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QUANTIFICATION OF MICROSTRUCTURE AND EVALUATION OF MECHANICAL PROPERTIES IN NON-ORIENTED ELECTRICAL STEELS

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This paper presents an original method of the estimation of average grain size in microstructure of broad grain size distribution and the parameter, describing the homogeneity of microstructure. The coefficient of microstructure homogeneity is defined. The mechanical properties of non-oriented electrical steels are predicted using new equation of grain size estimation.

Key words: *average grain size, coefficient of homogeneity*

Kvantifikacija mikrostrukture i vrednovanje mehaničkih svojstava u neorijentiranim elektro čelicima. Ovaj rad predstavlja originalnu metodu utvrđivanja prosječne veličine zrna u mikrostrukturi prosječne veličine zrna i parametra te strukture opisivanjem njene homogenosti. Definiran je koeficijent homogenosti takve mikrostrukture. Mehanička svojstva neorijentiranih elektro čelika su predviđena novom jednadžbom za utvrđivanje veličine zrna.

Ključne riječi: *prosječna veličina zrna, koeficijent homogenosti*

INTRODUCTION

The quantification of material's microstructure is important forthe description of some material's properties [1, 2]. The size of grains in metallic microstructure strongly influences many of the properties of the material. Size and size distribution, therefore, type as the most important parameters in describing the microstructure of materials.

A new requirement to non-oriented electrical steels is a combination of mechanical and magnetic properties. Regarding this demand different types of inhomogeneous (non-isotropic) microstructure were developed to the problem solution. In the case of microstructure with broad grain size distribution, a problem of average grain size arises. The evaluation methods described in technical norms [3-6] are inapplicable for inhomogeneous microstructure.

The paper [7] presents the possibilities of evolution of quantification concerned with microstructural grain layouts in case of inhomogeneous grain size distribution. Statistical parameters are used for the description of a layout. Papers [8] and [9] present quantification of grain size in ferrite and austenite region respectively. However, only grain size for homogeneous microstructure was evaluated.

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R. T. DeHoff and others evaluated the grain size from the point of grain topology. It is shown that the topological complexity of a grain in polycrystal is related to its diameter, as opposed to its area and volume [10-12].

F. N. Rhines evaluated the grain size by so-called "global parameters": length of line, area of surface, volume fraction, curvature of line and surface, etc. The topological parameters provide us information that how many pieces each feature of the structure is divided and in how many places these pieces are connected. These properties are dimensionless and depend in no way upon the scale of the microstructure [13].

For the most general case of irregular grains of varying shape it is completely impossible to establish the true spatial distribution from planar or thin-section measurements. G. Bocksteigel [14] solves this problem by assumption of spherical geometry for irregular grains. This model based on the calculation of so-called "equivalent sphere-size distribution". However, the equivalent sphere-size distribution does not coincide with the true distribution at all points and, therefore it is of limited applicability.

All the methods proposed for the evaluating of the true spatial size distribution are restricted in some way. None of the above-mentioned methods is sufficiently representative and provides information about the value of average grain size in the case of microstructure with broad

grain size distribution. The average grain size can not be calculated by the above methods, because from the physical view this value will be incorrect. Because in the case of broad distribution (from 5 to 200 μm), the parameters of small grains shift to lesser values. As a result, an average value of grain size will be estimated incorrectly.

This paper presents the methods for the estimation of the homogeneity of microstructure and average grain size of microstructure with broad grain size distribution by means of computer analyses. The microstructure of specimens was observed using an optical microscopy. DIPS-5 software was used to estimate average grain size.

MICROSTRUCTURE HOMOGENEITY

At first, it is important to characterize the type of microstructure from the view point of homogeneity. Within non-oriented electrical steels the following types of microstructure can be defined:

I. Homogeneous microstructure:
   a) equiaxed microstructure (Figure 1.D);
   b) non-equiaxed microstructure (Figure 1.C).

II. Inhomogeneous microstructure:
   a) equiaxed microstructure of broad grain size distribution (Figure 1.B);
   b) non equiaxed microstructure of broad grain size distribution (Figure 1.A, E, F).

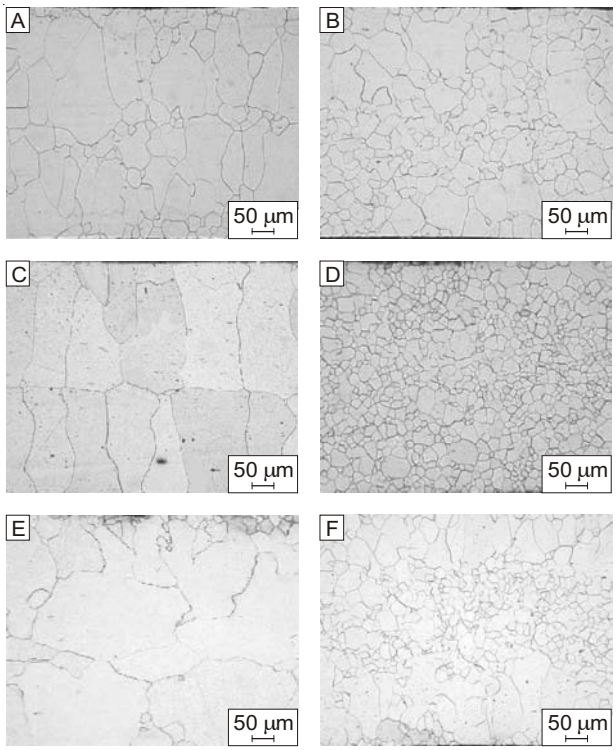

Figure 1. **Microstructure of samples A - F**
Slika 1. **Mikrostruktura uzoraka A - F**

The inhomogeneous non-equiaxed microstructure can be subdivided into three groups: columnar microstructure of broad grain size distribution (Figure 1.A), large non-equiaxed grains of broad grain size distribution (Figure 1.E) and columnar grains mixed with large quantity of small grains (Figure 1.F).

The homogeneity of microstructure can be described using the following model.

In this model, the volume of each grain changed to a corresponding ellipsoid (see Figure 2.). In the plane of section we obtain the plane filling by ellipses.

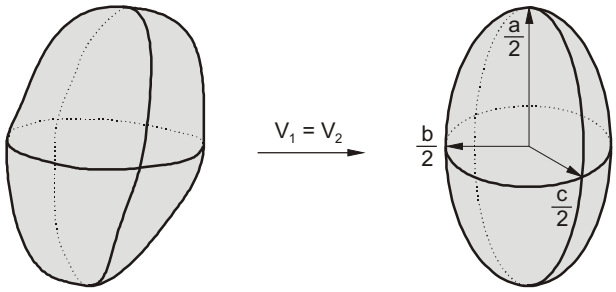

Figure 2. **Scheme for changing of grain volume**
Slika 2. **Shema promjene veličine zrna**

A volume coefficient of homogeneity was defined for microstructure description. Introduce a volume coefficient of homogeneity as:

$$G_v = \frac{\overline{V}}{\frac{4}{3}\pi\overline{a}\overline{b}\overline{c}} = \frac{1}{N}\frac{\sum_{i=1}^{N} a_i b_i c_i}{\frac{\sum_{i=1}^{N} a_i}{N}\frac{\sum_{i=1}^{N} b_i}{N}\frac{\sum_{i=1}^{N} c_i}{N}} = N^2 \frac{\sum_{i=1}^{N} a_i b_i c_i}{\sum_{i=1}^{N} a_i \sum_{i=1}^{N} b_i \sum_{i=1}^{N} c_i} \quad (1)$$

where

$\overline{V}$ - average volume of grains,
N - total number of grains.

If the grains are same ($a_i \approx$ const., $b_i \approx$ const., $c_i \approx$ const.), then introduce relations between a, and b, c as:

$$a = l\, b; \;\; a = k\, c, \quad (2)$$

then

$$G_v = N^2 \frac{N\frac{a^3}{lk}}{N \cdot a \cdot N \cdot \frac{a}{l} \cdot N \cdot \frac{a}{k}} = 1 \qquad (3)$$

As it can be concluded from equations (1) - (3), the volume coefficient of homogeneity is independent from microstructure equiaxity. The value of coefficient G_v is equals to one for "ideal" (equiaxed or non-equiaxed) homogeneous microstructure.

RESULTS AND DISCUSSIONS

Estimation of average grain size by homogeneous groups

DIPS-5 software was used for the analyses of the microstructure of specimens. Samples were investigated in the plane of sheet surface and in the plane of sheet thickness. The software transforms the grain shape to a corresponding ellipse of the similar shape and area equals 1. If the A_i and B_i - ellipse axes and the S_i - grain area are known, for $A_i > B_i$, then the grain sizes ai and bi may be calculated using the following equations:

$$a_i = \sqrt{S_i}\, A_i \qquad (4)$$

$$b_i = \sqrt{S_i}\, B_i \qquad (5)$$

Within non-oriented electrical steels, the values of a_i and b_i are similar in the plane of surface and different in the plane of thickness. So, the value of c_i (see Figure 2.) is evaluated as the average value of a_i and b_i in the plane of surface.

The values of G_v calculated by equation 1, using experimental data for cases A - F are presented in Table 1. It can be seen that in the case of more homogeneous microstructures (samples C, D), the coefficients of homogeneity approximate to the respective previously theoretically calculated one. The difference between the theoretical G_v and calculated one may be explained by the existing distribution of the grain size and by the difference between the grain's area, volume and the grain's shape. As noted in Table 1., the more considerable the value of coefficient G_v, the more considerable grain sizes distribution. Thus, the coefficient G_v characterizes the homogeneity of the microstructure.

Table 1. **Coefficients of homogeneity and values of $\overline{a}, a^*, \overline{b}, b^*, \overline{c}, c^*$ of samples A - F**
Tablica 1. **Koeficijenti homogenosti i vrijednosti $\overline{a}, a^*, \overline{b}, b^*, \overline{c}, c^*$ uzoraka A - F**

Sample	A	B	C	D	E	F
G_v	3.7	3.15	1.21	1.24	4.1	3.2
$\overline{a}$ [μm]	26.8	18.0	135.0	10.0	36.7	17.0
a^* [μm]	11.0	11.0	121.0	8.9	12.0	7.3
$\overline{b}$ [μm]	15.3	14.2	60.0	7.8	21.0	10.0
b^* [μm]	6.8	7.7	54.6	6.5	10.7	5.14
$\overline{c}$ [μm]	14.9	14.0	62.0	8.0	20.5	9.8
c^* [μm]	7.8	7.1	56.5	6.9	12.0	6.2

Using the data from DIPS-5, the distributions of grain size were obtained. The distribution of grain sizes in all cases are broad and asymmetrical, besides cases C, D. Due to the fact that the microstructure of these samples is homogeneous, the value of average sizes can be introduced. The value of average grain size $\overline{d}$ is calculated by (6). In other cases (A, B, E, F) the average value can't be introduced because the microstructure of specimens is inhomogeneous and the distribution of grain sizes is broad as well. These distributions are well described by the logarithmic normal function (7) (log-normal distribution).

$$\overline{d} = \sqrt[3]{\overline{a}\,\overline{b}\,\overline{c}} \qquad (6)$$

$$y = y_0 + Ae^{-\frac{\ln^2 \frac{x}{x_C}}{2\varpi^2}} \qquad (7)$$

where

ω is the standard deviation of function,
x_c is the median and, at the same time, the geometric mean of the distribution.

The median values of the grain size (a^*, b^*, c^*) and the average values of $\overline{a}, \overline{b}, \overline{c}$ calculated by (7), are presented in Table 1. It can be noted that the average values and the median values of the grain size are different from one another. These values are equal only in the Gauss (normal) distribution. But the histograms of grain size distributions for microstructures (A - F beside C, D) can't be described by Gauss function because the difference between grain sizes is large and their distributions are broad and asymmetrical. Only in cases C and D, the values of $\overline{a}, \overline{b}, \overline{c}$ and a^*, b^*, c^* are similar. So, only for homogeneous microstructure the distribution of grain sizes is symmetrical and values $\overline{a}, \overline{b}, \overline{c}$ and a^*, b^*, c^* are the same. Thus, in case of homogeneous microstructure, the grain size can be calculated by equation (6), where the values of $\overline{a}, \overline{b}, \overline{c}$ calculated by (8):

$$\overline{x} = \frac{\sum_{i=1}^{N} x_i}{N} \qquad (8)$$

In order to avoid the affect of a non-linear distribution on final values of $\bar{a}$, $\bar{b}$, $\bar{c}$ the grains were divided into three homogeneous groups (small grains, middle grains, large grains) according to the volume coefficient of homogeneity. The calculated coefficient G_v for these groups are as follows: G_v=1.1 ± 0.1. Furthermore, the values of $\bar{a}$ and a^*, $\bar{b}$ and b^*, $\bar{c}$ and c^* are similar (see Table 2.). These facts conclude that these grain groups are homogeneous.

Table 2. **Values of $\bar{a}$, a^*, $\bar{b}$, b^*, $\bar{c}$, c^* of homogeneous grain groups of samples A - F**
Tablica 2. **Vrijednosti $\bar{a}$, a^*, $\bar{b}$, b^*, $\bar{c}$, c^* homogenih grupa zrna u uzorcima A - F**

Sample	A	B	E	F
$\bar{a}^*_{big}$ [μm]	96.1	85.6	103.0	96.3
$\bar{b}^*_{big}$ [μm]	52.7	67.6	64.4	48.7
$\bar{c}^*_{big}$ [μm]	52.7	67.6	64.4	48.7
$\bar{a}^*_{mid}$ [μm]	34.2	35.5	40.3	31.5
$\bar{b}^*_{mid}$ [μm]	20.1	27.3	22.2	18.5
$\bar{c}^*_{mid}$ [μm]	21.1	28.2	22.4	19.0
$\bar{a}^*_{sm}$ [μm]	12.5	10.8	11.4	11.0
$\bar{b}^*_{sm}$ [μm]	7.0	8.45	6.12	6.7
$\bar{c}^*_{sm}$ [μm]	8.0	8.2	7.0	6.8
$\bar{a}^*_{big}$ [μm]	84.0	82.3	92.8	95.0
$\bar{b}^*_{big}$ [μm]	47.7	64.2	48.7	43.5
$\bar{c}^*_{big}$ [μm]	45.0	65.0	48.4	42.5
$\bar{a}^*_{mid}$ [μm]	27.7	31.6	37.4	25.4
$\bar{b}^*_{mid}$ [μm]	17.2	25.8	18.3	15.4
$\bar{c}^*_{mid}$ [μm]	17.0	27.0	19.3	14.9
$\bar{a}^*_{sm}$ [μm]	9.8	9.1	10.7	9.1
$\bar{b}^*_{sm}$ [μm]	5.9	6.9	5.7	5.1
$\bar{c}^*_{sm}$ [μm]	5.6	7.0	6.0	5.6

The average grain size was calculated using equations (9- 11), by considerations of the ratio of the area of certain grain groups to total area:

$$\bar{a} = n_1\bar{a}_b + n_2\bar{a}_m + n_3\bar{a}_s \quad (9)$$

$$\bar{b} = n_1\bar{b}_b + n_2\bar{b}_m + n_3\bar{b}_s \quad (10)$$

$$\bar{c} = n_1\bar{c}_b + n_2\bar{c}_m + n_3\bar{c}_s \quad (11)$$

where: n_1, n_2, n_3 - are ratios of the large, middle and small grains area to their respective total area. Table 3. presents the calculated values of $\bar{a}$, $\bar{b}$, $\bar{c}$.

If $\bar{a}$, $\bar{b}$, $\bar{c}$ are known, then the average grain size $\bar{d}$ can be calculated by (6).

Table 3. **Elongation of homogeneous grain groups and average grain size of samples A-F**
Tablica 3. **Izduženja homohenih grupa zrna i prosječne veličine zrna u uzorcima A - F**

Sample	A	B	C	D	E	F
$\bar{l}_{big}$	1.9	1.22	2.27	1.26	1.64	2.1
$\bar{l}_{mid}$	1.73	1.27	2.27	1.26	1.83	1.75
$\bar{l}_{sm}$	1.78	1.25	2.27	1.26	1.87	1.57
$\bar{a}$ [μm]	66.4	50.0	135.0	10.0	90.6	44.5
$\bar{b}$ [μm]	37.2	38.8	60.0	7.8	54.1	24.0
$\bar{c}$ [μm]	38.1	37.1	63.0	9.0	62.0	26.5
$\bar{d}$ [μm]	45.6	41.6	79.9	8.9	67.3	30.5

Equiaxity of microstructure

An analysis of equiaxity of homogeneous microstructure can be performed by a description of grain elongation. In non-oriented electrical steels the grains are elongated only in the plane of thickness and equiaxed in the plane of surface. However, for inhomogeneous microstructures, the equiaxity of whole microstructure can not be evaluated, because different grain groups have different elongation (samples A, E, F). For both homogeneous and inhomogeneous equiaxed microstructures, the average elongation of grains $\bar{l}$ should be close to value 1.

Table 3. presents the elongations of large, small and middle grain groups calculated by (8). Average elongation of the above-mentioned groups characterizes the equiaxity of microstructure. If the elongations of these groups are similar and ≈ 1, than the microstructure is equiaxed. As it can be concluded from Table 3., structures B and D are equiaxed because the average elongation of their grain groups approaches 1. Structures A, E, F are non equiaxed because the average elongation of their grain groups is high. The homogeneous non equiaxed (columnar) microstructure (sample C) is characterized by a typically high average elongation of grains: $\bar{l}$ = 2.27.

Modelling of mechanical properties

Mechanical properties can be evaluated using Hall-Petch like equations. Mechanical properties of non-oriented electrical steels of fully processed grades have been estimated regarding the influence of the grain size and the effect of chemical composition. The following models are used for the prediction of yield stress - σ_y (or R_{p02}) and tensile strength - σ_u (or R_m): Gladman's equation [15], Le Bon - Saint Martin's model [16], Gibs - Hodson's equation [17], Pinoy's model [18]. Beside this, it is supposed that the influence of chemical composition is linear in the narrow range of composition. The relationships received for σ_y and σ_u are as follows:

$$\sigma_y = 26.5 + 27.1\ Mn + 54.5\ Si + 605\ F + \\ +3200\ (N + C) + 47.8\ Al + 32.8 / (10*d)^{0.5} \quad (12)$$

$$\sigma_u = 173.9 + 53.6\ Mn + 95.9\ Si + 731.9\ F + \\ + 3339\ N + 11 / (10*d)^{0.5} \quad (13)$$

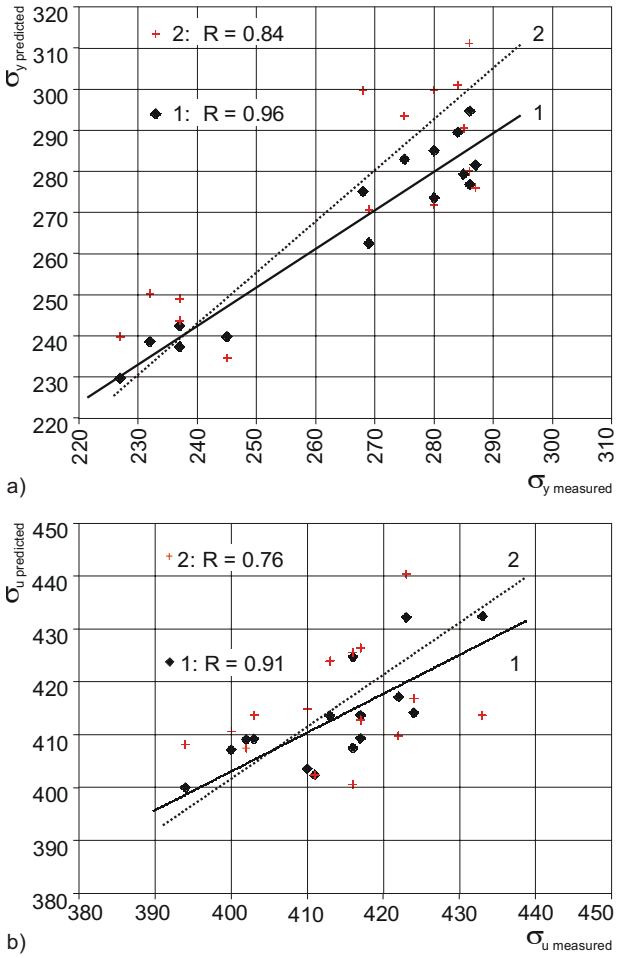

Figure 3. **a) the dependence of measured yield stress on predicted one (diamond predicted σ_y by equation (12), using the value of average grain size, calculated by (11); cross - predicted σ_y by equation (12), using the value of average grain size, calculated by technical norms)**
b) the dependence of measured tensile strengths on predicted one (diamond predicted σ_u by equation (12), using the value of average grain size, calculated by (11); cross - predicted σ_u by equation (12), using the value of average grain size, calculated by technical norms)

Slika 3. **a) Ovisnost granice razvlačenja o predviđenoj vrijednosti (vrijednost σ_y određena jednadžbom (12) (dijamant) uporabom vrijednosti prosječne veličine zrna, izračunate jednadžbom (11); vrijednost σ_y određena jednadžbom (12) (križ) uporabom vrijednosti prosječne veličine zrna i izračunate pomoću tehničkih standarda [4-6])**
b) Ovisnost izmjerene vlačne čvrstoće o predviđenim vrijednostima (dijamant - σ_u određena jednadžbom (11) uporabom vrijednosti prosječne veličine zrna, izračunate jednadžbom (11); križ - σ_u određena jednadžbom (12) upo-rabom vrijednosti prosječne veličine zrna izračunate pomoću tehničkih standarda [4-6])

The strengthening coefficients for solutes are comparable with considered one in above-mentioned models. The coefficient for grain strengthening is higher then in above models. It is because these models were developed for homogeneous and equiaxed microstructures. As can be seen from Figure1., microstructures of non-oriented steels are mainly inhomogeneous and non-equiaxed. That is the reason why the coefficient for grains strengthening in this model and mentioned models are different from one another.

The mechanical properties (σ_y and σ_m) of non-oriented electrical steels are well described by equations (12) and (13). Figure 3. presents dependencies of measured yield stress and tensile strength on predicted one by equation (12) and (13) respectively. As can be concluded from Figure 3., the better results were received by using the value of average grain size calculated by equations (6) using (9) - (11). The maximal deviations for line 1 in both cases are low: $(\Delta\sigma_y/\sigma_y) * 100\ \% = 4.8\%$, $(\Delta\sigma_y/\sigma_y) * 100\ \% = 3.2\ \%$. Furthermore, the correlation coefficient R for line 1 higher than for line 2.

CONCLUSIONS

A theoretical model was created for description of the homogeneity of microstructures. The ratio of average grains volume to their sizes describe the volume homogeneity of a microstructure. The more considerable coefficient G_v is, the more considerable grain size distribution.

The average grain size can be evaluated by technical norms or by Gauss distribution parameters only for homogeneous microstructure. In the case of microstructure of broad grain size distribution, the average grain size evaluated as a function of the average grain sizes of homogeneous grain groups.

Average elongations of homogeneous grain groups describe the equiaxity of microstructure. For inhomogeneous microstructures, the equiaxity of whole microstructure can not be evaluated, because different grain groups have different elongations. For equiaxed microstructures, the elongation of all grain groups should be close to 1.

The mechanical properties of non-oriented electrical steels are well described by Hall-Petch like equation, using the value of average grain size as a function of the average grain sizes of homogeneous grain groups.

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