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DIGITAL IMAGING ANALYSIS OF MICROSTRUCTURES AS A TOOL TO IDENTIFY LOCAL PLASTIC DEFORMATION

DIGITALNA ANALIZA POSNETKOV MIKROSTRUKTUR KOT ORODJE ZA UGOTAVLJANJE LOKALNE PLASTIČNE DEFORMACIJE

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This paper presents a methodology to detect plastic deformation at the micro level. The analysis is based on the statistical data describing the morphological and crystallographic textures of a sample microstructure. This data was obtained from optical microscopy using a digital imaging analysis. The important parameters necessary to describe the microstructure were identified as the grain-size and grain-orientation distributions. A change in the weighted product of these two parameters, the grain size as the area of grains and the grain orientation as the moment of inertia of grains, can represent a measure to identify plastic deformation on a small area. A demonstration of its applicability was performed on a real object as part of a ruptured-pipe-failure analysis in a thermal-power-plant boiler. The presented analysis leads to a fast identification of the local plastic deformation and, in the case of periodical analysis of the same sample, it can even be used as a measure to identify creeping.

Keywords: digital imaging analysis, plastic deformation, grain orientation, local-deformation analysis

V prispevku je predstavljena metodologija za odkrivanje plastične deformacije na mikroravni. Metoda temelji na podlagi statističnih podatkov, ki opisujejo morfološke in kristalografske teksture mikrostrukture. Vir podatkov je digitalna analiza posnetkov, pridobljenih iz optične mikroskopije. Kot pomembna parametra, potrebna za opis mikrostrukture, sta opredeljena distribucija velikosti zrn in usmerjenosti zrn. Sprememba tehtanega zmnožka teh dveh parametrov: velikosti zrna kot površine zrna in usmerjenosti zrna kot vztrajnostni moment zrna, je lahko merilo za identifikacijo plastičnih deformacij na majhnem področju. Za prikaz uporabnosti metode je bila izvedena analiza na realnem objektu kot del analize poškodb počene cevi v kotlu termoelektrarne. Predstavljena analiza omogoča hitro identifikacijo lokalne plastične deformacije, pri časovno zaporedni analizi istega vzorca pa se lahko celo uporablja za identifikacijo lezenja.

Ključne besede: digitalna analiza posnetkov, plastična deformacija, orientacija kristalnega zrna, analiza lokalne deformacije

1 INTRODUCTION

The quantification of a material microstructure is important for an evaluation of a material and some of its properties. Many properties of the material are strongly influenced by the size and shape of the grains. Observations of the changes in the geometric features of the grains may be quantified by an image analysis. Microscopy is a powerful non-invasive tool for studying a material microstructure, especially if complemented with an image analysis.

The paper presents the possibilities of evaluating plastic deformation based on microstructural grain layouts. Contrary to the other researchers' work, our methodology of identifying the grain shape and evaluating their orientation is based on the moments of inertia of individual grains. When a load is applied to a material, it will cause the material to change its shape. The observed effects of the deformation process on the material's microstructure using optical microscopy[1] can be evidently seen on **Figure 1**. The changes in the microstructure can be easily described for the grain level by using three parameters: the change in the grain area, the shape (elongation) and the orientation. The new proposed methodology for evaluating these three parameters is presented in the following sections.

1.1 Digital imaging

There are many imaging techniques available for viewing a microstructure in 2D and thus useful for collecting images of each cross section. These imaging methods include the techniques like secondary electron (SE), back-scattered electron (BSE), ion-induced secondary electron (ISE) and electron back-scatter diffraction[2] (EBSD) (**Figure 2**). While each method generates an image in 2D, important issues are to be discussed with regard to some of the techniques[3].

Many laboratories are unfortunately limited to the use of the optical microscopy as an essential and the only available method for evaluating microstructures. If grain boundaries are very clearly defined, the computer programs can be written in such a way that they allow higher-dimensional measurements (the area and shape measurements) recorded on digital images, but often many grain boundaries are hard to distinguish. The

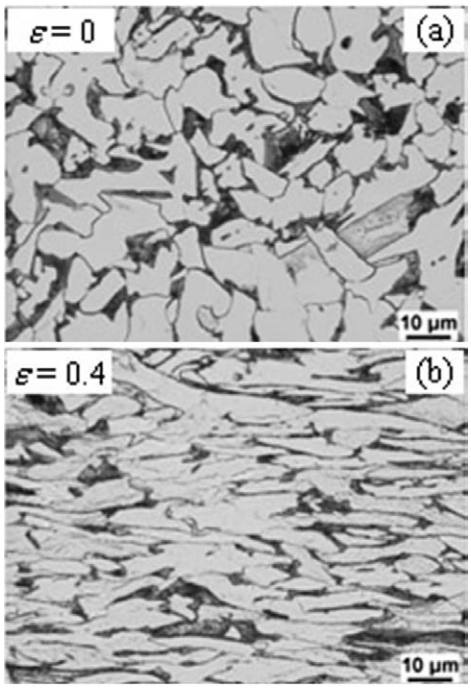

Figure 1: Microstructures of the C-Mn steel: a) the initial state; b) the microstructure after a deformation[1]
Slika 1: Mikrostruktura C-Mn-jekla: a) začetno stanje; b) mikrostruktura po deformaciji[1]

current state of the optical recognition software offers many tools to improve image resolutions, so that grain boundaries can be easily recognized.

1.2 Quantitative characterization

The quantitative characterization is an obvious tool for the researchers to use when attempting to establish a relationship between a microstructure and its properties. As a result of many studies numerous different methods and rules have been developed. In reality the application of the characterization greatly dictates the nature of the measurement technique chosen. Often the measurements are performed only in 2D using optical microscopy and digital imaging. In order to maximize the value of the data, microstructural quantification should be designed effectively. Almost an infinite number of parameters and correlations can be used to describe a microstructure, but just some of these parameters are actually important.

The measurement of the grain size is the most used method of all the techniques for quantifying the microstructural features. It is known that the grain size of a polycrystalline material is extremely important for determining its properties. Various properties exhibit a correlation with the grain size, such as: yield stress, ductility, and hardness[4]. Generally, the grain size is measured as an average scalar value, such as the intercept length, the grain area or the grain volume[5].

1.3 Grain shape and the principal-axis orientation

The shape of grains is likely to be of major significance in a number of applications, but irregular geometries of the grains in a polycrystalline microstructure make the grain shape a difficult parameter to quantify. The difficulty lies in the need for the data to express the true grain shape. Usually a number of simplifying assumptions are made.

Like the calculation of the grain size, the determination of the grain shape has been greatly aided by the EBSD maps. The boundaries of each grain can be clearly found and measured by identifying the local changes in the orientation. A problem may occur when two neighboring grains have the same orientation. The image analyzer can consider these two grains as one grain and that can lead to an error in determining the grain size and its shape. The difference between quantifying a grain shape and a grain size is related to the inability to clearly describe the shape. Determining a grain area is a relatively straightforward measurement yielding a scalar value, while a shape really needs to be described by the local curvatures, which is more complicated and requires higher-order mathematical descriptors. It is most common in everyday work to use simple objects to describe a shape, such as an ellipse. In this case, a

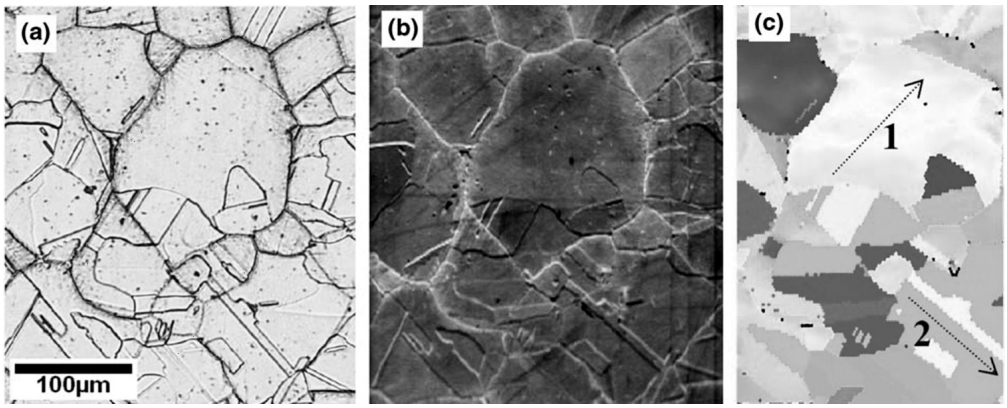

Figure 2: Analysis of the microstructure with: a) optical microscopy, b) secondary electron microscopy image, c) EBSD[3]
Slika 2: Analiza mikrostrukture: a) optična mikroskopija, b) SEM, c) EBSD[3]

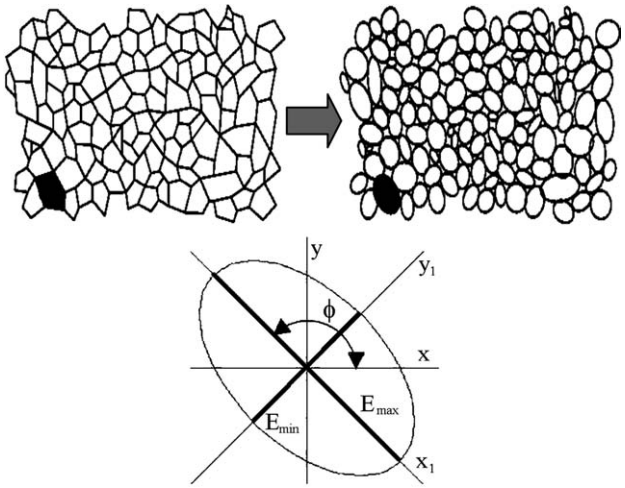

Figure 3: Schematic representation of the grains approximation with the equivalent ellipse

Slika 3: Shematski prikaz aproksimacije kristalnega zrna z njemu enakovredno elipso

quantification of the grain shape is done with the calculation of the length of an equivalent ellipse major E_{max} and minor axis E_{min}, where the area of a grain is equivalent to the area of the approximated ellipse. The ratio of the minor axis of the equivalent ellipse to its major axis represents the measure for grain roundness. The roundness is a measurement of the length – width relationship, with a value in the range from 0 to 1. A perfect round grain has a roundness of 1, while a very narrow, elongated grain has a roundness of about 0.

In addition, many shape descriptors involve combining groups of size parameters to generate dimensionless values like length/width (aspect ratio), area/convex area (solidity) and length/fiber length (curl)[6], which can sometimes be ambiguous. Some scalar parameters, such as the moments of inertia, can do an adequate, or a better, job of expressing the grain shape and orientation.

The principal-axes orientation quantifies the orientation of the grains' principal axes relative to the global coordinate system of the cross section. It is important to distinguish between the principal-axes orientation, which is the orientation referring to the principal axes and the crystal-lattice (crystallographic) orientation, which is usually determined with EBSD. In the case of an ellipse, the orientation is presented as angle ϕ measured counterclockwise from the horizontal axis x to the axis of lowest moment of inertia x_1, as shown on **Figure 3**.

2 METHODOLOGY

Generally, the microstructure images suffer from the defects of improper illumination, artifacts and noise that are developed at the time of the sample preparation. The first stage is important for attaining higher grain-segmentation accuracy. An RGB microstructure image was processed using the tools of digital imaging with the final goal to achieve an image without any noise, showing a set of individual grains and excluding the border grains. This is also the most important step for analyzing the differentiation between individual grains in the microstructure. If the grains are not clearly distinguished then the next steps of the methodology are purposeless. An application called the Particle Analysis, or the Blob Analysis, in the National Instruments IMAQ Vision software was used for digital imaging and calculating. The blob analysis is the process of detecting and analyzing distinct two-dimensional shapes within a region of the image. It can provide information about the number of grains, location, shape, area, perimeter, and the orientation of grains.

One of main results provided by the analyzing software is the moment of inertia, or the second moment of area, which is a property of a cross section and can be used to predict the resistance of the cross-section areas to the bending and deflection around an axis lying in the cross-sectional plane. The moments of inertia for any cross section defined as a simple polygon on the $x - y$ plane can be computed in a generic way by summing the contributions from each segment of the polygon. The equations marked as 1, 2 and 3 can be used to calculate the moments of inertia, where the parameters x_i and y_i represent the distance from the origin to the elementary triangle center point and a_i represents the area of this triangle.

$$I_x = \frac{1}{12}\sum_{i=1}^{n-1}\left(y_i^2 + y_i y_{i+1} + y_{i+1}^2\right)a_i \tag{1}$$

$$I_y = \frac{1}{12}\sum_{i=1}^{n-1}\left(x_i^2 + x_i x_{i+1} + x_{i+1}^2\right)a_i \tag{2}$$

$$I_{xy} = \frac{1}{24}\sum_{i=1}^{n-1}\left(x_i y_{i+1} + 2x_i y_i + 2x_{i+1} y_{i+1} + x_{i+1} y_i\right)a_i \tag{3}$$

From these values that represent the moment of inertia for the $x - y$ axis, the moments of inertia for the principal axis $x_1 - y_1$ can be calculated (for the axis presentation see **Figure 3**).

$$I_{x1,y1} = \frac{I_x + I_y}{2} \pm \sqrt{\left(\frac{I_x - I_y}{2}\right)^2 + I_{xy}^2} \tag{4}$$

In this case I_{x1} represents the minimum eigenvalue of the moment of inertia, while I_{y1} is the maximum value. The roundness of a grain can then be calculated using the ratio of these two values and it ranges from 0 (an extremely elongated grain) to 1 (a round grain).

$$R = \frac{I_{x1}}{I_{y1}} \tag{5}$$

The angle of the rotation of the coordinate system around the grain center of mass ϕ can be calculated using Eq. 6. It is used as a parameter to quantify the orientation of an individual grain. A correction of angle ϕ is needed to transform the angle range from 0–180° to

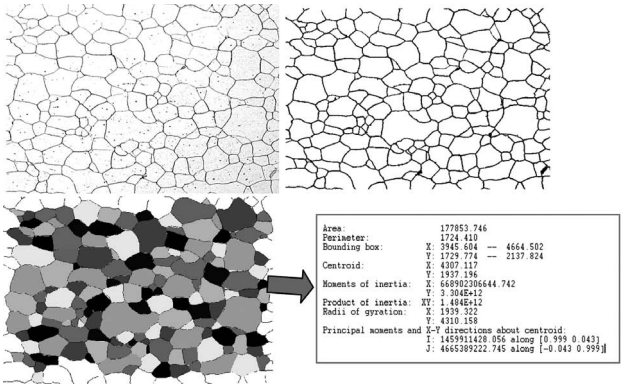

Figure 4: Schematic representation of the steps of digital imaging and the calculated result for one grain

Slika 4: Shematski prikaz faz digitalne obdelave posnetkov in rezultat izračuna za eno kristalno zrno

0–90° (e.g., the grain orientation for the angle of 1° is almost equal to the one for the angle of 179°).

$$\phi = \frac{1}{2}\operatorname{atan}\frac{2I_{xy}}{I_x - I_y} \tag{6}$$

3 EXPERIMENTAL RESULTS AND DISCUSSION

For the experimentation we have used many microstructure images of low-carbon and austenitic stainless steel at various resolutions (i.e., magnifications) and with different grain shapes. These images were obtained with optical microscopy. An example of a microstructure image (500-times) of the austenitic stainless steel and the steps of digital imaging are shown in **Figure 4**.

On the left-hand side of **Figure 5** the results for the examined sample from Figure 4 are shown. From the graph it can be concluded that the roundness of the grains in the microstructure is around 0.46 and that the median of the grain-orientation angle is approximately 15°, while the average value is 21°. In short, it can be said, that the grains are elongated in the direction close to the horizontal axis.

The results presented on the right-hand side of **Figure 5** show a comparison between the roundness calculated by using the ratio of the equivalent-ellipse axis and the roundness calculated by using the ratio of the moment of inertia for the principal axis. It is observed that the latter is much more sensitive to the grain shape then the former. The range of the calculated results is also much wider, which is a more authentic description of the real state.

4 CASE STUDY

For the practical demonstration, two samples taken from the ruptured steam pipe, marked as No. 2 and No. 4 (200-times), were analyzed using the above-described methodology. The average value of the roundness calculated by using Eq. 5 for sample No. 4 is 0.4, while it is 0.36 for sample No. 2. As it can be seen from **Figure 6**, the grains are more elongated in the case of sample No. 4 than in the other case. A similar difference can also be found when observing the grain-orientation angles. The grain-orientation angle distribution for sample No. 4 is

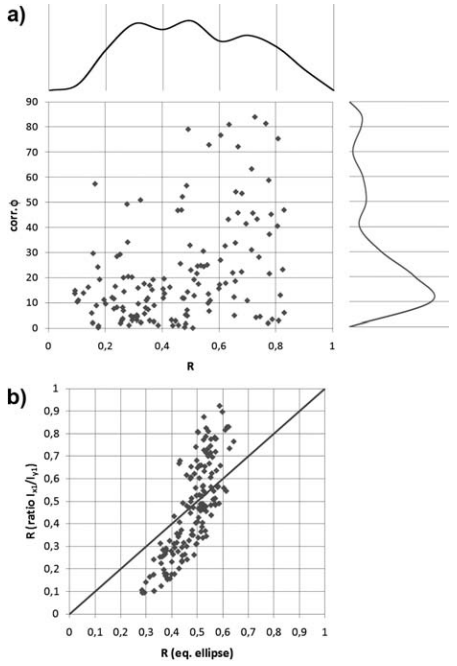

Figure 5: a) Correlation between the roundness and the orientation angle ϕ and b) the correlation between different calculations of the roundness

Slika 5: a) Korelacija med okroglostjo in kotom usmerjenosti ϕ in b) korelacija med različnima metodama izračuna okroglosti

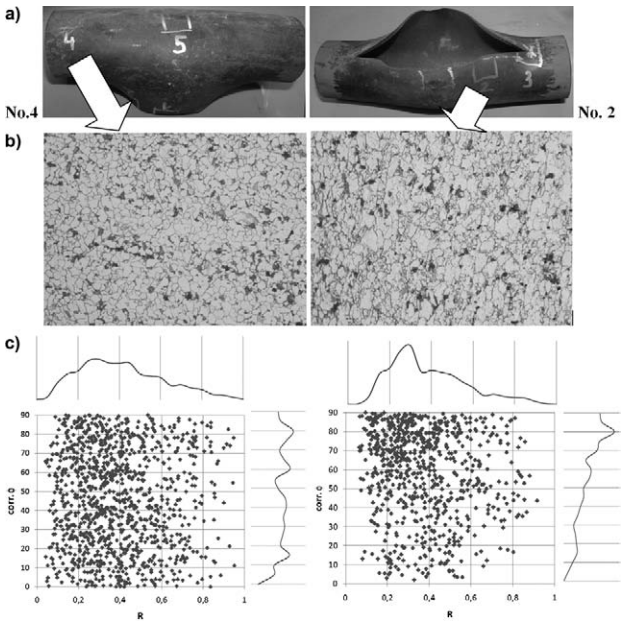

Figure 6: a) Positions of samples No. 4 (left) and 2 (right) of the ruptured steam pipe, b) the corresponding microstructures and c) the results of the analysis

Slika 6: a) Položaj vzorcev št. 4 (levo) in 2 (desno) na počeni cevi parnega kotla, b) pripadajoči mikrostrukturi ter c) rezultati analize

almost flat and its median is 45°, which means that these grains have no orientation tendency. In the second case the median of the grain-orientation angle is 64°, while the average value is 59°. This can also be observed from the grains in the microstructure on the right-hand side of **Figure 6**.

5 CONCLUSIONS

In this paper, a semi-automatic, digital, microstructure-image-analysis system for quantifying a microstructure is developed. As an input in the analysis process, the image obtained with optical microscopy was used. In the calculation part of the investigation, the moment of inertia was introduced as the major parameter to quantify the grain shape and the orientation. The results obtained with the above method are reproducible and repeatable, but can be misleading if the differentiation between individual grains in the microstructure is not clear. We can demonstrate the accuracy and usefulness of this method by comparing the computed values with the results of the other methods. The presented case study of the sample of a ruptured steam pipe demonstrates its usefulness for the laboratory and industrial applications in the field of material investigations.

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