PHYSICAL INTERPRETATION OF THE REFERENCE FEATURES IN TEXTURAL FRACTOGRAPHY OF FATIGUE FRACTURES

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Abstract
Reference features of a fatigue fracture surface are the reference texture and reference crack growth rate which are unambiguously mutually related. The reference texture is a subset of the image texture in SEM fractographs. It is expected to be common to all fractures caused by loadings in which significant events occur sufficiently regularly and frequently. The ratio of the reference and the conventional crack growth rate called reference factor is a characteristic of a particular loading. Its value may be related to the sequence of successive sizes of the cyclic plastic zone, while the mechanism of the effect of overloads follows the models of Wheeler and Willenborg. Application to a set of nine test specimens from aluminium alloy loaded by three different loading regimes is shown.

Keywords: fatigue, crack growth rate, textural fractography, reference concept, plastic zone

1 Introduction

1.1 Morphology of fracture surface in mezoscopical dimensional range

The morphology of a crack surface reflects the interaction of the material, including its microstructure, and the process of crack growth. The coincidences of the morphological structure of crack surface and material microstructure were proved for example in [1,2]. The topic of this paper is an investigation of the relation between morphology of a fatigue crack surface and parameters derived from fracture mechanics.

Typical features of fatigue fractures were discovered a long time ago. In the field of microfractography, striations were found, related to the mechanism of crack growth [3], and widely used for quantitative analyses [4-7]. In the dimensional range of macrofractography, beach lines were joined with significant changes in parameters of loading, especially overloads. In cases when they could be related to a known time, the reconstitution of the history of crack growth was possible [8-12]. In contrast to this, the mezoscopical range between micro- and macrofractography holds its secrets up to now.

The mezoscopical fractographic range is characterized by SEM magnifications from about 100 to 500x. These magnifications were rarely used in quantitative fractography, because images of fracture surfaces taken under them contain a complicated random structure without any distinct borders. Therefore, no objects can be simply extracted to be counted and measured.

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Since 1989, textural fractography is developed to utilize the information contained in fracture morphology in the mezoscopical dimensional scale. Images of fracture surface are understood as random fields - image textures, and analysed by means of the image textural analysis. Global characteristics - image features - are estimated for the whole image of fracture surfaces.

1.2 Expected relation to cyclic plasticity

The main mechanism of fatigue crack growth is plastic deformation. In microvolume, the primary process is reflected - creation of plastic striations by single crack increments. Also beach lines visible by macro-observation are traces of plastic deformation. Therefore, it may be expected the same also in the mezoscopical range: the morphological structure of fracture surface should be related first of all to characteristics of plastic deformation. Within this dimensional range, the relevant characteristic of plastic processes is the size of plastic zone at the crack tip.

However, there are two plastic zones accompanying fatigue crack growth: the static and the plastic one. Static plastic zone, governed by K_{max}, is responsible for a shift of stress/strain loop at the crack tip towards a position symmetrical around zero, as well as for the effects of retardation or acceleration of crack growth after overloads. Under a constant cycle loading, it develops slowly and quasi continuously. Under a variable cycle loading, it significantly changes only in overload cycles.

On the contrary, the cyclic plastic zone, governed by ΔK_{ef}, "breathes" with single loading cycles and is closely related to individual crack increments. So, just the cyclic plastic zone should be expected to be "inscribed" in the morphology of fracture surfaces. Therefore, we looked for the "trace" of plasticity in mezoscopical fracture morphology as some coincidence with the size of the cyclic plastic zone.

2 Textural fractography

Various alternatives of the textural method were proposed during the last 12 years [13-15]. Among them, the direct fractographic solution of the reference concept brought the best results. Its application is limited to loadings satisfying the condition of *stationarity over short distances*. It means that all significant events, especially overloads, occur sufficiently regularly and frequently.

The *Reference concept* [14, 15] is based on a discovery of the *reference texture* - a textural component in fatigue fractographs which is common to fracture under various loading regimes. The reference texture is unambiguously related with the *reference crack growth rate* v_{ref} , a product of the conventional crack rate v and the reference factor B,

$$v_{ref} = v \, . \, B \, . \tag{1.}$$

Factor B is a characteristic of the type of loading. In case of constant cycle loading, $B = 1$, i.e., v_{ref} is equal to the conventional crack growth rate: $v_{ref} = v$. For variable cycle loadings with dominating effects of tensile overload, $B > 1$, i.e., $v_{ref} > v$. By means of introducing of the factor B, an unambiguous relation between the reference texture and reference crack growth rate v_{ref} was achieved (in contrast to the relation between the morphology of crack surface and the conventional crack growth rate v). Examples of reference textures corresponding with the same v_{ref} are shown in Fig. 7.

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Let following indices denote: *i* - test specimens, *j* - images of the fracture surface, *k* - the applied loading regime, *u* - image features, *q* - selected functions. Each image is characterized by a set of numerical textural characteristics - image features f_{uij} , and assigned a mean local macroscopic crack growth rate v_{ij} estimated from experimental records of crack growth. The relation between the crack growth rate *v* and image features f_u may be expressed via a multilinear model (equation for *j-th* image of *i*-th specimen)

$$\log v_{ij} = c_0 + \sum_{u,q} c_{u,q} h_q (f_{uij}) - \log B_k \ , \qquad (2.)$$

where h_q denotes a set of selected functions of image features, e.g. $\boldsymbol{h} = \{f, \log(f), f^{1/2}, f^2, 1/f,$ etc$\}$. Free coefficients c_0 and $c_{u,q}$ (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. Statistical significance of particular terms of the sum in eq. (2) is tested by a *t*-test and non-significant terms are excluded [16]. The set of image features composing the final model defines the reference texture.

3 Physical explanation of the reference features

By reference features we mean the reference texture, crack rate v_{ref} , and factor *B*. For reasons which were discussed in Introduction, we will look for a relation between reference features and the size of the cyclic plastic zone w^* [17].

Under a constant cycle loading, both the crack growth rate (CGR) *v* and the size of cyclic plastic zone w^* are functions of ΔK_{ef} :

$$v = A \Delta K_{ef}^{\alpha} \ , \quad w^* = \frac{1}{S\pi} \left(\frac{\Delta K_{ef}}{2R_p} \right)^2 , \quad S = \text{const.} \qquad (3.)$$

Simultaneously, the morphology of crack surface is strictly related to the CGR, and, therefore, it is also 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 are also controlled by ΔK_{ef}.

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 seemly 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. 1**, 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:

$$a + w^* \geq a_m + w_m^* \ , \qquad (4.)$$

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

$$w_m^* = w^* \ \text{and} \ a_m = a \, . \qquad (5.)$$

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Our hypothesis is that the reference features are controlled by the *residual major cyclic plastic zone* (**Fig. 1**, dotted line) whose size is

$$\Delta w_m^* = a_m + w_m^* - a \,. \tag{6.}$$

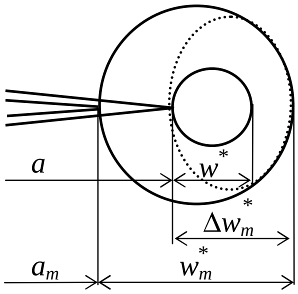

Fig. 1 The major and residual major cyclic plastic zone

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 w_M which may be computed as a moving average of the sequence of values $\Delta w_m^*(j)$ from individual cycles. For a given cycle *n*, it may be expressed as

$$w_M(n) = \frac{\sum_{k=n-K}^{n+K} \Delta w_{m,k}^* \Delta a_k}{\sum_{k=n-K}^{n+K} \Delta a_k} \,, \tag{7.}$$

where $2K$ *is* the length of the moving average. For periodical loadings by repeating a block of cycles, w_M is computed for particular blocks and assessed to corresponding middle crack length.
Let the symbols $v(w_M)$ and $v_{ref}(w_M)$ denote crack growth rate and reference crack growth rate related to the given value of w_M. The assumption that 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

$$B'_{variable\ cycle}(w_M) = \frac{v_{constant\ cycle}(w_M)}{v_{variable\ cycle}(w_M)} \tag{8.}$$

should be approximately constant (independent of w_M) and similar to the corresponding value of the parameter *B*, estimated within the fractographic reference solution (eq. (1), (2)).
b) The dependence $v_{ref}(w_M)$ should be independent of the type of loading.

4 Experimental materials and methods

CT specimens (Fig. 2) from aluminum alloy 2024 were loaded at 20°C in air by various loading regimes. Crack growth was regularly measured and recorded.
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 [17].

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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. 3**) 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. (2).

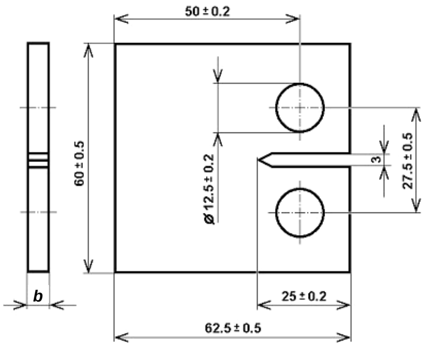

Fig. 2 Specimen for fatigue tests. $b \in \langle 7.45, 8.1 \rangle$ mm.

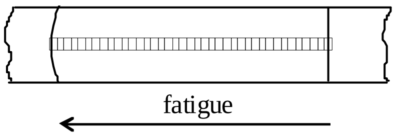

Fig. 3 Layout of SEM images along the middle axis of the fracture surface.

5 Results and discussion

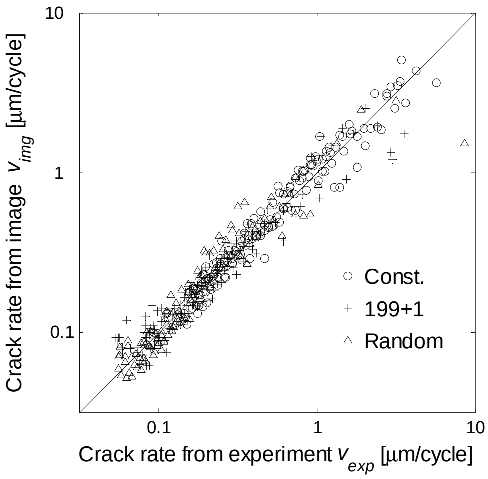

Fig. 4 Comparison of input (known) and output (estimated from images) crack growth rates. Markers represent single images of the fracture surface.

The final model contains 16 most significant features. Resulting estimates of reference parameters *B* are presented in **Table 1** [17]. The quality of the model is documented in **Fig. 4**. Examples of reference textures are shown in Fig. 7. Original images assigned various crack rates

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are evidently mutually different. Reference textures are similar - visually as well as analytically in the sense of a random field.

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

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

The sizes of residual major cyclic plastic zones Δw_m^* and their moving averages w_M were computed from equations (3) - (7). Dependences between w_M and the conventional crack growth rate v are shown in **Fig. 5**. 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 **Table 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 w_M and the reference crack growth rate v_{ref} are shown in Fig. 6. Also the expectation b) may be said to be approximately valid.

Table 1 Comparison of estimates of the reference parameters *B* (eq. (1,2)) and *B'* (eq. (8))

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

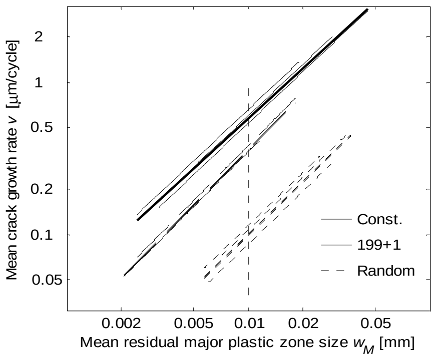

Fig. 5 The dependence between w_M [1/] and the mean conventional crack growth rate *v*. [2/]

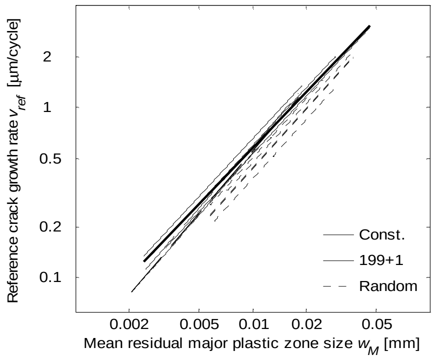

Fig. 6 The dependence between w_M [1/] and the reference crack growth rate v_{ref}. [2/]

[1/] The local mean size of the residual major cyclic plastic zone.

[2/] Thick lines represent mean dependences for each loading.

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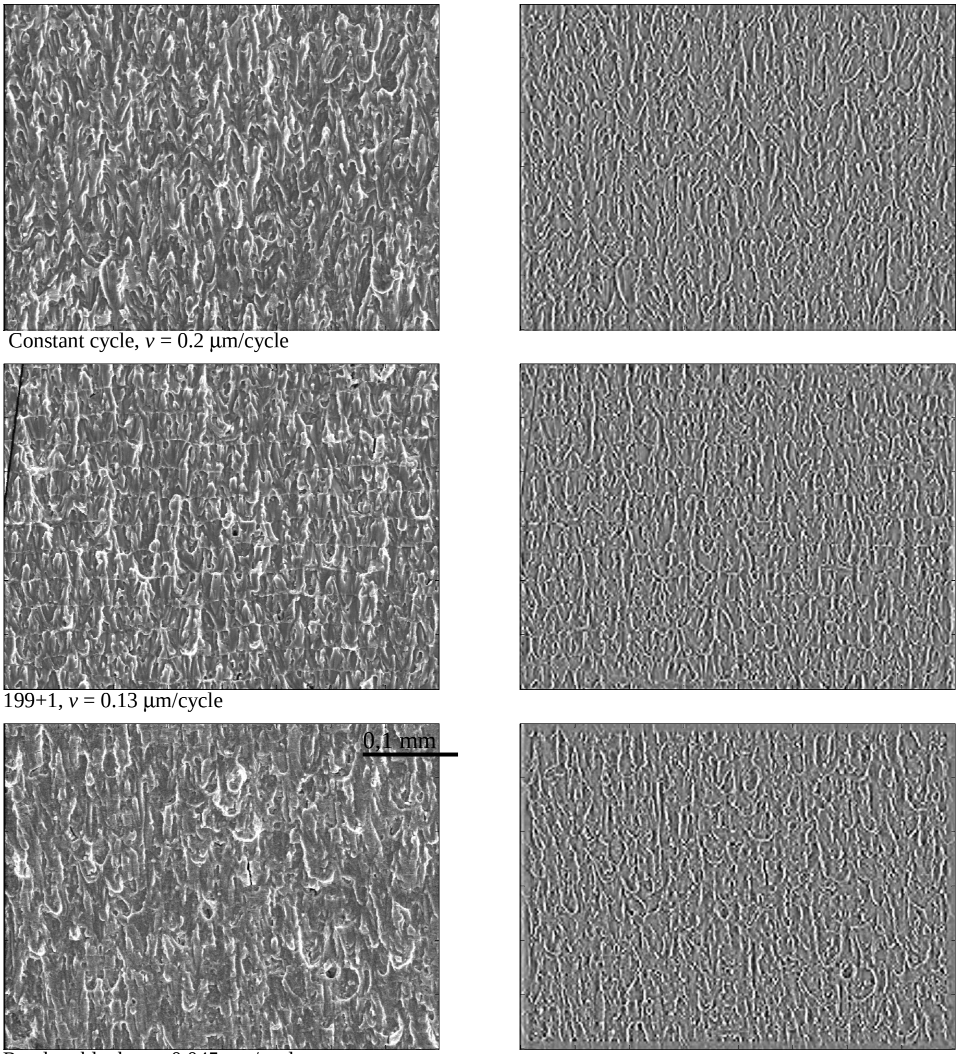

Constant cycle, v = 0.2 μm/cycle

199+1, v = 0.13 μm/cycle

Random block, v = 0.045 μm/cycle

Fig. 7 a) Normalized SEM images of the crack surfaces. Reference crack growth rate v_{ref} = 0.2 μm/cycle. b) Corresponding reference textures.

6 Conclusion

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 a detailed structural investigation of the mezoscopical dimensional component of the morphology of fracture surface in relation to plastic processes at the crack tip.

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