TECHNISCHE MECHANIK, 32, 2-5, (2012), 408 - 415
submitted: October 18, 2011

Scaling Analysis of Defect Induced Structure of A6061 Alloy at Dynamic Strain Localization

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Plastic strain localization and fracture of dynamically loaded metallic samples, occurred during plug formation, are investigated. These processes are closely related to the instability of plastic flow and can be attributed to structural-scaling transitions in mesodefect ensembles. The multiscale nature of defect structure allows us to use the fractal concept for quantitative analysis of both the fracture surface and the inner structure of a deformed material. The scaling properties of fracture surfaces are established in terms of the roughness index (Hurst exponent) as the characteristics of strain localization and fracture.

1 Introduction

Since Mandelbrot's early work (Mandelbrot, 1983), it has been known that a wide variety of fracture surfaces exhibit self-affine geometry. This property of materials manifests itself in the scale invariance of fracture, which indicates the general multi-scale character of fracture processes. Fractal dimension offers a useful tool for describing such a geometry. However, the relationships between the measured and predicted values of a roughness exponent are not obvious, and sometimes even controversial. A reader interested in theoretical and experimental investigations of the scaling properties of materials can find more detail in other publications (Bonamy, 2006, Bouchaud, 1997, Bouchaud, 1990, Bouchaud, 2002, Shmitbuhl, 1995, Wnuk, 2003, Weiss, 2003). Apart from the self-affinity, the fracture surfaces often exhibit anisotropy, i.e., the fracture relief that develops along the crack front differs from that proceeding in the direction of crack front propagation. It means that a single scaling exponent is not enough for describing the fractal properties of fracture surfaces. For instance, in the work (Bouchaud, 1997, Ponson, 2006) three scaling parameters are used: the roughness exponent ζ corresponding to the direction along the crack front, the growth exponent β describing the properties of materials along the crack front propagation and the dynamic exponent obtained as $z = \zeta / \beta$. We note that all these exponents are to a certain degree universal. A comprehensive overview of the most recent works concerning the quantitative analysis of the fracture surface morphology of a vast type of materials was made in (Bonamy, 2011).

It is evident that a relief formed during the fracture process is specified by the microstructure and mechanical properties of the material and by loading conditions. Estimation of the relationships between the fracture surface morphology, the material microstructure and the loading parameters is a non-trivial issue. There have been many attempts to explain the above peculiar features of fracture. In some approaches the fracture surface formation is established as a result of the motion of an elastic line (crack front) through a random medium (Bouchaud, 1997). The notion of fractal crack is used in (Wnuk, 2003) to develop the quantized fracture mechanics approach. With this approach, the authors have pursued the evolution of fractal dimension in relation to the distance from the crack initiation area and arrived at the conclusion that the longer is the distance from the notch, the higher is the fractal dimension. In other words, the fracture surface becomes rougher, and the Mirror-Mist-Hackle effect is analytically predicted for fractal cracks.

Despite a vast number of theoretical and experimental works devoted to the problem of quasi-static crack expansion in quasi-brittle materials, no significant progress has been attained in the study of fracture of materials under dynamic loading conditions. The reasons for this are complicated experimental loading schemes, which impede correct interpretation of the experimental results, as well as the complex nature of processes occurred during dynamic deformation.

One of the fracture mechanisms responsible for the failure of the material under dynamic loading is shear deformation, caused by plastic flow instabilities and plastic strain localization. These effects play a significant role in the perforation of metallic targets during plug formation. It has been found that plastic strain localization under such loading conditions depends on many factors, including the geometry of a target and a projectile, the target thickness to projectile diameter ratio, the collision velocity, the target microstructure, etc. (Borwik, 2001, Awerbuch, 1974, Meyer, 1994). Failure of the material under such intensive loading is closely linked with collective effects arisen in the process of defect evolution. According to the approach (Naimark, 2008), plastic strain localization and instabilities are explained in terms of collective effects in microshear ensembles at structural-scaling transitions. These transitions result in the formation of a multiscale oriented defect structure.

The present work provides a quantitative analysis of morphology of the fracture surfaces and cross-sections of dynamically deformed samples. Our investigations allow us to obtain the properties of a defect subsystem on the mesoscale when the significant localization of shear strains takes place in a thin layer of material. The multiscale nature of defect structures generated in the dynamic loading process has motivated the use of the fractality concept.

2 Experiment

Dynamic loading of cylindrical samples by a hard steel projectile with a flat face part was carried out on the original ballistic gas gun. The experimental scheme provided the high shear strain localization in the area around the projectile. Different stages of the penetration process were obtained by varying the projectile velocity. The preparation of deformed samples for microscopy involved the following. For studying the evolution of the inner structure of the deformed samples, they were cut in the direction of loading. The obtained cross-sections were subjected to mechanical and electrochemical polishing for scanning election microscopy and optical microscopy. Besides, selective etching allowed us to obtain the images of individual structural elements of the highly-deformed layer near the fracture surface. The fracture surfaces were investigated without any previous treatment, which made it possible to obtain information about their morphology generated under dynamic loading.

As the projectile moves into the material, the plastic strain localization occurs in a thin zone. The neighbouring grains experience high plastic deformations and extension; a coalescence of microvoids results in crack expansion (Fig. 1).

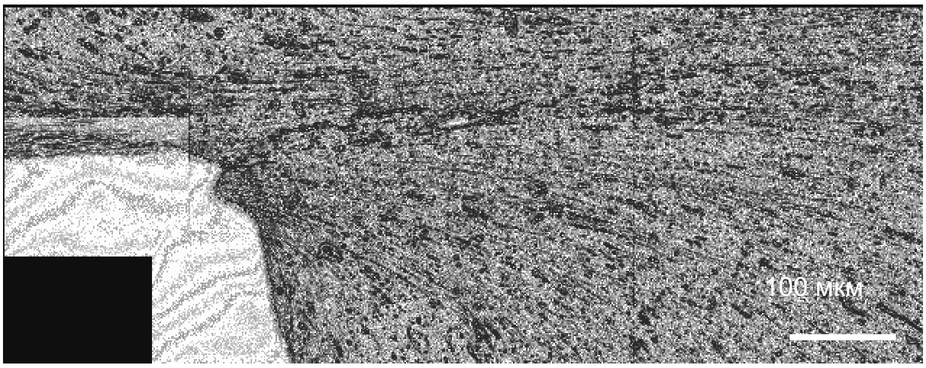

Figure 1. Crack formation near the projectile edge due to coalescence of microvoids

Near the fracture surface there are plastic flow bands, corresponding to the main direction of the flow of the examined material. The multiscale nature of these bands can be envisaged by selective etching. Each plastic flow band consists of 15-20 more tiny flow lines (Fig.2).

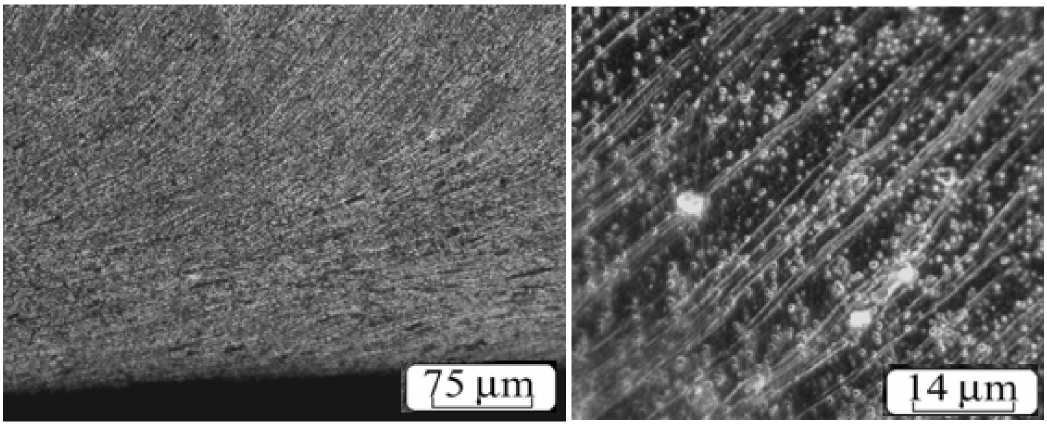

Figure 2. Structure of the deformed sample near the fracture hole in the area corresponding to plug formation on the scale of macro flow-lines) (left), and on the scale of micro flow-lines (right). The macro flow-lines were obtained by electrical polishing and etching with 10% HF in water solution, the micro flow-lines were envisaged by electrical polishing and etching with 1 % NaOH in water solution at 70ºC.

The sample films obtained by thinning the cuts of a highly deformed layer located near the fracture surface were studied using transmission electron microscopy. Figure 3 illustrates the initial structure of subgrains with low-angle boundaries, and the formation of the ultramicroscopic structure with a new grain size about 300 nm is shown in Fig. 4. A circular type of electron diffraction pictures (Fig. 4, right) indicates the presence of high-angle disorientations of grains. All these factors demonstrate the high level of deformation.

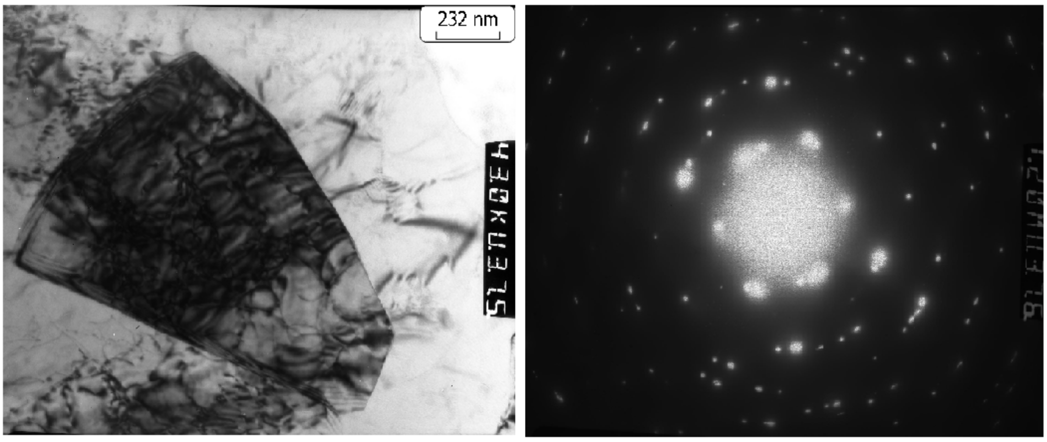

Figure 3.Microstructure of the undeformed material; big subgrain (left) and its electron diffraction image (right)

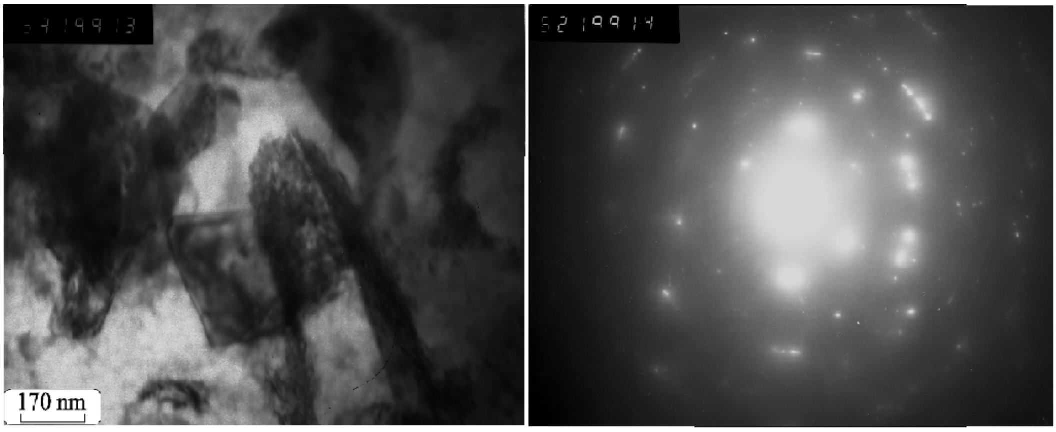

Figure 4. Microstructure of the highly deformed material near the fracture surface (left) and its electron diffraction image (right)

3 Fracture Surface Analysis

A quantitative analysis of the relief morphology has been carried out using the method of averaged difference between minimum and maximum heights, the DFA method, and the height power spectrum method. These are the most common techniques for analysis of fracture surfaces, fragmentation statistics, etc. The detailed description of these methods can be found in (Shmittbuhl, 1995, Bouchaud, 1997). The presence of a linear segment in the log-log plot of a correlation function indicates the scale invariance of the surface relief on some spatial scales. These scales and the value of the slope of the correlation curve (the Hurst, or roughness, exponent) characterize the law of surface transformation and the roughness level. To verify the validity of the applied methods, we have simulated the self-affine profiles with different roughness exponent using the midpoint shifting algorithm (Feder, 1989). Since all these methods agree well with each other both for simulated and experimental profiles, we will only discuss the results obtained by a single method.

There are two characteristic zones on the fracture surface of the perforated samples: the mirror zone corresponding to friction between the projectile and the material, and the rough zone corresponding to the formation and moving of the plug. A transition from the mirror to the rough surface has a step-like character. The rough surface structure is not homogeneous and indicates defect structure evolution in the material under dynamic loading.

The main purposes of the current work are: 1) the velocity dependence of the morphology of the fracture surface; 2) the investigation of the evolution of scaling parameters as the distance from the crack initiation increasing.

In order to get such information, fracture surfaces corresponding to different projectile velocities, were scanned by interferometer-profiler «New View 5010» along the direction of crack propagation. As a result 3D data about fracture relief in 13-20 consecutive areas (the number of scanned areas depends on using resolution of the microscope), each of 680x480 points, was obtained. Quantitative analysis of morphology of each of these areas allows us to plot a detailed map of evolution of scaling parameters with increasing distance from the crack initiation zone. The calculation procedure was as follows. For each of the scanned areas, six mean profiles averaged over 80 lines were recovered. Figure 5 presents the mean profiles and correlation functions of one of the examined areas. Therefore, the Hurst exponent interval for estimation of the spatial heterogeneity of the relief in the examined area was obtained.

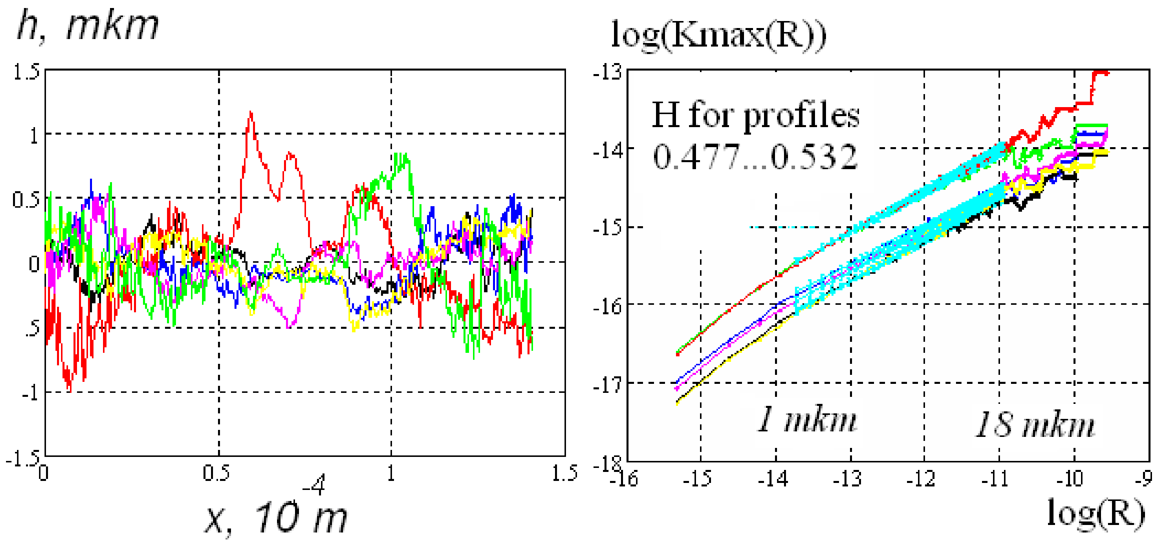

Figure 5. Mean profiles (left) and correlation functions with the evaluated roughness exponent (right) for a single scanned area.

The results of the fracture surface analysis of the A6061 alloy samples perforated by the projectiles accelerated to different initial velocities are shown in Figs. 6, 7. For low projectile velocity (slightly exceeding the ballistic limit), there occur two zones on the rough fracture surface, of which one, with small roughness, corresponds to the initial stage of expansion of the strain localization area, and the other, with huge-scale structures, to the developed stage of fracture, which may be ascribed to quasi-brittle fragmentation. The analysis reveals the scale-invariance in the range of spatial scales from 1 to 18 microns over the entire fracture surface. Almost the same value of the Hurst exponent in each of these areas testifies the appearance of similar structural relaxation

mechanisms. At the projectile velocity 2.5 times higher than the ballistic limit, only one type of the fracture relief occurs – the roughness exponent values are nearly the same as for the second zone in the previous case.
The obtained values of the Hurst exponent are likewise the results, reported in (Ponson, 2006) for commercial aluminium alloy A7475, where the roughness exponent value in the direction along crack propagation was found to be 0.58±0.03.

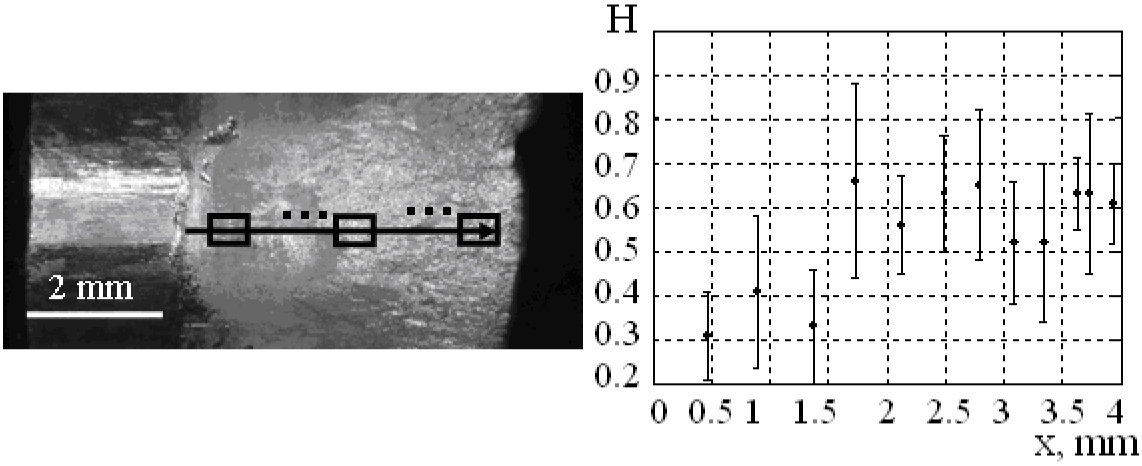

Figure 6. Fracture surface for the low projectile velocity (left). The projectile moves from left to right. The Hurst exponent evolution for the fracture surface (right).

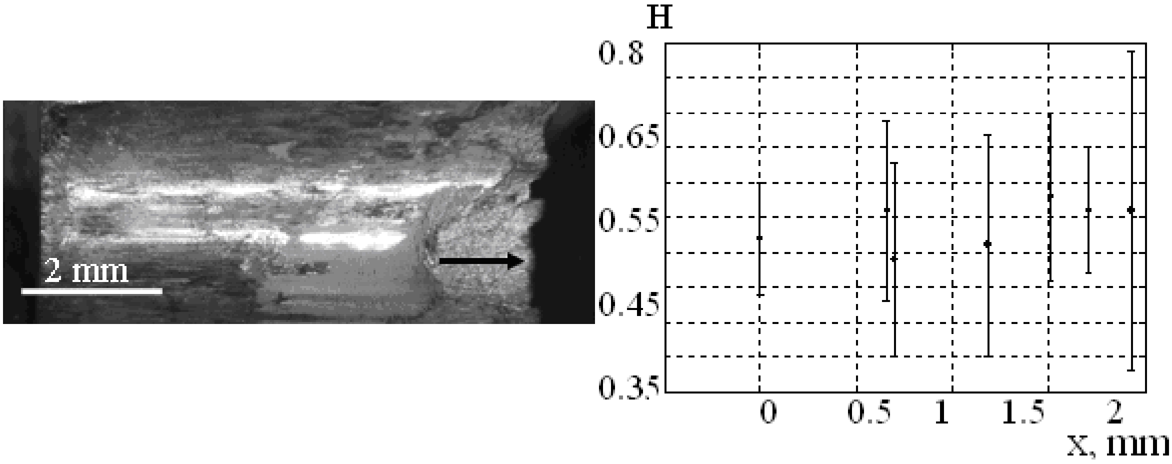

Figure 7. Fracture surface for the high projectile velocity (left). The projectile moves from left to right. The Hurst exponent evolution for the fracture surface (right).

The possible reason for occurrence of two regimes with different scaling exponents on the fracture surface obtained after low-velocity penetration is following. The first zone with small Hurst exponent, corresponding to high level of roughness, is formed due to intensive plastic deformation in this area: the nucleation of microvoids provides not very high crack velocity. As the crack length becomes more than some critical value, drastic expansion of a crack with high velocity occurs. This changing in the crack propagation regime is reflected in a step on the fracture surface and the increasing of the Hurst exponent value on the final fracture zone, reflecting the formation of huge-scale structures.

4 Inner Structure Scaling Analysis

For investigation of the scaling properties of the electropolished cross-sections of the deformed samples, the 2D method for estimation of the Hurst exponent has been used. It allows us to evaluate the roughness exponent without considering the direction of the analyzed profile. By analogy with the one-dimensional method for roughness exponent evaluation, the correlation function in 2D averaging is obtained as

$$K(R) = \left\langle \left| \max(z(r)) - \min(z(r)) \right| \right\rangle_{R+x_i<r<x_i} \propto R^{H} \tag{1}$$

where the averaging is made over all the cells of a size R. The reader who is interested in details of such methods is referred to experimental investigations (Xie, 1998, Ponson, 2006).

The cross-sections of deformed samples were scanned by the interferometer-profiler, and the data on the 3D relief of different sections were obtained. For each section, we observed the same tendency of decaying of the roughness exponent with decreasing distance from the fracture surface. The scaling regime was found to be in the scale range from 1 to 39 microns. The evolution of the roughness exponent in the area close to the fracture surface has shown another result: near the transition to plug formation and moving there is a local increase in the Hurst exponent.

5 Influence of Surface Treatment on the Scaling Properties of the Material

Because the grain boundaries, microvoids, slip line pattern and other microstructural elements become visible after electropolishing or/and etching procedures, a quantitative analysis of the cross-sections of materials treated in such a manner provide us with additional information about their inner structure. Therefore, the fractal concept can be considered to be a powerful tool for analysis of such information. To interpret correctly the obtained results, we need to elucidate the following questions. How does the duration of surface treatment affect the quantitative parameters, scaling exponents? Are these parameters dependent on the material structure subjected to treatment? These issues are at the focus of the current discussion.

To demonstrate the sensitivity of the methods to surface changes during the electropolishing procedure, the multi-stage electropolishing of metallic samples was performed. The samples were rigidly mounted at the microscope table to observe the same area at each stage of surface treatment. 3D data on the surface relief for x500 and x1000 magnification were obtained by the microscope «NewView 5010» at the following treatment stages: upon the completion of mechanical polishing and 1, 2 and 3 minutes after electropolishing. The analyzed profiles were 6272 points in length for x500 magnification (total physical length 2.78 mm) and 9344 points for x1000 magnification (2.05 mm). The distance between the neighboring points was 0.44 and 0.22 microns for x500 and x1000 magnification, respectively. Figure 8 shows the typical profiles of the mechanically polished surface and the surface 1 minute after electropolishing.

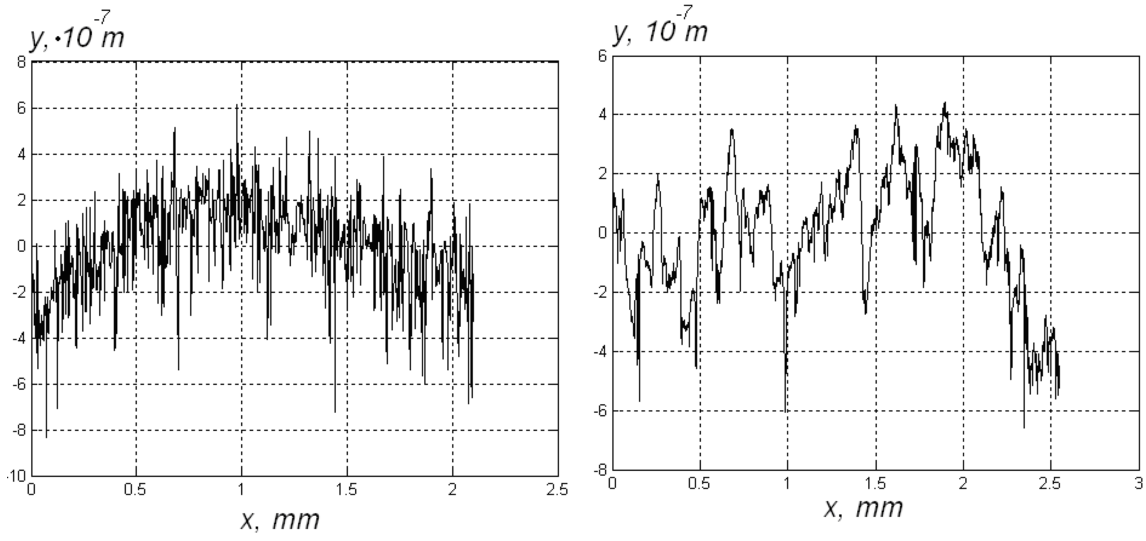

Figure 8. Profiles of the Cu sample surface before electropolishing (left) and after 1 minute of electropolishing (right).

Figure 9 shows the correlation functions for different stages of electropolishing. The slopes for small and larger scales are calculated for these curves. The correlation analysis of both the aluminium and copper samples shows that the difference between the two parts of the correlation curve reduces with increasing duration of treatment. These facts demonstrate that the roughness exponent is an adequate parameter for characterizing the material structure.

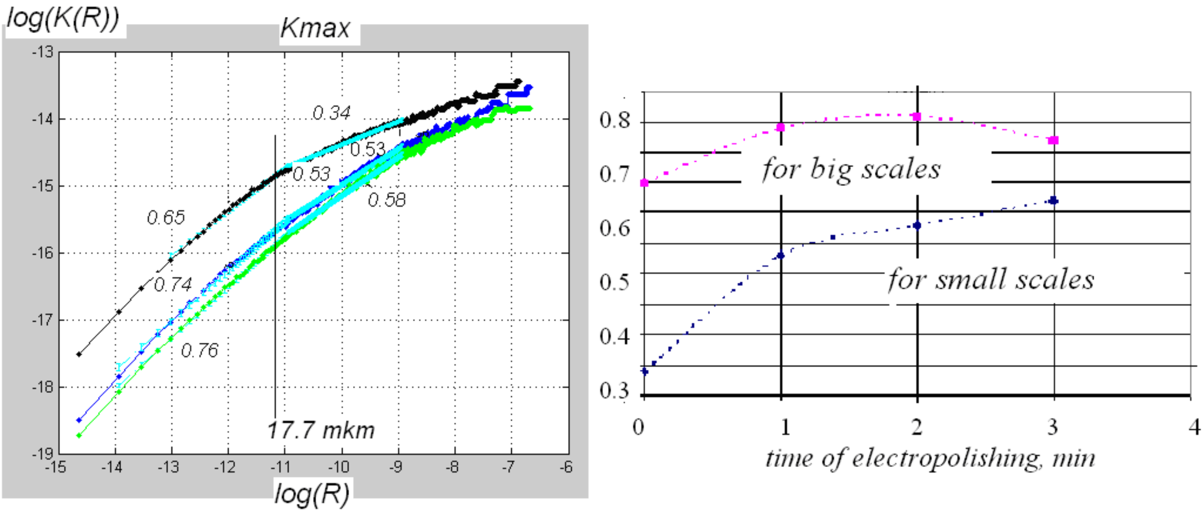

Figure 9. Correlation functions for the surface profiles at different stages of treatment (left): after mechanical polishing (black line), 1 minute (blue line) and 2 minutes (green curve) after treatment The evolution of the Hurst exponents at different range of scale with increasing duration of electropolishing (right).

The bend of the K(R) curve for the mechanically polished surface at scales about 17 microns corresponds to the presence of periodically arranged scratches produces by the abrasive.

Discussion of results:
Dynamic plastic strain localization and fracture of A6061 alloy were investigated by means of optical microscopy, scanning electron microscopy and transmission electron microscopy. The scale invariance of defect induced morphology was found, and the fractal analysis of fracture surface morphology and cross-sections of the deformed material was carried out.

Based on the obtained results, we can conclude that the correlation methods are good techniques to get a deep insight into deformation processes taking place, for instance, in ductile materials.
The applied methods exhibit sensitivity to structural changes induced by different types of loading or treatment.

The authors would like to acknowledge the Russian Foundation for Basic Research (grant RFBR 09-01-92005, grant RFBR 11-01-96010, grant RFBR 11-01-00712) for support of this work.

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