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ESTIMATION OF MATERIALS MICROSTRUCTURE PARAMETERS USING COMPUTER PROGRAM SigmaScan Pro

List of symbols:

S – area of the object
L – perimeter of the object
$l_{\max}$ – maximal overall dimensions of the object (distance between the most distant points of the object)
$l_{\min}$ – minimal overall dimensions of the object (perpendicular line to $l_{\max}$ and such that the rectangle achieved comprises the object)
L_h – maximal diameter of the object horizontally
L_V – maximal diameter of the object vertically
r_{min} – minimal distance of the contour from the center of mass of the object
R_{max} – maximal distance of the contour from the center of mass of the object
r_i – distance of the object pixel from the center of mass of the object
l_i – minimal distance of the pixel from the object contour
d_i – distance of pixels from the center of mass
n – amount of pixels of the contour
i – pixels number of the object

1. INTRODUCTION

Image analysis consists generally in morphological, geometrical and arithmetical transformations of the image to make it measurable in a specified way, and then consists in measurement of values of our interest. Opportunities for transformations of the image and for measurements depend on software applied.

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There is a plenty of very good and advanced image analysis software. One of such programs is SigmaScan Pro (SPSS Science^{TM}) [1] that can be used for analysis in scope of quantitative metallography. The characteristic of SigmaScan Pro program as well as the assessment of its potential regarding measurements of microstructure of metals and alloys have been already presented by the authors in previous works [2–4] and also in other publication [5].

The results of subsequent tests within the range of application of SigmaScan Pro to measure a single phase granular microstructure, a dispersed microstructure and microstructures of complex morphology formed during the cementite spheroidization process in pearlite are presented in this paper.

2. SINGLE PHASE MICROSTRUCTURE

The measurement possibilities of SigmaScan Pro regarding a single phase microstructure will be presented on the example of size and homogeneity of an austenite grain assessment for 40Cr7 steel (0.4% C, 1.8% Cr, 0.08% V, 0.06% Al and 0.036% N). Specimens of steel were heated at 900°C and 1200°C for 40 min. and quenched in water. Examples of microstructures of steel with revealed grain boundaries of austenite existing at austenitising temperatures are shown in Figure 1.

a) b)

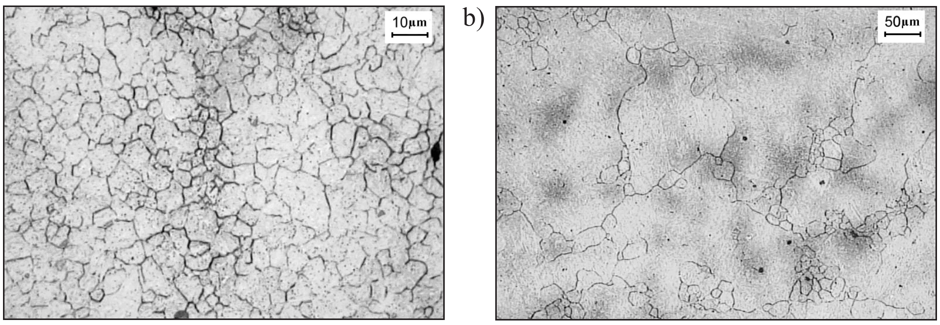


***Fig. 1.** Microstructure of 40Cr7 steel with revealed austenite grain boundaries after austenitising at the temperatures: a) 900°C; b) 1200°C*

At the austenitising temperature 900°C the austenite grains are small and uniform (Fig. 1a) whilst at 1200°C an abnormal grains growth occurred (Fig. 1b).

The image preparation for measurement (intensity calibration, distance calibration etc.) has been presented in details by Staśko and Adrian [6]. For each variant regarding an austenitising temperature the grain chords length has been measured using a semi-automatic method [3, 6]. Quantitative analysis of the microstructure were carried out to determine: the mean grain chords length $\bar{l}$, the standard deviation of chords length $s(l)$, and the heterogeneity coefficient ν defined as the ratio $s(l)/\bar{l}$. The results of the analysis of obtained date are presented in Table 1.

Table 1. Results of statistical analysis of austenite grains chords length (*n*-number of grains measured)

T, °C	n	$\bar{l}$, μm	$s(l)$, μm	ν
900	645	5.64	3.31	0.59
1200	846	30.86	41.24	1.34

Presented data show high value of heterogeneity coefficient, for austenite chords lengths at 1200°C (ν = 1.34), in comparison with 900°C (ν = 0.59). Cumulative curves for chord lengths and linear fraction of L_L of chord lengths were calculated. Results of analysis are presented in Figure 2.

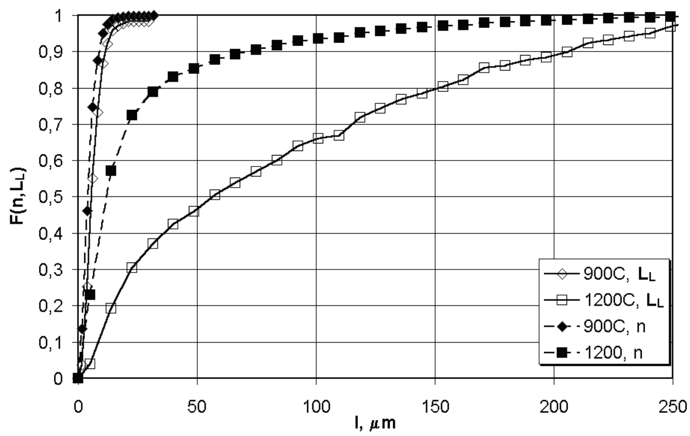


Fig. 2. *Cumulative curves for chords lengths and linear fractions chord lengths of austenite grains at temperatures of 900 and 1200°C*

It is worthy emphasizing significant difference in cumulative curves for chords length l, and linear fraction of L_L. In case when austenite grains size is uniform, (T = 900°C) there is practically no difference between both curves. When austenite grains size is nonuniform (T = 1200°C) both curves are quite different. Cumulative curve for L_L is more practical, because on the base of this curve there is available information what fraction of grains is for specific size. For example in specimen heated at 1200°C number of austenite grains with chord lengths, l > 100 μm is 8%, whilst their fraction is 35%.

3. DISPERSED MICROSTRUCTURE

The investigations have been carried out for Fe-0,67% C carbon steel. A dispersed microstructure achieved by the cementite coarsening (the annealing at 700°C / 150 h) has been assessed quantitatively (Fig. 3). The preparation of image for measurements (intensity calibration, distance calibration, morphologic transformations etc.) was according to the previously presented way [4]. In case of particle distribution construction, special attention should be given to particle sections cut through the edge of a particle image. In order to assure a correctness of the measurement a „protective frame" technique has been used. Position of each object of the image (of section of a particle) is defined by its center of mass; only the objects for which the center of mass is inside the "protective frame" are taken for measurement [7].

Generally, n = 1215 measurements of diameters of particles sections have been executed (Fig. 4). Test of goodness of fit (χ^2 Pearson test) was performed in order to compare empirical and theoretical distributions (using Statgraphics 5.1). It was stated that diameters of cementite particles sections are subject to the Weibull distribution (significance level α = 0,05; p-value = 0.415).

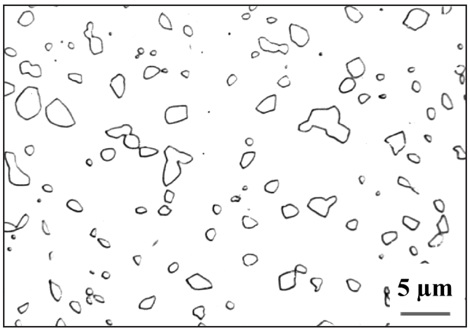


Fig. 3. *Dispersed microstructure, Fe-0.67%C steel*

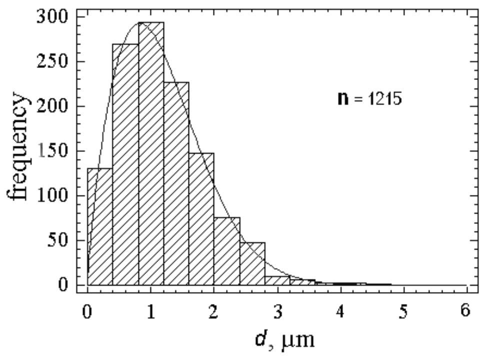


Fig. 4. *Histogram of particles sections diameters approximated with Weibull distribution*

4. MICROSTRUCTURES ACCOMPANYING SPHEROIDIZATION OF CEMENTITE IN PEARLITE

Characteristic of image objects regarding shape

Describing a microstructure it is often necessary to consider also the shape of objects. To describe the shape quantitatively shape factors can be used. To determine them we apply results of direct measurements of the image (area, perimeter, center of mass coordinates etc.).

The rules of construction of shape factors are very diversified. Ones refer a real object shape to a certain standard (e.g. to a circle), others have quite empiric character [7, 8]. However, apart from the construction method, the shape factors should be independent on change of the object position, its orientation and size. Various factors fulfill those expectations in a different level. Information about shape contained in one number which is a determined shape factor – regarding to real state – has always synthetic and reduced character. Nevertheless, such a method of shape description is very useful in practice, as it enables identification of the object class determined in advance, determination of a similarity of unidentified object for particular identified classes, description of shape object changes resulting from processes proceeded (e.g. spheroidization) etc. [8].

SigmaScan Pro program offers three parameters destined to describe a shape, as follows:

– Shape factor, calculates how circular an object is. A perfect circle has a shape factor of 1, and a line has a shape factor approaching 0,

$$Shape\ Factor = \frac{4\pi S}{L^2} \quad (1)$$

– Compactness factor; in case of a circle it is 4π, it can be a good elongation measure,

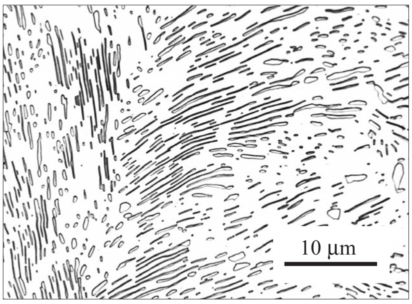
$$Compactness = \frac{L^2}{S} \quad (2)$$

– Feret diameter, calculates the diameter of a fictitious circular object that has the same area as the object being measured, it depends on a size of the object,

$$Feret\ Diameter = \sqrt{\frac{4S}{\pi}} \quad (3)$$

Three factors mentioned above have been used for the quantitative description of microstructures achieved from spheroidizing annealing of the Fe-0,7% C alloy during 50 and 800 hours (Fig. 5).

a)



b)

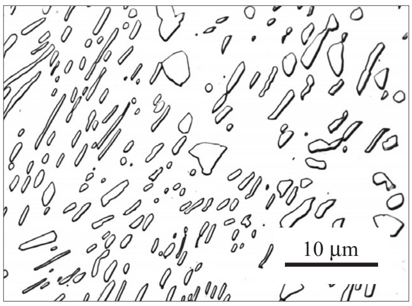


Fig. 5. *Microstructures of steels annealed at temperature 700°C during: a) 50 hours; b) 800 hours*

The list of the shape factors most often applied in image analysis is presented in Table 2.

As result of cementite spheroidization in pearlite of eutectoid steel some very complex microstructures come into being (Fig. 5). Besides the areas where spheroidization took place, there are also others observed in which are well kept plates or all colonies of lamellar pearlite. There was the attempt of quantitative description of such a microstructure type with the help of shape factors.

Table 2. List of selected shape factors [7, 8]

Factor	Formula	Remarks/comment
Feret Factor	$R_F = \frac{L_h}{L_V}$	It assumes a small value for elongated objects, is characterized by a large variability. It is easy to calculate, but susceptible to a change of scale
Malinowska Factor	$R_M = \frac{L}{2\sqrt{\pi S}} - 1$	It is characterized by a medium range of values, its values are larger for objects of elongated shape. It does not show a big influence on a scale changes and a figure turn
Circulation Factor (1) (in SigmaScan Pro it corresponds to a parameter of Feret Diameter)	$R_{C1} = \sqrt{\frac{4S}{\pi}}$	It calculates the diameter of a fictitious circular object that has the same area as the object being measured. It depends strongly on the object size; it does not differentiate shapes of the objects. **(accessible in SigmaScan Pro)**
Circulation Factor	$R_{C2} = \frac{L}{\pi}$	It determines a diameter of the circle with a perimeter equal to the perimeter of the object analyzed; it depends strongly on the object size; it does not differentiate shapes of the objects
Compactness Factor	$Compactness = \frac{L^2}{S}$	Its values are larger for objects of elongated shape (for a circle =4π). **(accessible in SigmaScan Pro)**
Shape Factors	$Shape\ Factor = \frac{4\pi S}{L^2}$	For a circle =1, for a line =0. **(accessible in SigmaScan Pro)**
Lp_1	$Lp_1 = \frac{r\min}{R\max}$	It reflects well circulation of the object; for a circle it is one
Lp_2	$Lp_2 = \frac{l_{\max}}{L}$	For figures with a very "jerked" edge the factor will be of a low value; for regular figures it reflects well an elongation of the object
Lp_3	$Lp_3 = \frac{l_{\max}}{l_{\min}}$	For regular figures it reflects well an elongation of the object
Blair-Bliss Factor	$R_B = \frac{S}{\sqrt{2\pi\sum_i r_i^2}}$	It does not show changes by the change of scale and the turn of the object examined
Danielsson Factor	$R_D = \frac{S^3}{\left(\sum_i l_i\right)^2}$	It is characterized by a large range of variability; it is neither too resistant to a scale change nor the object turn; time for the factor calculation is tens times longer than in case of other factors
Haralick Factor	$R_H = \sqrt{\frac{\left(\sum_i d_i\right)^2}{n\sum_i d_i^2 - 1}}$	It is characterized by a very low variability range; it is not being deformed either through a shape change or an object turn

Preparation of the image for measurement was according to the previously presented way [4]. As the aim of the analysis is not a distribution of particle sizes, it was unnecessary to use procedure of the „protective frame" (like in the case of a dispersed structure). It was sufficient to apply a procedure of deleting edge objects, i.e. only those particles are taken into account that are fully included in the image. Accessible in SigmaScan shape factors of the analyzed microstructure have been determined. The values of those factors and their distributions (Tab. 3, Fig. 6) depend on a degree of progress of the spheroidization process.

Table 3. Changes of average values of shape factors together with spheroidizing annealing time

Annealing time, h	Shape Factor (1)	Compactness (2)	Feret Diameter (3) μm
50	0.47	49.58	0.46
800	0.57	27.16	0.87

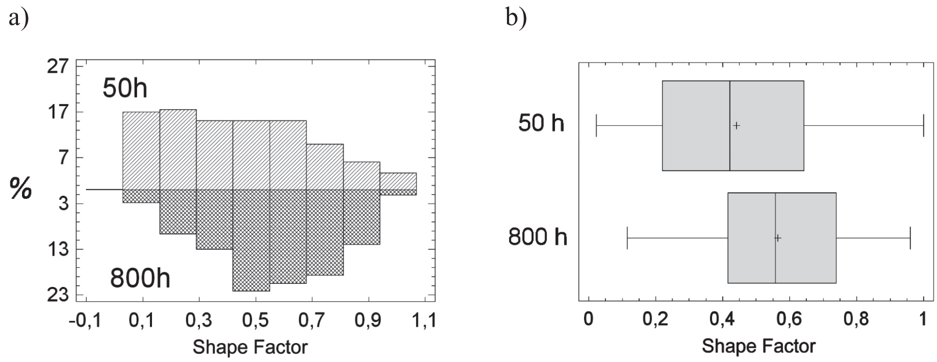


Fig. 6. *Comparison of Shape Factor distributions of the microstructure after 50 and 800 hours of annealing: a) histograms; b) Box and Whisker plots*

5. SUMMARY

The analysis made in this and previous works [2–4] is the proof for rich measurement possibilities of SigmaScan Pro relating to microstructures of metals and alloys. The set of tools offered by the program for preparation of the image for measurement, built-in calculation sheet, friendly interface, acceptable equipment requirements etc. enables a number of application in range of quantitative microstructure analysis.

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