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Reconstruction and Evaluation of 3D Fracture Surface Morphology

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Summary

In the paper a procedure for evaluation of the fracture surface morphology is described in detail. It consists of the stereophotogrammetrical 3D surface reconstruction followed by the Delaunay triangulation of obtained set of surface points. The potential of the procedure is demonstrated using fracture surfaces generated under combined bending-torsion fatigue loading of specimens made from high-strength low-alloy Cr-Al-Mo steel. Fracture profiles extracted from calculated 3D meshes are characterized by the root mean square roughness and the Hurst exponent. As a main result of the analysis the critical portion of the torsion loading component after which the character of the crack path changes rapidly is estimated to be approximately 50%.

Introduction

Despite the long scientific interest, an evaluation of fatigue of structures and materials (nowadays especially under multiaxial loading conditions) is still one of the most important topics in the material science [1,2]. As the fracture surface can be considered to be a degradation process gauge, the quantitative fractography as a method of fracture morphology description has recently been used to obtain appealing information on the fatigue crack propagation as well as on the interconnection between the crack path and loading conditions, see e.g. [3-6]. Most of the mentioned studies, however, are confined to uniaxial fatigue and a significant lack of experimental data from fracture surfaces generated by multiaxial dynamic loading remains to be a crucial problem of this modern scientific branch.

Common techniques for 3D surface measurements can roughly be classified into three main categories. These are (i) mechanical methods (e.g. profilometry), (ii) methods based on optical principles, and (iii) other techniques including methods from SPM family, stereophotogrammetry, and destructive methods like a metallographic sectioning or a slit island technique. For fractographical research stereophotogrammetry is very suitable. The main advantage is a good accuracy at arbitrary magnification allowing to analyse even very rough surfaces such as usually are encountered in fatigue. Also the possibility to find corresponding regions on both fracture surfaces rather easily is important for many applications. The drawback of the method is a non-equidistant sampling of fracture surface meaning

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that a triangulation is required in order to decide the spatial connections between measured points. In next two sections stereophotogrammetry and the Delaunay triangulation are described followed by an example application using fracture surfaces generated under combined bending-torsion (biaxial) fatigue loading of specimens made from high-strength low-alloy Cr-Al-Mo steel.

Stereophotogrammetry

Stereophotogrammetry is a method that makes use of the stereoscopical principles in order to obtain topographical data of fracture surface under investigation. Inputs of the method are two images of analysed region taken from different positions of view (so-called stereoimages, stereopair) and some additional parameters characterizing a projection used during their acquisition. Usually, a scanning electron microscope (SEM) equipped with an eucentric holder is employed and the stereopair is obtained easily by tilting the specimen in the microscope chamber by an angle that depends on a local ruggedness of the surface. In such a case magnification, a working distance, and a tilt angle are provided as additional inputs. The prerequisite of successful reconstruction is the high-quality stereopair, especially an optimal and comparable contrast and good sharpness of all regions on both stereoimages are required.

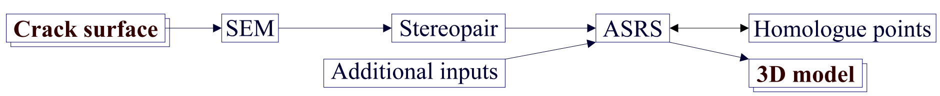

Figure 1: The procedure of the stereophotogrammetrical reconstruction. ASRS represents a software system that provides algorithms for both matching and relative height calculation.

As can be seen from Fig. 1, calculation of 3D surface model proceeds in two steps. In the first step the stereopair is processed via a hierarchical matching algorithm in order to find corresponding points on both images (homologue points). In the second step relative z-coordinates of all homologue points are calculated from their parallaxes using the Piazzesi algorithm [7]. The output of the stereophotogrammetrical reconstruction is a 3D model of depicted surface area consisting approximately of 20,000 points in the case of 1024×768 pixels stereoimages. An example of the procedure is shown as Fig. 2.

Delaunay Triangulation

Given a set of points S in d-dimensional Euclidean space (E^d) a task of triangulation is to connect these points into non-overlapping simplices, e.g. triangles in E^2, tetrahedrons in E^3, etc. From all of possible triangulations, the one invented by Boris Delaunay in 1934 is the most prominent. Delaunay triangulation $DT(S)$ in E^3 is a diagram satisfying following conditions:

- A point P is a vertex of the simplex from $DT(S)$ if and only if $P \in S$, i.e. the

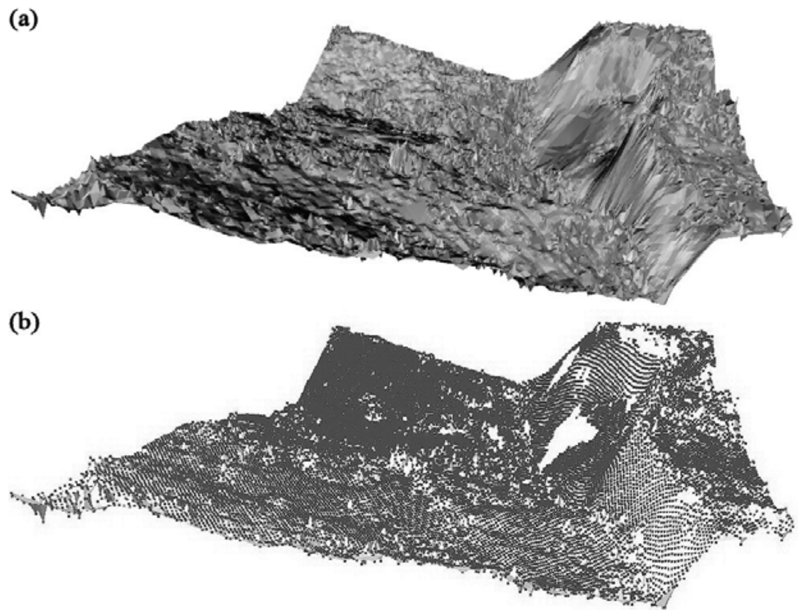

Figure 2: An example of the reconstruction of the part of the fracture surface generated under pure torsion: (a) image with texture, and (b) homologue points. The size of the region is $3\times10^4\,\mu\mathrm{m}^2$ approximately.

vertices of the simplices are points from the input set S;
- Any two simplices intersect in a shared vertex, a shared edge, or a shared face, or do not intersect at all;
- The triangulation $DT(S)$ is maximal: there is no simplex that can be added into without violating previous rules;
- Circum-sphere of any simplex does not contain any other point of S in its interior (empty circum-sphere criterion).

It comes from the last condition that $DT(S)$ maximize the minimum angle. This property together with uniqueness of $DT(S)$ in the general case as well as its close relation to the Voronoi teselation makes $DT(S)$ very attractive for a wide variety of engineering application. For a description and comparison of a number of common algorithms designed for a calculation of $DT(S)$ see e.g. [8].

Application Example

In this section a practical example is given using the fracture surfaces of smooth specimens made from high-strength low-alloy Cr-Al-Mo steel (σ_y = 840 MPa, σ_u = 950 MPa). Specimens were loaded at the room temperature using a symmetric bending, symmetric torsion (both of frequency f =29 Hz) and their synchronous in-phase combinations. Experimental data are collected in Tab. 1, where σ_a is the bending amplitude, τ_a is the torsion amplitude, $Z = \tau_a/(\sigma_a + \tau_a)$ is a loading ratio and N_f represents fatigue life expressed in a number of cycles to failure. It is noted that the fatigue life of all specimens falls into a transition region between the high-cycle and the low-cycle fatigue ($N_f \in (10^4; 10^5)$ cycles). The differences in the fatigue life are small enough to enable a mutual comparison of fracture morphologies of investigated specimens.

Stereophotogrammetrical reconstruction of selected regions on analysed surfaces was carried out by means of the commercial software system *MeX*. On each fracture surface the square area of size 0.25 mm^2 was chosen with its centre at the distance of 0.8 mm from the fatigue crack initiation site on the specimen surface. Square sites were oriented to be parallel with (or perpendicular to) the local direction of the fatigue crack propagation. Using Delaunay triangulation of obtained 3D data, two sets each consisting of 100 profiles were traced: the first one in the crack propagation direction (y-direction) and the second one in the perpendicular direction (x-direction) marking thus different positions of the progressing crack front.

Table 1: Experimental data.

Specimen	Type of loading	σ_a [MPa]	τ_a [MPa]	$Z[-]$	N_f[cycle]
1	Pure bending	738,17	0	0	102 560
2	Bending-torsion	559,86	203,38	0,27	14 880
3	Bending-torsion	329,37	330,30	0,50	55 600
4	Bending-torsion	135,95	372,82	0,73	100 160
5	Pure torsion	0	398,73	1	100 400

Profile Roughness Evaluation

In order to quantify roughness of extracted fracture profiles two parameters were evaluated. First is the root mean square roughness, R_q, representing a standard deviation of z-coordinates. This quantity is given as

$$R_q = \left[\frac{1}{n} \sum_{i=1}^{n} \left(z_i - z' \right)^2 \right]^{\frac{1}{2}}, \tag{1}$$

where n is the number of valid data points and z' is the mean height value. The root mean square roughness is a good descriptor of fracture surface macro-ruggedness. As a fully acceptable alternative the arithmetic roughness, R_a, frequently used in metrology may be compiled.

Fractal character of profiles is quantified by the so-called Hurst exponent, H. This parameter is directly related to the fractal dimension, D, as $D = 2 - H$ [9]. Hurst exponent is usually calculated via the variable bandwidth method (VBM). In VBM a profile is subdivided into k moving windows (or "bands") of fixed width ε, parameter R_q is calculated for each window, and then averaged over all possible windows:

$$W = \frac{1}{k}\sum_{i=1}^{k} R_{qi}. \tag{2}$$

Finally, the Hurst exponent H is obtained from a log-log plot according to the following fractal power law:

$$W(\varepsilon) \propto \varepsilon^{H}. \tag{3}$$

Results and discussion

Resulted R_q-values are plotted in Fig. 3. It is noted that the parameter R_q becomes nearly the same value for fracture surfaces of specimens 1-3 ($R_q \approx 5\,\mu$m). Significantly higher R_q-values correspond to specimens 4 and 5 (torsion prevails) that also show a rapid increase of the crack front "macroroughnes" during the crack propagation (Fig. 3b).

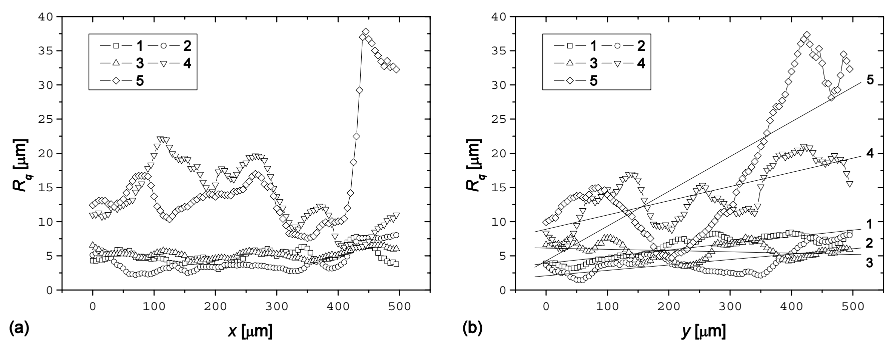

Figure 3: Root mean square roughness, R_q, of profiles oriented in (a) the direction of crack propagation, and (b) parallel with the crack front.

Results of the Hurst exponent, H, are shown as Fig. 4. It is noted that all profiles in y-direction (Fig. 4a) are characterized by H in the range of 0.5-1 indicating a long-range correlation ("memory effect") of the fatigue process [9]. Distinctly higher values that are observed for specimens 4 and 5 suggest higher sensitivity of fracture surface morphology to previous fracture events under loadings with portion of torsion higher then 50%. Moreover, increase in H on the crack front during propagation (Fig. 4b) implies increasing coordination of fatigue crack growth that might be related to the merging of initially separated crack segments.

Conclusions

- In the paper a procedure for evaluation of the fracture surface morphology is described. It consists of the stereophotogrammetrical 3D surface reconstruction followed by the Delaunay triangulation of obtained set of surface points.

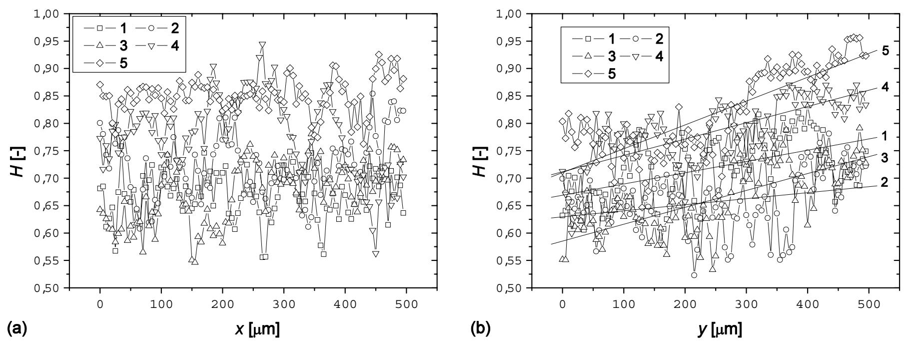

Figure 4: Hurst exponent, H, of profiles oriented in (a) the direction of crack propagation, and (b) parallel with the crack front.

- The procedure was applied to fracture surfaces generated under combined bending-torsion fatigue of specimens made from high-strength low-alloy Cr-Al-Mo steel. The analysis of extracted profiles in terms of parameters R_q and H has confirmed, in agreement with previous results [10], the great influence of torsion loading component on the fracture morphology. The critical portion of torsion after which the character of the crack path changes rapidly is estimated to be approximately 50%.

Acknowledgement

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