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DIGITAL IMAGE ANALYSIS OF VOIDS FORMED DURING THE DEFORMATION OF STEEL SAMPLES WITH SEMI-SOLID CORE

CYFROWA ANALIZA OBRAZU DEFEKTU W POSTACI PUSTEK POWSTAŁYCH PODCZAS ODKSZTAŁCANIA PROBEK STALOWYCH Z PÓŁCIEKŁYM RDZENIEM

A b s t r a c t

In this paper the digital image analysis of voids formed during the deformation of steel samples in the GLEEBLEE 3800 physical simulator device with the semi-solid core. The presented and characterized indicators describe the shape of voids, and their relative position as qualifiers quality indicators as well as the correlation between the indicators and possible defects in the material. The paper contains the results and discussion of presented analysis.

Keywords: digital image analysis, voids, defects, semi zone.

S t r e s z c z e n i e

W artykule przedstawiono analizę obrazu pustek powstałych podczas odkształcania próbek stalowych z półciekłym rdzeniem na urządzeniu GLEEBLEE 3800. Przedstawiono oraz scharakteryzowano wskaźniki opisujące kształt pustek, oraz ich wzajemne położenie jako kwalifikatory jakości próbek. Przestawiono także korelację pomiędzy wartościami wskaźników opisowych pustek a możliwymi defektami w materiale. Praca zawiera wyniki oraz omówienie przeprowadzonej analizy.

Słowa kluczowe: cyfrowa analiza obrazu, pustki, defekty, strefa półciekła.

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1. Introduction

Measurement of properties of material structures and the quality control constructions takes in the recent years considerable attention. This is partly caused by the development of new stereological methods and benefits coming from automatic image analysis. Quantitative measurement of the microstructure has also great significance in both research and quality control as well as by determination of material properties. Optical microscopy combined with digital image recording and specialized software dedicated to automatic image analysis becomes a productive tool, which allows to acquire information within a short time. Thus, science offers increasingly better tools for structural analysis of materials and detection of resulting manufacturing defects. Presented analysis was performed on digital images formed during the deformation samples with semi-solid core on the physical simulator GLEEBLEE 3800 on the Institute for Ferrous Metallurgy in Gliwice. Although deformation process of the steel in semi-solid core state as well as continuous casting is a process that has been already a subject of series of studies, there are still problems with quality of continuously casted intermediate products. It is particularly important in case of alloyed steels casting when the steel is subjected to further processing in integrated processes of plates casting and rolling. Occurring in this respect risk of cracks can be minimized by appropriate selection of a favourable state of stress – which is not always possible – and by suitable, fine-grained microstructure of the as-cast steel. As indicated in [1] even for carbon steels the microstructure formation mechanism depends on steel chemical composition – mainly on the carbon content. Therefore, an important issue is to accomplish an appropriate quantitative analysis of substantial number of microstructure [2]. The final product (f.e cast ingots) purity strongly depends on the liquid steel flow conditions, especially in the tundish and mould. Very important are also such parameters like character and rate of heat generation in crystallizer. Both of them significantly influence segmentation and microstructure evolution, as well as stress field, material mechanical properties and defects of the ingot after solidification process. Coincidence of unfavourable stress distribution and coarse columnar crystal structure leads to cracks and shape defects of the cast strip. Therefore, it is important to develop appropriate models of solidification process and formation of internal stress. In this aspect, the computer aided analysis of material structures becomes particularly important. It can contribute to significant acceleration of research by eliminating the human factor. Moreover, the applied methods of classification based on artificial intelligence [2] allow to reduce the study effort.

The paper presents an attempt of application of digital image processing to analysis of the occurrence and distribution of voids caused by solidification process in samples which demonstrate semi-solid core. The investigation is an introduction to the analysis of a semi-solid zones in the as-cast strips, and thus may become a source of boundary conditions for the models being the basis of computer simulation of semi-solid plates. The presented results were formed with the help of an authorial, presented in [2] software dedicated to qualitative and quantitative image analysis.

2. Methodology

From the sake of occurrence and distribution of voids the analysis of as-cast steels structure is an important issue. It is a complex problem that employs both digital image processing and application of auto-expert systems and statistical methods. The schema of entire process is shown in Figure 1.

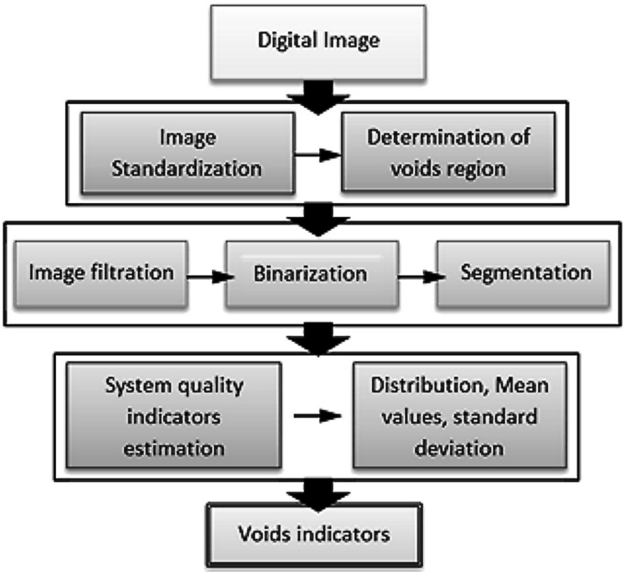

Fig. 1. The general scheme of the voids estimation and image analysis process

Rys. 1. Główny schemat procesu wyodrębnienia i analizy obrazu pustek

At the initial step the digital image is converted into a form which is most useful for further segmentation. Image scale adjustment is also taken into consideration in aim to correct even minor differences in size of analysed regions. The standardization transformations have strong impact on the final results and hence on the effectiveness of the presented solutions. The next operation is done in aim to obtain the voids occurrence polygonal region (area that includes voids). Both the operations, i.e. standardization and voids region estimation create the image preparation stage of the analysis process [2].

The subsequent and most important chain of operations is the image digital filtration consisted of three sequential operations: image filtration, binarization and segmentation. Because the presented process was performed automatically for each digital image, input parameters values of employed methods strongly depend on source images. The main goal of image filtration is both voids boundaries enhancement and minimization of the image total noise level which allows the distinction of small fragments of the image. It might have real influence on achievement of real final result [5]. The image filtration is consisted with several transformations like: removal the non-flat background illumination, contrast enhancement and median filtration in order to remove image artefacts and false voids. The sequent operation is called binarization. The essence of this transformation is the extracting of voids from the image and rejecting its rest as useless for further analysis. The Otsu auto binarization method is employed to calculate the correct threshold level. The method provides the best results in comparison to the other approaches (minimum histogram variance, entropy, *k*-means). In addition the ultimate erosion points are estimated and serve as reference points for the system of quantity indicators. The final image filtration method is called segmentation. This operation divides image into the list of subgroups, i.e. list of voids groups. The conjunction of the entire image filtration methods have the strongest impact on finial results of the analysis [6].

The list of voids images serves as an input data to the next phase of analysis called segments descriptors estimation. At this stage a segments descriptors shape estimation is executed for each individual void. Its results are parameters representing shapes of individual segments and theirs mutual correlation. To evaluate the quality of samples with semi solid core the authors have taken into consideration following parameters that were used to calculate the system quality indicators:

A. The average void equivalent diameter and diameter standard deviation:

$$D_{eq} = \sqrt{4\pi / Area};\ \overline{D_{eq}} = \frac{1}{N}\sum_{i=1}^{N} D_{eq}^{i} \tag{1}$$

B. Standard deviation of voids orientation:

$$\sigma_\alpha = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(\overline{\alpha} - \alpha_i)}; \quad \text{where} \quad \alpha = \tan^{-1}\frac{K + \sqrt{K^2 + 4M_{xy}^2}}{2M_{xy}} \tag{2}$$

C. The number of voids per unit length:

$$N_L = \sqrt{\left(\frac{N_{OX}}{L_X}\right)^2 + \left(\frac{N_{OY}}{L_Y}\right)} \tag{3}$$

D. The average distance between voids (calculated in specific distance from centre):

$$L_i^O = \frac{1}{N_R}\sum_{i=0}^{R} L_i \tag{4}$$

E. The volume fraction level of voids:

$$V_V = \frac{V_{\text{voids}}}{V_{\text{region}}} \tag{5}$$

Where symbols in equations (1) to (6) denote:

- M_{ij} – moment invariants calculated in ij directions,
- N – the number of voids,
- N_R – the number of grains located inside the circle of radius R,
- N_{OX} – the number of voids located over a segment of length L_X in X direction,

V_{voids} – the volume occupied by voids,
V_{region} – the volume of analysed region.

Each individual parameter indicates the most common value and the range of occurrence. The average void equivalent diameter represents the most common void size and the standard deviation represents the range of occurrence of various sizes. In addition at the description estimation stage the histogram of occurrences is calculated. It serves as a supplementary information parameter concerning the voids distribution. The parameter histograms can be a source of second step of voids segmentation leading to the shape factor, but the authors did not take this issue into consideration, because in the presented case it has not been required. Voids orientation coefficient and theirs standard deviations as well as the distribution histogram indicate the privileged orientation of voids – both global and local. It also shows the potential directions of defects formation in casted steels. The number of voids per unit length together with average voids equivalent diameters show how specific voids sizes form local clusters. If the local cluster is situated near the material surface the risk of material cracking significantly increases. The parameter describing the distance between voids (calculated in the specific distance, relative to each void centre) with assistance of its histogram and variation parameter show the tendency to form a single local cluster of voids. The distance between voids is calculated on basis of reference points acquired at the ultimate erosion image filtration stage. The last parameter being under consideration of the current study is called voids volume fraction level. This value is scaled to aim image magnification and voids occurrences region and plays role of standard volume invariant. Volume fraction of voids represents the ratio of voids volume to total region volume and describes the state of volumetric defects of a sample after solidification process. The fallowing indicators were used to estimate system quality (tested sample quality): formability of local clusters, cluster type, privileged voids orientation, volumetric defects state. Methods of determining above indicators as well as theirs values are shown in Tables 1–4.

Table 1

Formability of local voids cluster indicator

$\overline{D}_{eq}$ [mm]	L_i^O [mm]	Formability of local clusters
Low	Low	Medium or High
Low	High	None or Low
High	Low	Very High
High	High	Medium

Table 2

Cluster types indicator

$\overline{D}_{eq}$ [mm]	N_L [mm^{-1}]	Cluster type
Low	Low	Local cluster with small sizes voids
Low	High	No cluster or local cluster with scattered voids
High	Low	Local cluster, potential location of material failure
High	High	No cluster

Table 3

Indicator describing privileged voids orientation occurrence

σ_α [°]	Privileged voids orientation occurrence
Low	High
Medium	Medium
High	Low

Table 4

Indicator of the volume state of defects in the form of voids

V_V [%]	Volumetric defects state
Low (< 0.2%)	Insignificant
Medium (0.2%–1.0%)	Possible sample
High (> 1.0%)	Faulty sample

3. Results

Figure 2 shows the pre-processed image of longitudinal cross section of a sample, which was previously used in the study of strain-stress relationship at very high temperature. The mechanical properties of semi-solid steel were investigated using physical GLEEBLE 3800 simulator in the Institute for Ferrous Metallurgy in Gliwice Poland.

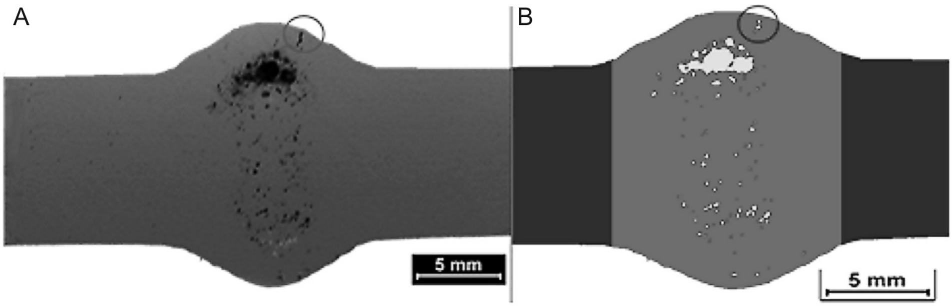

Fig. 2. A non-etched sample deformed at 1460°C using GLEEBLE 3800 physical simulator with marked surface crack: A – original, B – voids region marked (the red colour highlights the analysed area, the light blue colour emphasizes unclosed voids)

Rys. 2. Obraz próbki nietrawionej otrzymanej na symulatorze fizycznym GLEEBLE 3800 w temperaturze 1460°C z zaznaczonym powierzchniowym pęknięciem: A – obraz wyjściowy, B – obszar z uwidocznionymi pustkami (kolor niebieski – oznaczone niezamknięte pustki, kolor czerwony – osnowa – metal

The presented in figure 2 shape of the sample central part is a result of its deformation in final stage of solidification process [3, 4]. The quantitative analysis were performed to estimate parameters used in the system quality indicators based on equations (1) to (5) as shown in table 5. In the figure 2 two separated voids clusters are seen. The largest and occupying the most space cluster is located near the material surface and could emerge in case of high compressive force during the testing in the GLEEBLE equipment. Moreover, the figure demonstrates the specific privileged orientations. The second cluster with significantly lower average equivalent diameters and greater value of average distance coefficient is located below the centre of the tested sample. In addition the surface perforation crack (marked with blue circle on images A and B) can be identified and with high probability will cause material failure at this region during further sample deformation. Assessment of visualized morphology of voids and sparse regions allow better analysis of the material properties and its resistance to cracking. The exemplary result of the analysis is collected in Table 5 and Table 6.

Table 5

The values of quality indicators taken for the digital analysis of the image shown in Figure 2

$\overline{D}_{eq}$ [mm]	α [°]	N_L [mm^{-1}]	L_i^O [mm]	V_V [*100%]
0.24	8.6	0.19	1.08	1.2

Table 6

The results of the analysis of the deformed sample included into a of quality indicators

Clusters Formability	Cluster type	Occurrence of privileged orientation	Volumetric defects state
High	Local cluster, potential location of material failure	Low	Faulty sample

Quality indicators analysis of the steel sample presented in this paper with semi-solid core after deformation process shows that there is high cluster formability indicator and the local clusters are constructed with large voids. This type of cluster may cause material damage during further deformation and forming parameters of the steel sample process should be considered risks subjected and chanced. The privileged orientation is not found in the tested sample.

4. Conclusions

The voids analysis method presented in this paper provides good descriptive characteristics of sample defects state as well as gives expert-system-like results. The applied indicators are computed very quick in fully automated process from input image to the received results. The most critical operations in chain of subsequent transformations are both standardization and segmentation. Theses transformations have strong impact on the recognition results and hence on the effectiveness of the presented analysis. It is necessary to focus in the nearest future to perform method optimization and selection of the segmentation methods that not only detect local defect clusters but also estimate the most critical and favourable locations of defect formation. This paper presents the results from the prototype application of digital image processing to analysis of the occurrence and distribution of voids caused by solidification process in samples which demonstrate semi-solid core.

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