

Recent developments in textural fractography of fatigue fractures

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ABSTRACT. *Textural fractography consists in relating fatigue crack growth rate (CGR) with the image texture in SEM fractographs. Two improvements were finalized in 2010-2011: 1. Textural analysis based on 3D crack surface representation was proposed and tested on CT specimens made from aluminum alloy. Crack surfaces were documented by SEM images, and four methods of 3D reconstruction. Results based on 3D reconstruction from equidistantly focused optical images almost reached quality of standard analysis from SEM images. 2. A physical explanation of reference features was proposed. A common subset of image textures in fractographs of fatigue fractures, reference texture, is unambiguously linked with the reference crack growth rate. Reference features were found to be closely related to a parameter derived from successive sizes of cyclic plastic zone. In application on CT specimens from aluminum alloy loaded by 3 loading regimes, a maximal discrepancy of reference factors of about 20% was reached.*

INTRODUCTION

Textural fractography [1,2] deals with SEM fractographs created in the mesoscopic magnification range (100 - 500x). It was repeatedly discredited for its source of information - image texture in SEM fractographs. In the contrary to traditional fractographic features, e.g. striations and beach lines, features of the image texture of a fractograph may be affected by selected parameters of the projection. Therefore, it is recommended that images for training of the model and for application are done by the same operator at the same apparatus. The requirement of an objective information source led us to design and verify a method of relating of the fatigue crack growth rate with 3D representation of crack surface. The quality of obtained model was compared with the results based on images from a scanning electron microscope (SEM).

The *Reference concept* [1,2] overcomes the problem that the conventional crack growth rate $v = da/dN$ cannot be uniquely related to the morphology of crack surfaces

which were caused by various variable amplitude loadings. Application of the reference concept is limited to loadings satisfying the condition of "stationarity over short distance". It means that all significant events, especially overloads, occur sufficiently regularly and frequently. A proposal of physical explanation of reference features is described in the second part of this paper.

TEXTURAL FRACTOGRAPHY BASED ON 3D RECONSTRUCTIONS OF THE MORPHOLOGY OF FRACTURE SURFACE [3]

An image and a 3D reconstruction of a crack morphology present formally the same type of $R^2 \rightarrow R$ transformation. Instead of image brightness, the local height of fracture surface may be used. Therefore, methods of textural image analysis may be applied also on 3D reconstructions. Relations in the data matrix, e.g. similarity, regularity and ordering are the source of information, which is expressed by means of numerical features.

Experiment was accomplished on six CT specimens made from aluminum alloy, loaded in pairs by a constant cycle, a sequence of constant cycles with regular overload, and a block of cycles with random characteristics.

3D reconstructions were acquired by four methods: as an output of confocal microscope Olympus Lext, as a calculation by MEX software from stereo-pairs made by SEM, as a calculation by DFF software from a series of equidistantly focused images made by metallographic microscope, and as an output of interferometrical Zygo microscope. The image documentation of crack surfaces was realized by SEM. Reconstructed or imaged areas are situated along central axis of crack surface, their spacing and format size being in tenths of millimeters. 3D reconstructions were pre-processed with the aim to remove declination and large-scale waving of crack surface. Images were normalized.

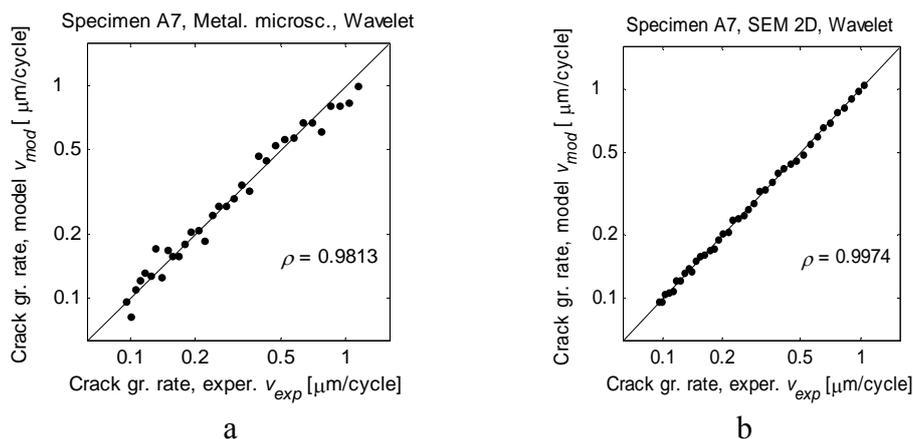


Fig. 1: Examples of results. Comparison of input (known) and output (estimated by model) crack growth rates. Constant cycle loading, analysis based a) on 3D reconstructions from images made by a metallographic microscope, b) on SEM images. Markers represent single 3D reconstructions or images of the fracture surface.

Each reconstruction or image was assigned the mean local macroscopic crack growth rate v estimated from experimental records of crack growth, and a set of features f_u , $u = 1, 2, \dots$. Spectral or wavelet features lead to the best results. The relation between features and crack growth rate was expressed by a multilinear regression equation:

$$\log v = c_0 + \sum_u c_u f_u . \quad (1)$$

Parameters c_u were estimated by the least squares method. The set of features composing the final model was optimized by a special stepwise procedure.

The quality of results was evaluated by indicators of conformity of real crack growth rates and their model estimates. The best fit was obtained on the basis of images of crack surfaces made by SEM. The quality of obtained models was almost reached by using 3D reconstructions from snaps made by metallographic microscope. Examples of results are shown in Fig. 1.

A PHYSICAL EXPLANATION OF REFERENCE FEATURES [4]

The *reference texture* is a specific textural component in fractographs. In contrast to traditional fractographic features (striations, beach lines, etc.) it is common to fractures under various loading regimes.

The reference texture is unambiguously related with the *reference crack growth rate* v_{ref} . In case of constant cycle loading, v_{ref} is equal to the conventional crack growth rate: $v_{ref} = v$. For variable cycle loadings with dominating effects of overload, $v_{ref} > v$. Examples of reference textures corresponding with the same v_{ref} are shown in Fig. 5.

The simplest way how the reference crack growth rate may be expressed is a product

$$v_{ref} = v \cdot B, \quad (2)$$

where the *reference factor* B is a characteristic of the given type of loading.

Let f_u , $u = 1, 2, \dots$ denote image features - numerical textural characteristics of images of crack surfaces. The relation between the reference crack growth rate v_{ref} and image features f_u may be expressed most simply via a multilinear model

$$\log v_{ref} = c_0 + \sum_u c_u f_u . \quad (3)$$

Let the index i denote the test specimen, the index j the image of the fracture surface, and the index k the applied loading regime. Each image is assigned a mean local macroscopic crack growth rate v estimated from experimental records of crack growth. A system of equations follows from eq. (2) and (3):

$$\log v_{ij} = c_0 + \sum_u c_u f_{uij} - \log B_k . \quad (4)$$

Parameters c_u (common to all images) and reference parameters B_k (common to images of specimens loaded by the same loading regime) are estimated by the least squares method. The set of image features composing the final model defines the reference texture.

Under a constant cycle loading, crack surface morphology is strictly related to the

crack growth rate (CGR). Simultaneously, CGR follows the generalized Paris - Erdogan crack growth equation, $v = A\Delta K_{ef}^\alpha$. It follows that also the morphology of crack surface is governed by ΔK_{ef} . Due to the equality $v_{ref} = v$ and the relationship between v_{ref} and the reference texture, the reference texture and the reference crack rate should also be controlled by ΔK_{ef} . Finally, also the size of cyclic plastic zone is a function of ΔK_{ef} :

$$w^* = \frac{1}{S\pi} \left(\frac{\Delta K_{ef}}{2R_p} \right)^2, \quad S = \text{const.} \quad (5)$$

It may be deduced that reference features are closely related to the cyclic plasticity.

In case of various variable cycle loadings, the same reference texture corresponds to different conventional crack growth rates, and, consequently, also to different mean values of ΔK_{ef} and to different mean sizes of the cyclic plastic zone. A seemingly contradiction to the case of constant cycle loading may be overcome by assuming that not all but only *major* cycles dominate in the process of creating the morphological structure of fracture surface, in particular the reference texture.

The algorithm of crack growth models of Wheeler and Willenborg was found to fit well experimental results. As illustrated in Fig. 2, a new *major plastic zone* arises when the front of the theoretical cyclic plastic zone in a given cycle exceeds the front of the foregoing major plastic zone:

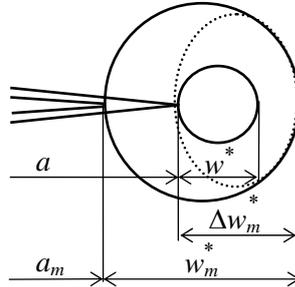


Fig. 2: The major and residual cyclic plastic zone

$$a + w^* \geq a_m + w_m^*, \quad (6)$$

where a is the crack length in the given cycle, a_m is the crack length at the origin of the previous major plastic zone, and w_m^* is its size. In this instance, new *major* parameters are set as $w_m^* = w^*$ and $a_m = a$.

We suppose that the reference texture and crack rate are controlled by the *residual major cyclic plastic zone* (Fig. 2, dotted line) whose size is

$$\Delta w_m^* = a_m + w_m^* - a. \quad (7)$$

The magnitude Δw_m^* is changing cycle-by-cycle, while the integral characteristics of the morphology of the fracture surface are changing more or less continuously. It means

that not the particular values of Δw_m^* but their resultant in certain surroundings must be considered. Let us represent it by the local mean size $\overline{\Delta w_m^*}$ which may be computed as a moving average of the sequence of values $\Delta w_m^*(j)$ from individual cycles.

Let the symbols $v(\overline{\Delta w_m^*})$ and $v_{ref}(\overline{\Delta w_m^*})$ denote crack growth rate and reference crack growth rate related to the given value of $\overline{\Delta w_m^*}$. The assumption that $\overline{\Delta w_m^*}$, i.e. *the mean local size of the residual major cyclic plastic zone*, controls the reference texture and crack rate, implies following expectations:

a) For a given variable cycle loading, the ratio

$$B'_{variable\ cycle}(\overline{\Delta w_m^*}) = \frac{v_{constant\ cycle}(\overline{\Delta w_m^*})}{v_{variable\ cycle}(\overline{\Delta w_m^*})} \quad (8)$$

should be approximately constant (independent of $\overline{\Delta w_m^*}$) and similar to the corresponding value of the parameter B , estimated within the fractographic reference solution (eq. (2), (3)).

b) The dependence $v_{ref}(\overline{\Delta w_m^*})$ should be independent of the type of loading.

Application

CT specimens (Fig. 3a) from aluminum alloy 2024 were loaded at 20°C in air by various loading regimes. Crack growth was regularly measured and recorded.

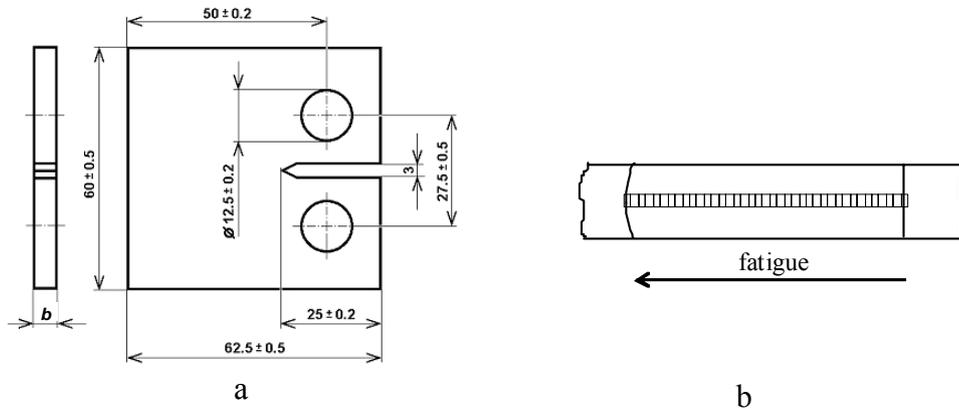


Fig. 3: a) Specimen for fatigue tests. $b \in \langle 7.45, 8.1 \rangle$ mm. b) Layout of SEM images aligned along the middle axis of the fracture surface.

For the present study, nine specimens were selected, loaded in groups of three by a constant cycle, regime 199+1 (constant cycle with a periodical overload after each 199 cycles), and a block of 1000 cycles with random characteristics.

Fracture surfaces were recorded using a scanning electron microscope (SEM) at a magnification of 200 x providing a field of view of 0.6 x 0.45 mm. Images were located along the middle axis of the fracture surface (Fig. 3b) and spaced in 0.4 mm increments.

The crack growth direction is aligned from bottom to top. More than 40 images were taken

from each specimen and the entire data set consisted of 396 images.

Wavelet image features were used. The relation between feature vectors and crack growth rate was sought by solving eq. (4). The final model was optimized by a special stepwise procedure to contain 16 most significant features. Resulting estimates of reference parameters B are presented in Table 1. The quality of the model is documented in Fig. 4. Examples of reference textures are shown in Fig. 5.

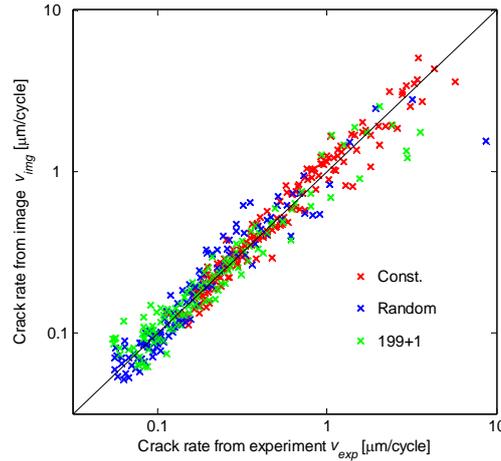


Fig. 4: Comparison of input (known) and output (estimated from images) crack growth rates. Markers represent single images of the fracture surface.

In the next step, cycle-by-cycle crack growth predictions were computed. The generalized Paris and Erdogan equation was used for crack growth under a constant cycle, and Wheeler's model for variable cycle loading. The variability of crack growth rates was respected by means of a multiplicative parameter β for each individual specimen. The value of ΔK_{ef} in each loading cycle was computed from model crack increment Δa according to the equation

$$\Delta K_{ef}(j) = \left(\frac{\Delta a(j)}{\beta A} \right)^{1/\alpha} \quad (9)$$

The sizes of residual major cyclic plastic zones Δw_m^* and their moving averages $\overline{\Delta w_m^*}$ were computed from equations (5)-(7). Dependences between $\overline{\Delta w_m^*}$ and the conventional crack growth rate v are shown in Fig. 6a. The data characterizing each test body follow a linear trend, and hence they may be represented by linear regression. On a logarithmic scale, the ratios B' (eq. (8)) are represented by distances between graphs for constant and variable cycle loadings. These distances are almost constant, exact values for the middle of the range are presented in Tab. 1. For the loading regime 199+1 the ratio B' is almost equal to the reference parameter B . In the case of random loading, a discrepancy of about 20% has been obtained. Up to this degree, expectation a) was verified.

Dependences between the magnitude of Δw_m^* and the reference crack growth rate v_{ref} are shown in Fig. 6b. Also the expectation b) may be said to be approximately valid.

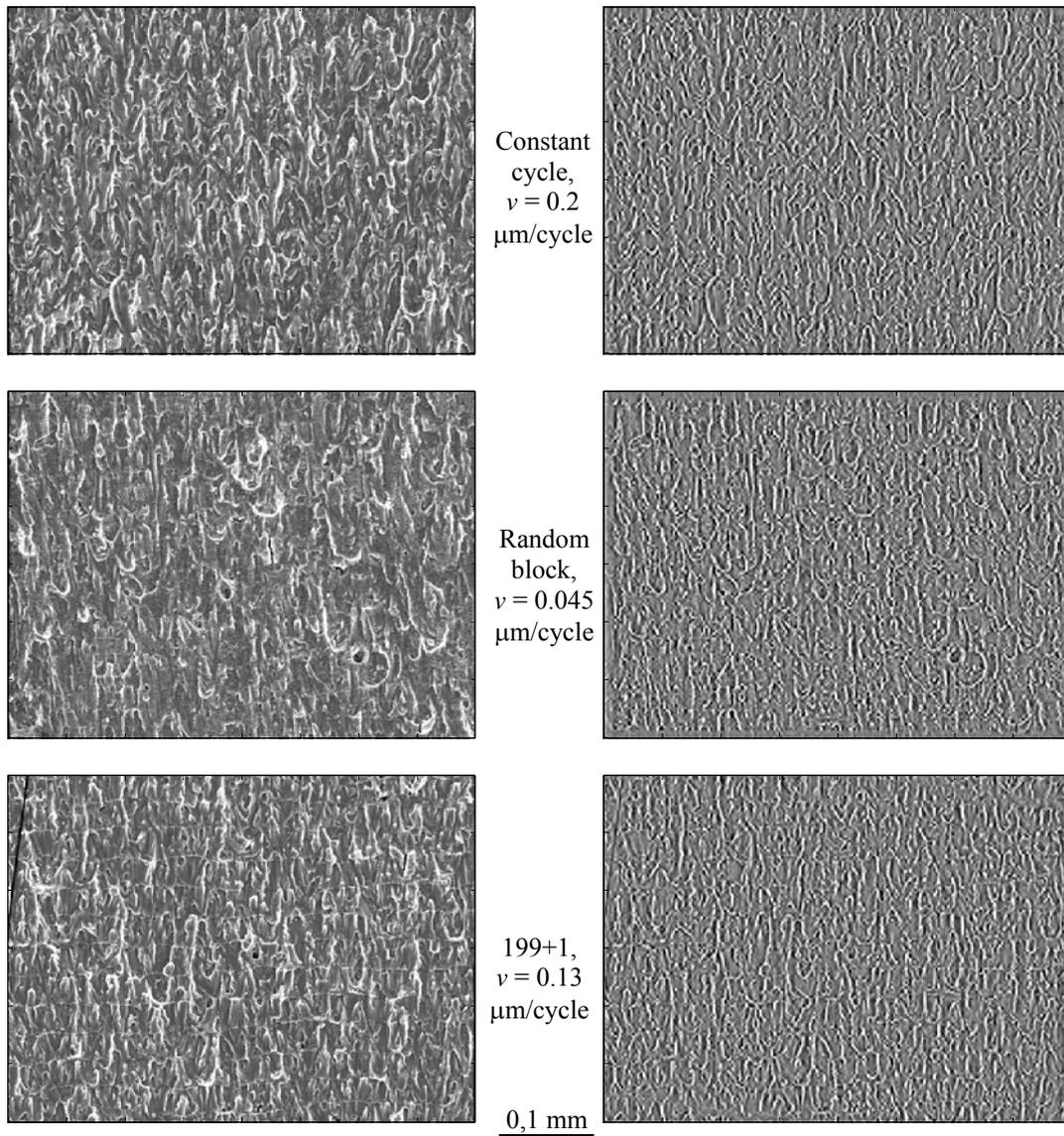


Fig. 5: Normalized SEM images showing the crack surfaces and reference textures for a reference crack growth rate $v_{ref} = 0.2 \mu\text{m}/\text{cycle}$. Original images assigned various crack rates are evidently different. Reference textures are similar - visually as well as analytically in the sense of a random field.

Tab. 1: Comparison of estimates of the reference parameters B and B' .

Loading	B	B'
Random	4.65	5.84
199+1	1.61	1.61

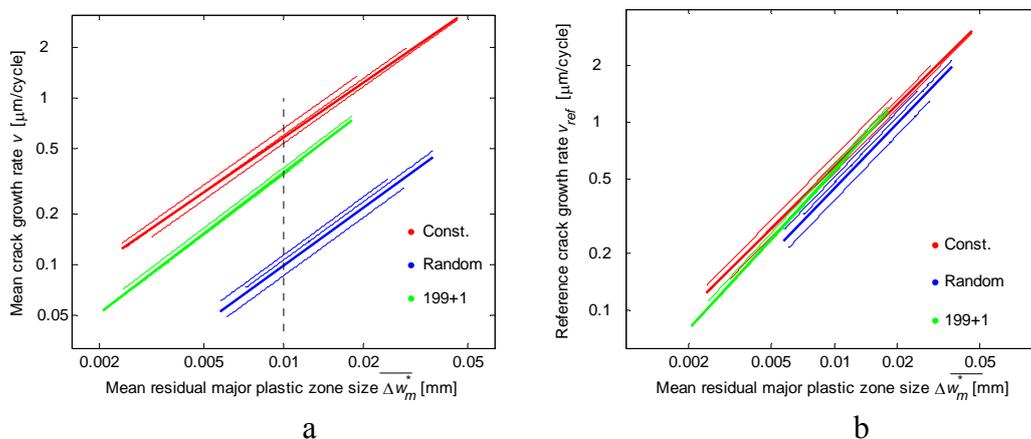


Fig. 6: Plot of the dependence between the local mean size of the residual major cyclic plastic zone Δw_m^* and a) mean conventional crack growth rate ν , b) reference crack growth rate ν_{ref} . Thick lines represent mean dependences for each loading.

CONCLUSIONS

Utilizing 3D representation of a fracture surface improves possibilities of the textural fractography. However, this method is not fully objective as we expected, because various methods of 3D reconstruction provide quite different results. Simultaneously, the price for this alternative to SEM images is a substantial increase of laboriousness.

Results obtained allow to argue that reference features are governed by cyclic plasticity corresponding to the major values of the effective SIF range ΔK_{ef} . This fact opens a way for investigation of the relation between physical parameters of crack growth process and the mesoscopical dimensional component of the morphology of fracture surface.

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