MULTISCALE CORRELATION EFFECTS DURING FATIGUE DAMAGE EVOLUTION OBSERVED BY SURFACE ROUGHNESS ANALYSIS

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ABSTRACT

Periodic and random surface roughness of cyclically loaded specimens of ferritic and austenitic steels was measured using new optical method based on laser light scattering on rough surfaces. Measured dependencies of autocorrelation length of surface T on relative number of cycles N/N_f indicate an onset of a stable extrusion/intrusion relief on the specimen surface caused by fatigue process. In addition to this, the qualitative and quantitative investigations of surface relief formation and evolution on Al single crystal thick films rigidly attached to specimens under cyclic tension were carried out by optical microscopy with the CCD camera in online regime, local investigation by X-ray method and analysis of interference fringes. Maximal information fractal dimensions D of surface roughness vs. numbers of cycles were found to appear earlier for the higher stresses of restricted tension. Spatial distribution of D was found to be heterogeneous only near strain localization sites in the basic specimen. It can be explained by multiscale roughness caused by the more intensive relief evolution processes there (in contrary to other parts of the film). We elaborated some new fractal procedures, which could be useful for evaluation of roughness fractality in 3D embedding space. In this sense these two independent techniques confirm the idea about multiscale correlation effects during different stages of fatigue life.

KEYWORDS

Surface roughness analysis, fatigue damage evolution, fractal dimension, autocorrelation function, fatigue life, laser beam scattering.

INTRODUCTION

Previous works by the Institute of Physical Engineering, FME TU (Brno, Czech Republic) and G.V.Kurdyumov Institute of Metal Physics of National Academy of Sciences and Kyiv National Aviation University (Kiev, Ukraine) [1–6] have shown that quantitative multi-scale surface characteristics of metals under fatigue loading correlate with the number of loading cycles and stress amplitude. This suggests that a simple method of measuring the accumulated fatigue damage of a structure at all stages of its life is to hand. Clearly this could be a valuable investigative tool in the introduction of new structural concepts, materials or processes.

EXPERIMENTAL

Laser light scattering on rough surfaces

Mechanical loading of flat specimens from ferritic and austenitic steels was performed using a Schenck-WEBI machine under alternating cyclic bending. The virgin specimens were treated by a special polishing technique resulting in a very smooth surface relief. Three different values of stress amplitude σ_a, corresponding to the fatigue limits of about 10^4, 10^5 and 10^6 cycles, were used for specimens of both steel specimens. The laser light scattering method is based on the analysis of a laser light (He-Ne laser, λ=632,8nm, P=30mW) reflected at the surface. The backscattered light is detected by the photodiode moving on the table with micrometric shifting controlled by computer, which simultaneously collects and analyses measured data. Specimens of ferritic and austenitic steels were measured using new optical method based on laser light scattering on rough surfaces (see Fig. 1).

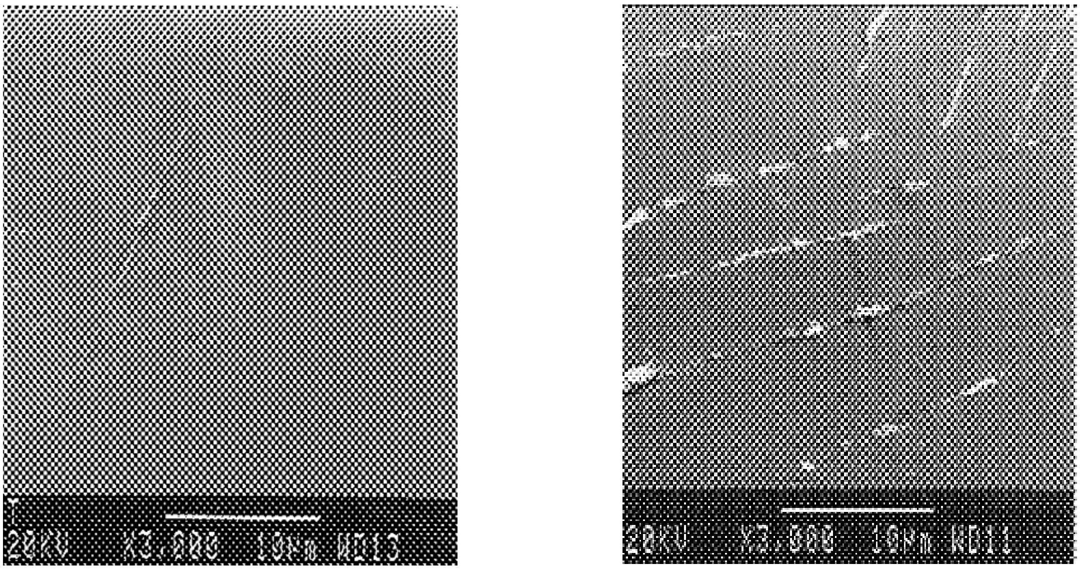


Fig. 1. Surface microrelief before and after formation of a stable extrusion/intrusion patterns (ferritic steel, SEM).

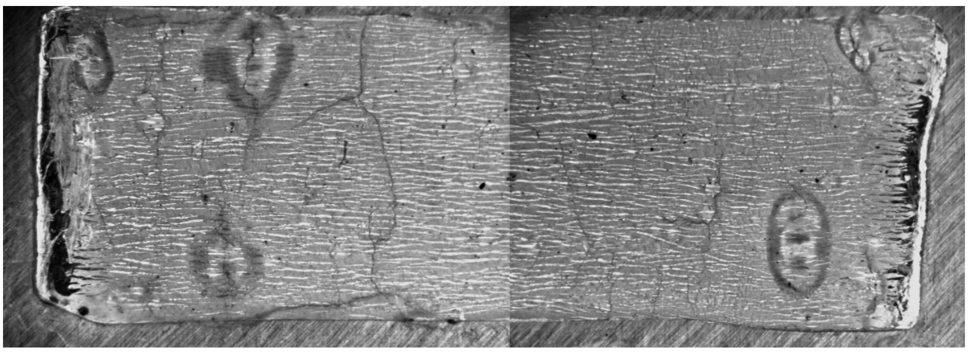


Fig. 2. Snapshot of the whole surface (16×6 mm) of the flat aluminium single crystal indicator attached to Al-alloy specimen after 10^6 cycles (light microscopy; diffuse illumination; stress is applied along the longest side).

Online optical topography analysis

Our experimental work consisted of the following stages (that are described in details in the previous paper [1–3]): preparation of sensors and their binding to specimens (see Fig.2); mechanical tests of specimens; image acquisition, conversion and storing. We prepared more than 50 sensors of high purity Al and more than 20 specimens of Al 2024 T351 of thickness 2–4 mm with/without weld (see Fig.2).

Fatigue tests were carried out with several stress levels (250 MPa, 232 MPa, 201 Mpa, 175 MPa, and 146 MPa). on hydropulse machine "MUP-20" (made in USSR, Armavir) with working frequency, which was equal to 11 Hz. The shape of loading cycle is a sinusoidal one with minimal loading value near zero. Before mechanical tests the special static and dynamic calibrations were carried out for providing necessary preciseness and reliability of measurements. For static calibration was used high-frequency dynamometer, and dynamic calibration was fulfilled by tenzometry. The calibration error was no more than 5%. The main idea in the process of obtaining the sensor relief is to organize the scheme of loading: the underlying specimen is deformed in elastic regime, when the sensor is strained in plastic mode. Numerous routines of image acquisition after each stop of testing machine were made by automated methods on the basis of Leica microscope with SONY CCD camera attached to personal computer by video adapter and TCI-Oculus frame-grabber card with storing on hard disk of personal computer.

DATA ANALYSIS

Laser light scattering on rough surfaces

Surface roughness of cyclically loaded specimens was measured in the form of dependencies of autocorrelation length T of surface on relative number of cycles N/N_f. Curves of T on N/N_f for different σ_a and both materials exhibit minima for all measured specimens and both materials used. With increasing σ_a, the minima shift to lower values of N/N_f. A comparison between curve connecting these minima, Woehler curve and the curve of fist slip appearance of an equivalent steel [4] is shown in Fig.3 for ferritic steel specimens (σ_s is the fatigue limit). Recent analyses [6,7] allowed us to interpret the minima as a subsequent development of two qualitatively different components of surface roughness — random and quasiperiodical. The T-value rapidly decreases with the first one and slowly increases with the latter one. The minimum corresponds to the moment, where the quasiperiodic component reaches the same contribution to the T-value as the random one. The quasiperiodic component carries the information on self-similarity and fractal properties. It is connected with the evolution of protrusion bands and slip line structure. This component can not be quantitatively analysed by the laser beam scattering method since the theoretical background of the method deals with the presumption of random roughness evolution. The quasiperiodic component is taken into account only as a defect mode.

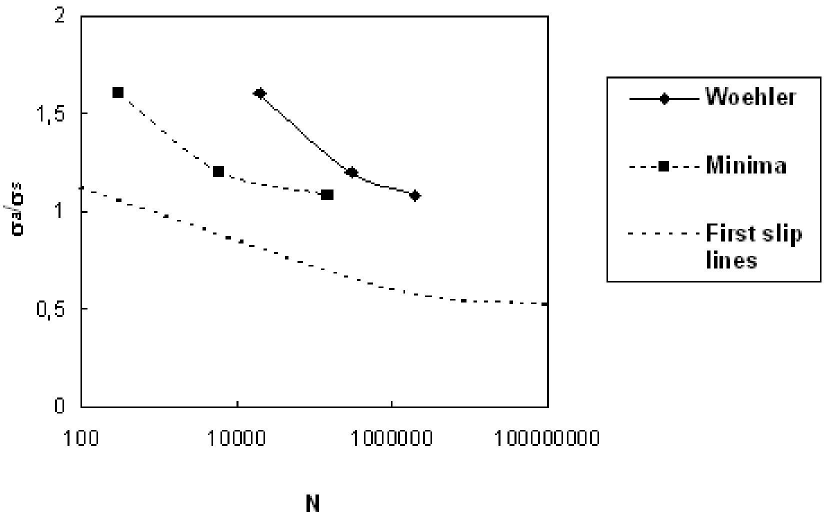
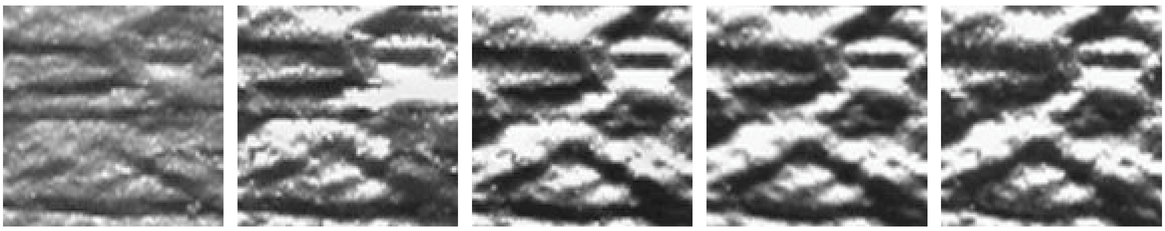


Fig. 3. Comparison of the curve of minima , the Woehler curve and the curve of the first slip appearance for ferritic steel.

Online optical topography analysis

Numerous solitary snapshots (more than 150–180 for the largest magnification; ×140) of neighbouring regions of sensor were merged by specially designed software. As a whole it gives us the big number of huge size panoramas from 5,000×2,000 to 10,000×4,000 pixels.

Our previous investigations have shown signs of multiscaling properties of surface relief on indicator attached to aluminum alloy specimens: self-similar patterns can be observed on different scale ranges, self-similarity range is changing with a change of loading conditions, quantitative multiscaling characteristics modify with time and with a change of loading conditions. That is why we intend to concentrate our attention on several spatial and temporal scales and we would like to apply multicscaling approaches (fractal, multifractal and wavelet analysis) widely used in many applications for characterization of objects of complex geometry with signs of self-similarity. In fact, natural systems hardly can be described by simple unified pan-scale approach, because such a rigorous case is a domain of pure mathematics. However, seemingly chaotic natural phenomena can be characterized by this multiscaling analysis with taking into account “relay-race” of different mechanisms and processes operating at different ranges of space-time scales (Fig.4).



96,000 cycles 180,000 cycles 270,000 cycles 390,000 cycles 600,000 cycles

Fig. 4. Evolution of regular extrusions on the single crystal sensor attached to Al alloy under fatigue (light microscopy; shadow patterns created by directed illumination from top to bottom), see animated sequences on the web [8].

For application of fractal geometry one can need to find the scope of self-similarity for the property investigated. This task is highly dependent on physical sizes of the system, because mathematical definition of self-similarity in relation to physical objects is highly concerned with the certain size limitations. We used three measures along X-axis (along tension direction), Y-axis (perpendicular to tension direction) and the so-called 'Z-axis' (coloration values).

The lowest scale level for digitized images is theoretically limited by the lowest value optical resolution of CCD-camera. Finally, in our case it was equal to one pixel. Taking into account the precautions of manufacturer we select it as 2-3 pixels. The highest scale level in X-Y plane is limited by the size of digitized image, which was equal to 500–600 pixels for single image and 1024–2048 pixels for panoramic view. In this work all images were captured in gray scales from 0 (black) to 255 (white) that is why the highest scale level in Z-axis was limited to 256 levels, *i.e.* slightly more than 2 decades.

Another point is for quantitative characterization one needs the knowledge of the true 3D-representation of the whole indicator surface relief. In our case we deal with some projections of this 3D-representation created by directed and diffuse ring illumination. These projections are only manifested in different coloration (Z-axis). The main idea is supported by theoretical results that projections of self-similar objects inherit the self-similarity of original objects.

Finally, under these conditions we considered two types of the processed patterns:

- irregular coloration pattern in 3D-embedding space, i.e. the gray scale map with the spatial X-axis, the spatial Y-axis, and coloration Z-axis;
- irregular coloration pattern in 2D-embedding space, i.e. the gray scale map with the spatial X-axis and coloration Z-axis.

The core formula that was used for calculation of information fractal dimension (D) is as follows:

$$D = \lim_{e \to 0} \left(\frac{\log\left[I(e)\right]}{\log\left[1/e\right]} \right),$$

where $I(e)$ is the average surprise in learning which e-cell contain a component of the complex object.

We preferred to use information dimension because it gives the richest and most useful information. We carried out some tests on the objects with well-known fractal dimension and information dimension was the most precise method among other box-counting methods. The idea of calculation was proposed by B.B.Mandelbrot, D.E.Passoja, and Paullay, A. J. [9]. The core formula was invented by Francis C. Moon [10] and the best optimization method was published in Internet by John Sarraille and Peter DiFalco (1997) [11]. On this basis we developed the code and used it for the further calculations.

Finally, we found that these multiscaling characteristics were modified with time and change of loading conditions. As a whole the information dimensions calculated now and the same dimensions obtained by us previously are in good coincidence. It concerns the main shape of dependence of information dimension vs. the number of cycles and stress amplitude. Moreover, the initial ideas about

- availability of maximum and
- shift of maximum caused by increase of stress amplitude

were not only supported (Fig.5,6), but also were extended by data on:

- abrupt appearance of ***two anisotropic*** values of information dimension (where the second value has much larger value than the initial one);
- availability of ***two anisotropic*** maximums;
- shift of ***two anisotropic*** maximums caused by increase of stress amplitude [12].

Moreover, the most stable and reliable results which can support the quantitative results are better for the higher stress amplitudes. This fact can be obviously explained by intrinsic physical nature of fatigue.

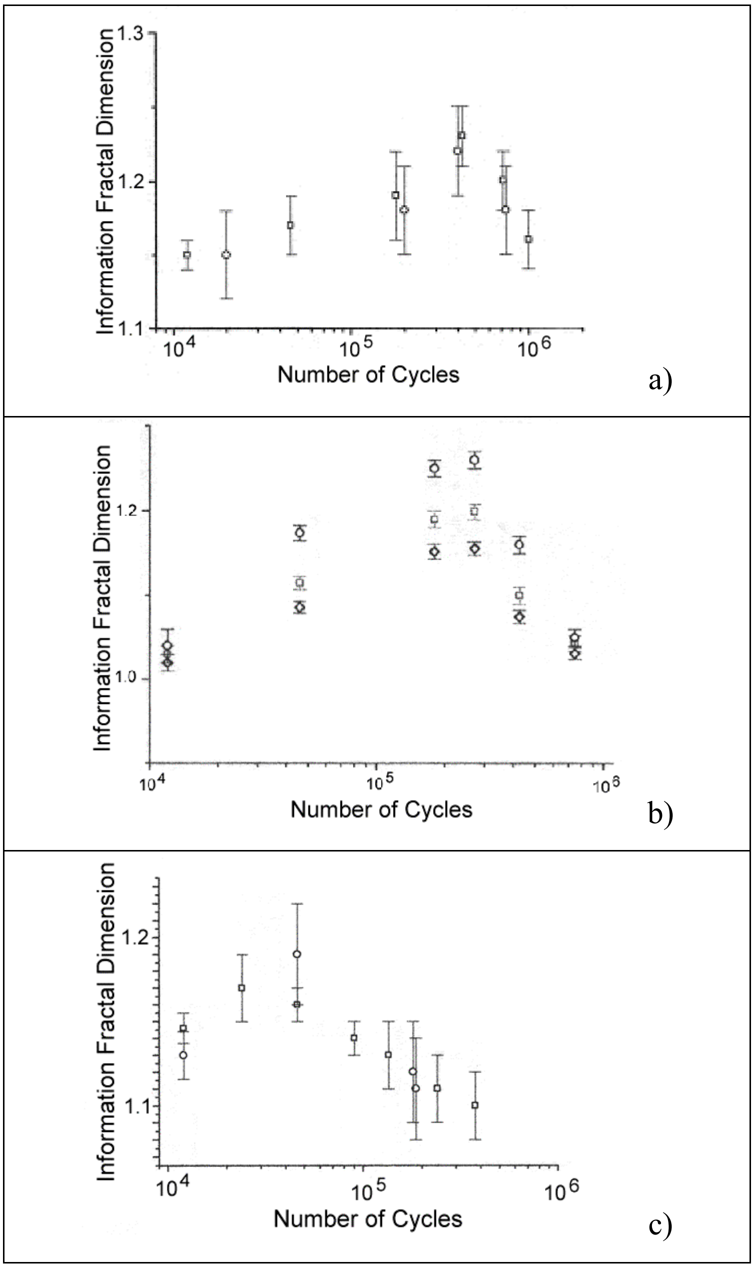


Fig. 5. Evolution of information fractal dimension in 2D embedding space (cross-sections) for different values of σ: a) 146 MPa, b) 175 MPa, c) 192 MPa.

Because of the big value of standard deviation we tried to investigate the spatial distribution of fractal measure on the single crystal sensor surface. In this case we proposed the calculation of *equidimensional maps* (Fig.7) [13]. This method allows not only to find strain localization places, but also to envisage its dynamics. It should be noted that large sensors which can fully cover the possible place of stress localization are necessary for this purpose.

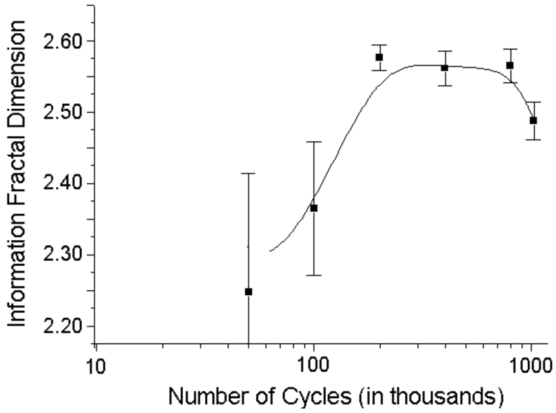


Fig. 6. Evolution of information fractal dimension in 3D embedding space for patterns shown in Fig.7 (σ = 190 MPa) .

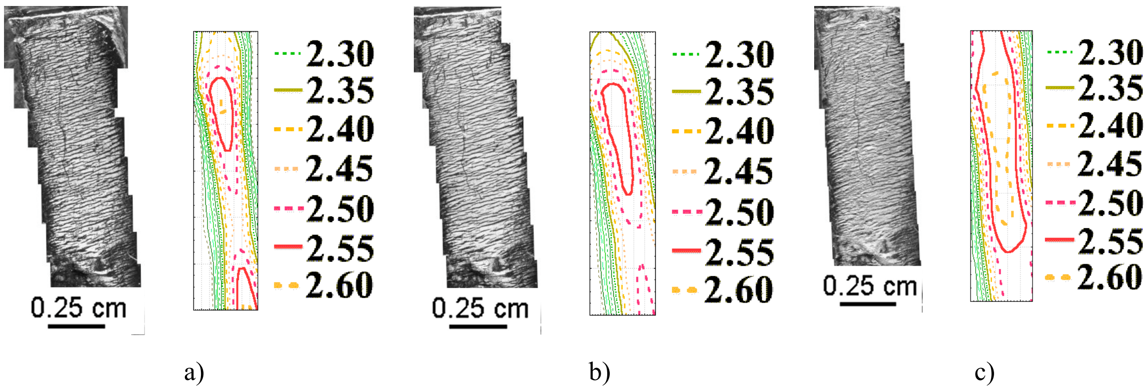


Fig. 7. Evolution of sensor surface near strain concentration site visualized by panoramas (left column) and contour plots of information dimension (right column): a) 12,000, b) 25,000, c) 200,000 cycles.

CONCLUSIONS

All above mentioned facts confirm that positions of minima at the autocorrelation length curves indicate the *short stages of fatigue life* in which a formation of a stable extrusion-intrusion relief takes place on the specimen surface. This stage precedes the short crack propagation period and is, therefore, of a great practical importance. After reaching the minima, quasiperiodical surface patterns of fractal character become to be dominant. It is to be stressed that the measuring of the minima curve for a given steel needs only a low number of specimens (3 or 4) and a very short experimental time in comparison with, e.g., the establishing of the French curve.

At the same time indirect method of multiscale (fractal) investigation of roughness evolution on the single crystal sensor attached to Al alloy under fatigue can give us additional hint on the nature of cyclic deformation damage.

In fact, we observed the persistent evolution of low-scale extrusion-intrusion relief for *short stages of fatigue life* and persistent evolution of the quite different and large-scale complex sensor surface relief *for the next stages of fatigue life*. In spite of the stochastic nature of deformation damage phenomena these facts support the idea about the pre-emptive character of deformation mechanisms that take place before exhausting the fatigue life and ability to monitor them.

Aforementioned methods of investigation of multiscale correlations of surface roughness can give us the more precise tool for monitoring and forecasting the deformation pre-history of the metals. The main advantages of this technique related with ability to estimate the level of exhausting of fatigue life on the basis of the sensitivity to (a) the number of cycles, (b) stress amplitude and (c) damage localization sites in metals under fatigue loading.

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