INFLUENCE OF DEFORMATION ON FRACTAL DIMENSION OF METALS STRUCTURE

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The image fractal analysis is actively used in all science branches. In particular in materials science the fractal analysis is applied to study microstructure of deformed metals because its structure can be interpreted as the fractal image. It is well known that such images can be described by fractal dimension. In this paper, the fractal dimension change for different kinds of metals in the processes of severe plastic deformation (SPD) is explored. It is shown that for the undeformed metals the stochastic network of structural elements boundaries has the fractal dimension \( D_{b} = 1.60 \pm 0.03 \). The SPD leads to increasing the fractal dimension up to \( D = 1.80 \pm 0.03 \). Possible reasons of changes in fractal dimension of metals structures in the SPD processes are analyzed.

I. INTRODUCTION

It is known that severe plastic deformation (SPD) allows to get materials with sub micro- and nanostructures possessing principally new complex of properties. However, physical principles of creating such materials haven’t been exposed completely. On this account it is actual to explore the evolution of materials structure in the SPD processes. In materials science, the fractal analysis and multifractal parameterization are actively used as deformed metals structures represent a kind of a self-similar set with grains and grain-boundary generating a network. Such network can be interpreted as the fractal image of the structure. As is generally known (Mandelbrot, 1983; Feder, 1991), such image is characterized by fractal or the so-called Hausdorf dimension which is an important quantitative description of the explored objects.

The basic hypothesis of the given work is that evolution of metals structure occurs in a self-similar manner with the formation of fractal structures that substantially simplifies their description. This hypothesis was proved theoretically: assuming that a successive set of high-angular boundaries is prefractal of the same fractal, we have the following estimation for the area of the given set in unit volume of material: \( S d - n \), where \( d - \) characteristic size of fragment, \( n = D - 1 \), and \( D - \) fractal dimension of lines set on the plane crossing high-angular boundary. The \( D \) value lies within the limits of \( 1 < D < 2 \). If the sizes of prefractal elements are distributed in a wide range, the dimension of fractal substantially differs from 2. If the sizes of elements are approximately identical, the dimension of fractal approaches 2. According to \( D \) at the self-similar stage of fragmentation \( n = const \), with value lying between 0 and 1, and at a final stage, when the sizes of fragments approach the minimum, \( n = 0 \). So, the main purpose of this work is to examine above listed hypothesis experimentally

II. MATERIALS AND METHOD

The theory of self-similar sets is the basis of the fractal analysis method. They can be got by transformation of initial (half-tone) images of structures to their black and white (binary) ones. This procedure was carried out by the special programs Adobe Photoshop 7.0, Corel Draw 11, Image Tool 2.0. In the given work the images were got by digitizing microstructures means of a scanner. There is a principle distinction in the nature of half-tone and binary pictures of structures. On microscope screen the half-tone picture is constructed by signals of variable amplitude. So, the contours of objects of the real material structure are determined by conditions of sample preparation (polishing and etching the specimen) and have the physical ground. On monitor the type of binary pictures is determined by the threshold of transformation and depends on the quantity of single pulses (zeros and unities) of constant amplitude.
Thus, the binary image should be considered as a discrete approximation of characteristic functions of an object or as a statistically-geometric model of the structure. With the successful choice of the threshold of transformation the operation of binarization does not bring in substantial distortions in statistical data files and conserves scale correspondence in the geometrical parameters of the analyzed objects. Therefore with the visual coincidence of images it is considered that the results of measuring on the black and white images characterize the observed objects of the real structures [4]. The explored objects were the approximation of glaze and asphalt structures (fig.4); approximation of iron wire (fig.2) and molybdenum (fig.3) microstructures, deformed by different methods and to different stress [5, 8]. To count the fractal dimension the so-called Box counting method was used. It works by covering fractal (its image) with boxes (squares) and then evaluating how many boxes are needed to cover fractal completely. Repeating this measurement with different sizes of boxes will result in logarithmic function of box size (x-axis) and number of boxes needed to cover fractal (y-axis). The slope of this function is referred as box dimension. Box dimension is taken as an appropriate approximation of fractal dimension, complete explanation is [12]. The HarFA 4.9 program is in the basis of this method developed in the Institute of Physical and Applied Chemistry, Technical University of Brno in Czech Republic. The given software has been tested on regular fractals, for example the Serpinsky carpet ($D = 1.79$). More detailed description of the given program can be found in [7]. The general interface of the program is presented in fig.1. The got binary im-
FIG. 4. Model nonmetal objects. Glaze (left), asphalt (right).

FIG. 5. Fractal dimension vs. plastic strain for iron wire. Longitudinal section.

ages of the explored metals structures were analyzed by the HarFA 4.9 program. In the process of analysis the pattern area structure was varied from 50 percent to 200 percent with the step of 50 percent. The pattern was also divided into four parts and the obtained constituents were processed.

III. RESULTS AND DISCUSSION

In this paper were analyzed different kinds of materials both metals and nonmetals. As nonmetals there were model objects glaze and asphalt, they are presented in Fig.4. These are natural objects and generated by them network of fragments boundary is generated in stochastic manner. Also we analyzed low deformed (plastic strain $e < 0.4$) metals: iron wire and molybdenum presented in Fig.2 and Fig.3 accordingly.

We can state that for both the nonmetal natural objects and low-deformed metals the fractal dimension remains constant $D = 1.60 \pm 0.03$ (Fig.4). This observation evidences that at low deformations or at recrystallization of metal the process of structure formation is probable. In the given work the fractal dimensionality is denoted in two ways: $D_S$ and $D_{div}$, where $D_S$ - fractal dimension value of whole studied picture. $D_{div}$ - means value of fractal dimension when the picture is divided in four parts. It should be noted (Fig.6), that $D_{div} < D_S$, that in opinion of the authors, speaks about heterogeneity of structural fragments distributing in size. When fragment sizes approach some $d$ the size of $D_{div}$ will also tend to $D_S$. Also there is a deviation of points from the straight line because of the got structural pictures is not regular fractals [11]. Thats why values of fractal dimension vary the limit of variation makes $\pm 0.03$.

Dependence of fractal dimension on plastic strain (cross section) for iron wire and molybdenum are presented in Fig.7a. During the deformation of iron wire there is the increase in fractal dimension of structural patterns (Fig.6a) from 1.60 (full circle) at $e < 1\text{tol.}1.80$ (full squares) at $e > 1$ and further maintenance at this level that speaks about self-similar structure evolution during severe plastic deformation.

In the case of molybdenum (Fig.7b) the fractal dimension also increases from 1.60 (without backpressure) to 1.70(with backpressure). Difference between the values of fractal dimension for molybdenum without backpressure and with backpressure, is because in the latter case there is a more intensive fragmentation of the material and more fine grain results from the same deformations than in the absence of backpressure. It follows that the finer the grain the higher fractal dimension in the case of a more uniform distribution of grains, that well correlates with theoretical data [1]. As a result, it can be concluded:

IV. SHORT CONCLUSION

In the initial undeformed or recrystallized metal, the same as in nonmetal model objects, the fractal dimension is permanent, $D = 1.60 \pm 0.03$. That speaks of the stochastic nature of structure evolution at the initial deformation stage;

At growth of deformation the fractal dimension grows from 1.60 $\pm 0.03$ to 1.80 $\pm 0.03$ and remains at the given level with further growth of deformation thus speaking about the self-similar process of structure evolution;
FIG. 7. Fractal dimension vs. plastic strain for iron wire (a) and molybdenum (b) cross section. Also self-similarity effect (a) and pressure effect (b).

The fractal dimension increases with deformation pressure;

The fractal dimension of structures is an important quantitative characteristic of the deformed metal and undoubtedly requires further study. It is interesting to compare the fractal dimension with the exponent of degree in the Holl-Petch law.

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