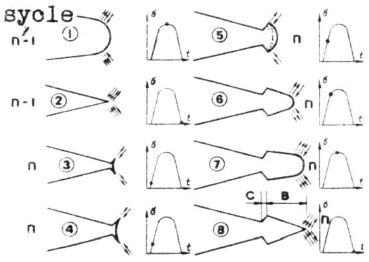

Fig.4 Schematic of the fracture process development in a load cycle when fatigue crack grows by striation mechanism.

With the completion of the preceding load cycle a plastic zone is formed in the vicinity of the crack tip pointed after the unloading half-cycle (position 2). At the beginning of the next load cycle shear fracture mechanisms predominate (pos.3-4). Here the plastic zone configuration can influence the fracture initiation trajectory. Subsequent increase in the load is accompanied by a gradual transition to the phase of plastic blunting (pos.5-7) and the shear mechanisms are replaced by tearing ones. After the unloading half-cycle the crack tip sharpens again (pos.8).

Stereometric measurements of striations profiles revealed that in the range studied the height as well as the width of the "tearing" and "shearing" parts of striations increased linearly with the striation spacing, while the spacing ratio of the subsequent and preceding striations and the width ratio of the "tearing" (**T**) and "shearing" (**Sh**) parts of a striation remained constant within the measurements scatter (Fig.5).The above observation was used in the derivation of a relationship for the evaluation of the kinetics of a crack propagating by the striation mechanism. Let $f_{i,k}$ be the specific area of the fracture surface formed by the action of the $i$-mechanism within the $k$-th loading cycle. Then the fracture surface increment per load cycle, which is controlled by the same mechanism, is $\Delta F_{i,k} = f_{i,k}\cdot\Delta S_k$ where $\Delta S_k$ is the total increment in the fracture surface area per one, $k$-th, load cycle. Taking the sum of the contributions of all the mechanisms into the fracture surface formation within one load cycle and relating this value to the specimen thickness h, we get an expression for the crack rate

$$\frac{dl}{dN} = \frac{1}{h}\sum_{i=1}^{p}\Delta F_{i,k} = \frac{1}{h}\sum_{i=1}^{p} f_{i,k}\cdot\Delta S_k , \qquad (1)$$

where $p$ is the number of mechanisms involved in the fracture process in the $k$-th load cycle. This summation is undoubtedly an extremely complicated problem, but in our case, when only striation mechanism is considered, it is appreciably simplified. Based on the above data, the formation of a striation can be divided into two more simple processes: shear and tearing.

In this case, the specific fracture surface area occupied by striations $f^{str}_{i,k}$ can be considered as consisting of the sum of specific areas formed by shearing $f^{sh}_{i,k}$ and tearing $f^{tear}_{i,k}$:

$$f^{str}_{i,k} = f^{tear}_{i,k} + f^{sh}_{i,k} . \qquad (2)$$

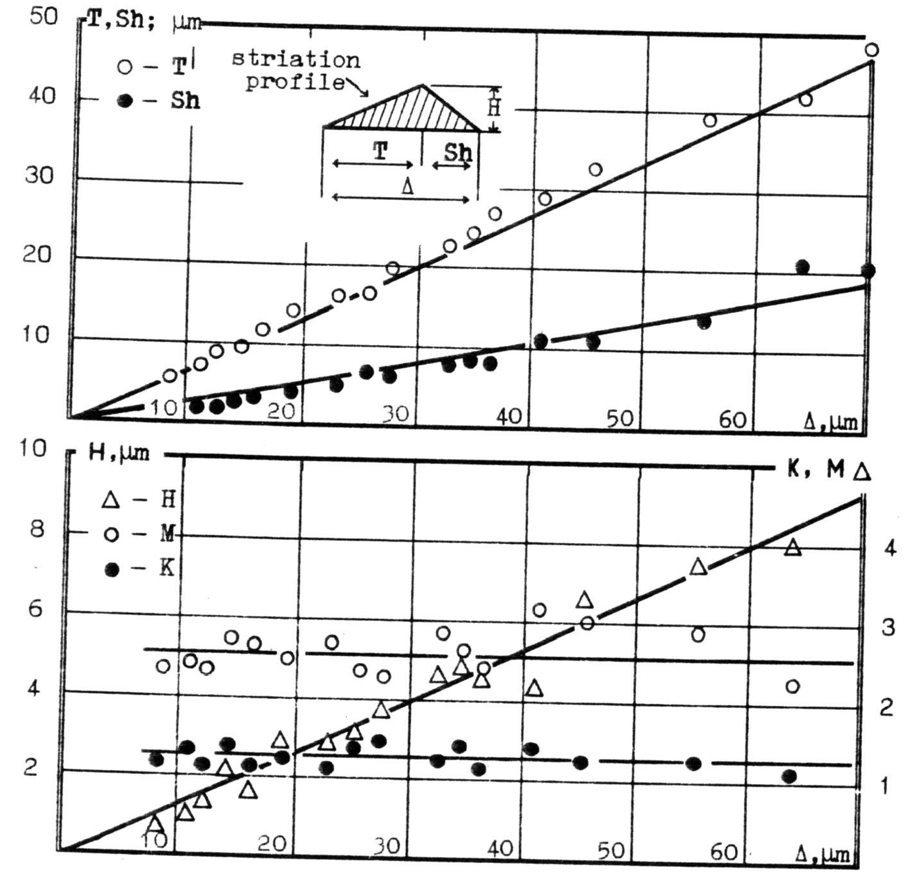

Fig.5 Variation of the magnitude of sfriation geometric parameters with an increase in striation spacing (Δ): M = T/Sh, $K = \Delta_n/\Delta_{n-1}$, H – striation hight.

In this context, the value of striation spacing is the crack velocity. For this reason we represent the expression for its determination as consisting also of two terms. The structure of those terms is selected to be similar to the known Paris's expression

$$dl/dN = C_1\Delta K^{n_1} + C_2\Delta K^{n_2} , \qquad (3)$$

where $C_1$, $C_2$, $n_1$, $n_2$ are the constants; the first one corresponds to tearing, the second to shearing. According to the data of stereometric measurements (Fig.5), the ratio of those terms is constant value (M):

$$\frac{C_1\Delta K^{n_1}}{C_2\Delta K^{n_2}} = \frac{T}{Sh} = M , \qquad (4)$$

This implies the necessity of equality $n_1 = n_2 = n$ and $M = C_1/C_2$. Taking the n value as 2 and following the model of Laird (1967), we get:

$$dl/dN = C_1(1/M + 1)\cdot\Delta K^2 . \qquad (5)$$

At plastic blunting the magnitude of crack incremennt is approximately equal to its half-opening $\delta_c/2$. Hence $C_1\Delta K^2 \approx \delta/2$. For small values of $\sigma_\infty/\sigma_{y,c}$:

$$\delta_c = \alpha\frac{\Delta K^2}{2\sigma_{y,c}\cdot E} , \alpha \approx 1 ; \qquad (6)$$

where $\sigma_{y,c}$ is the cyclic yield stress, E is the Young modulus, α is the proportionality coefficient. Then

$$C_1 \approx \frac{\alpha}{4\sigma_{y,c}\cdot E} . \qquad (7)$$

The expression for the estimation of the kinetics of the fatigue crack growth by striation mechanism takes the form:

$$\frac{dl}{dN} \approx \frac{\alpha(1/M + 1)}{4\sigma_{y,c}\cdot E}\Delta K^2 . \qquad (8)$$

The model proposed, as well as any other one, is not free from certain conditionality that is associated with the assumptions resorted to when the process is being schematized. But in such cases one should realize the range of its applicability. The use of the model will be most efficient in the following cases: firstly, when the striation mechanism is the dominating one in the fatigue crack growth, which is often encountered in practice; secondly, when there is a necessity of a retrospective local evaluation of the kinetic - force situation at the crack tip when there are striations on the fracture surfaces.

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