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Specifics of physico-mechanical characteristics of thermally-hardened rebar

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Abstract
Thermal hardening is widely used nowadays for modification of steel bar properties and obtaining effective reinforcing material. Strength and deformation characteristics of thermally hardened reinforcement is the complex indicator of reinforcement efficiency. Therefore, reliable assessment of physico-mechanical characteristics of thermally hardened rebar is topical and important issue. This article is intended to the analysis of physico-mechanical characteristics of thermally hardened rebar on the basis of experimental data. Thorough statistical processing of experimental data was made and specific features of strength parameters were identified. Analytical model of strength characteristics is proposed, which enables to take into account inhomogeneous strength properties of the rebar along its cross-section. It could be stated that assessment of physico-mechanical characteristics of thermally hardened rebar is topical and important issue, which is the prospective area of further research.

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1. Introduction

Construction industry in modern conditions occupies one of the most important places in the industrial development of society and could be considered as the main indicator of economic life (Bobalo et al., 2019a; Azizov et al., 2019; Pietraszek et al., 2020). Main trends in construction determine the overall scientific research proceeding and induce development and optimization of the latest effective technologies. Generally speaking, the most topical issues in the construction industry include the following: introduction of energy and resource-saving technologies, reduction of environmental impact, optimization of design solutions to reduce overall material and labor costs, efficient use of material resources (Andriulaitytė and Valentukeviciene, 2020; Blikharskyy and Selejdak, 2021). Solution of these problems anticipates optimal use of existing construction funds, extension of their life cycle (Wang et al, 2010; Lima and Barros, 2011; Okeil et al., 2002; Pham and Al-Mahaidi, 2008; Trentin and Casas, 2015). Therefore, reliable assessment of their durability and residual service life are important (Yogalakshmi et al., 2020)

As reinforced concrete has unique mechanical and technological properties, in modern conditions it is one of the most common materials for buildings and structures (Blikharskyy et.al., 2021c; Ouzaa and Chahmi, 2019; Shi et al., 2017; Gotal Dmitrović et al., 2019; Yang et al., 2019; Choe et al., 2020; Yokalakshmi et al., 2020). It is important to note, that this material is complex multicomponent heterogeneous system with synergistic properties, which on the one hand allows its effective use in a wide range of structures, and on the other - causes the ambiguity of its stress-strain state under the influence of external impacts (Fomin et al., 2021; Klymenko, et al., 2020; Klymenko et al., 2019). Modeling the work of reinforced concrete structures under adverse external influences should account specific properties of individual components, -concrete stone and steel bars (Bobalo et al., 2019b; Bobalo et al., 2020; Blikharskyy et al., 2021b; Blikharskyy et al., 2021a; Bambura et al., 2018; Czajkowska et al., 2020; Karpiuk et al., 2020; Blikharskyy et al., 2020b; Lipiński, 2017; Kramarchuk et al., 2021).

As recently reinforced concrete structures have reached increased demand, the need to reduce the material consumption has led to the search for ways to modify the properties of materials at both macro- and micro-levels. Thermal hardening of reinforcing steel is one of the most common ways to obtain specific physical and mechanical properties. Despite the widespread use of this method, the understanding of all the properties of the product, obtained after heat treatment of steel is not complete jet. Thus, the problem of reliable description of its strength and deformation characteristics is obvious.

2. Aims

The aim of the work is to provide detailed analysis of physico-mechanical characteristics of thermally hardened rebar according to experimental investigation. Work includes thorough statistical processing of experimental data and formulation of analytical model of rebar strength characteristics. In addition, prospective research areas of considered issue will be identified.

3. Literature review

The number of recent works is intended to reliable assessment of physico-mechanical characteristics of thermally hardened rebar, including theoretical and experimental studies, which considered different aspects of its microstructural characteristics.

In general, heat treatment of reinforcing steel could be defined as complex of operations that include heating at certain speed, holding at certain temperature level and subsequent cooling at given speed. As the result, after these operations it is possible to obtain material of the desired microstructure with specific physical and mechanical properties (Hamid, 2020; Ahaneku et al., 2012). Several scientists (Özdemir, 2021; Ahaneku et al., 2012; Nair et al., 2017; Wang et al., 2018) have identified specific features of thermally hardened steel samples, such as higher Brinell hardness, higher values of yield point and tensile strength and reduced relative elongation. Since the hardening of steel proceeds during short period of time, most of the temperature transformations occur in the outer layer of the steel bar (in the so-called "shell"). Herewith, in the inner part ("core") there are processes of "thermobalancing" and this part of the rebar remains more stable (Nair et al., 2017). Thus, certain point on the temperature diagram, which corresponds the austenitic temperature, indicates microstructural transformations, due to which composite material with inhomogeneous characteristics is obtained. In the outer layer the reinforcing steel enters the martensitic phase, which is harder form of the steel crystal structure (Wang et al., 2018). Martensite type of structure is characterized by smaller grain size with larger specific surface area and stronger bonds at the micro-level. Thus, the hardness is increased and plastic characteristics are reduced. In addition, the high content of ferrite fraction has significant effect on the deformation characteristics (Xiong et al., 2015). Messer (Messer et al., 2007) in his study noted general tendency towards reduction of plastic properties in steels with significant percentage of ferrite fraction, altogether with more intense development of intergranular cracks. The quenching temperature has significant effect on the size of the newly formed crystals. In particular, at higher temperatures the coarser structure is obtained during such stages of material transformation. For example, during austenitization austenite grains are formed, plastic martensite corresponds to hardening stage and during cooling thermally-reinforced trostyt is created (Siyuan et al., 2019; Szataniak et al., 2014).

Speaking about the inner layer of the reinforcing rod ("core"), in this part of the cross-section the temperature effect does not have enough time to cause critical structural changes in the material. Therefore, the thermodynamic processes in the material are less intense. This part of the rebar contains more residual austenite with lower hardness and strength (Maisuradze et al., 2020; Nair et al., 2017). Chemically the "core" of the steel bar consists of ferritic-pearlitic phase with higher elongation, and therefore is more plastic material (Nair et al., 2017; Zhang et al., 2015). According to research of Zhang (Zhang et al., 2015), thermally strengthened zone has higher strength characteristics and decreased deformation characteristics. On the basis of analysis of the fracture specific energy as an elastic-plastic fracture invariant characteristic, author (Zhang et al., 2015) identified susceptibility to brittle fracture.

In contrast, the inner zone has higher plastic values, according to this energy parameter. As noted in the number of works (Tóth et al., 2018; Torbati-Sarrraf and Poursaee, 2019; Zhang et al., 2015; Maisuradze et al., 2020; Nair et al., 2017), the heterogeneity of the characteristics along the cross section of the thermally strengthened steel bar is the cause of its complicated stress-strain state. Asymmetrical physical and mechanical parameters of the rebar cross-section could be the reason of asymmetric bending stiffness and additional local stresses in the element (Nair et al., 2017).

It is obvious that modifications in the microstructure of steel, especially in the size of crystals, their distribution and phase properties have significant effect on corrosion resistance (Tóth et al., 2018; Torbati-Sarrraf and Poursaee, 2019). As states Torbati-Sarrraf and Poursaee (2019), electrochemical analysis shows, that thermal hardening has a positive effect on the corrosion resistance of reinforcing steel and has great impact on formation and destruction of the passivating layer. Changes in corrosion resistance are more significant for steel with uniform structure and lower content of free ferrite at the grain boundaries.

It is important to note, that in order to obtain a corrosion-resistant material the microstructural transformations should be stabilized, as small grains of the heat-strengthened layer can cause stress concentrators (Tóth et al., 2018). However, it should be taken into consideration, that the heterogenity of the steel could be the cause of early spot corrosion and unpredictable behaviour of the reinforced concrete structure under loading (Tóth et al., 2018).

Reliable assessment of structures with thermally-hardened rebar requires analytical description of its physical and mechanical parameters (Tu et al., 2020). Thus, it is important to formulate an objective reliable strength model for heat-strengthened steel, especially for cases of large deformations. The proposed theoretical model should be based on experimental data, which would take into account that each material shows specific kinetics of hardness change (Tu et al., 2020). Another paper presents the thermally reinforced rebar in the form of a three-layer model with variable carbon content (Santos and Henriques, 2015). Therefore, the rebar section could be considered as complex mutually balanced system, in which the outer layer with higher strength characteristics determines the strength of the reinforcement, whereas plastic characteristics are defined mostly by the "core" (Santos and Henriques, 2015). However, work (Santos and Henriques, 2015) does not provide analytical description of the rebar physical and mechanical parameters, which could be used in the calculation. On the basis of conducted literature review it could be summarized, that changes of physical and mechanical properties of reinforcing steel after thermal hardening is topical issue, which needs further investigation.

4. Theoretical investigation

In this work analytical assessment of physico-mechanical properties of thermally strengthened rebar includes statistical processing and thorough analysis of experimental data. The results of lab tests, published in (Blikharskyy et al., 2020a) are taken as the basis. Strength and deformation characteristics of Ø20A500C reinforcement after its thermal hardening have been experimentally investigated and different structural layers of the rebar have been distincted.

Experimental studies were performed on samples made of thermally hardened rebar Ø20A500C. For each stage of the experiment, the samples were drilled on the zone of 100 mm length, thus obtaining different effective diameter values. The samples were tested for tension, according to the instructions of normative regulations (DSTU ISO 6892-1:2019). During the experiment load level, changes in the shape of the damaged area, longitudinal elongation and relative narrowing of the cut area were registered. Local deformations and stresses were determined with the use of digital image correlation (DIC).

The principle of DIC technology includes following stages. First of all, the investigated surface is illuminated by coherent (laser) light or incoherent radiation, the speckle image of this surface is recorded in the form of CCD or KMON matrix by a matrix detector in the form of a CCD matrix or KMON matrix. At this stage the speckle pictures of the undeformed (original) and deformed surfaces are registered and described by the function r(x, y) and $r_{m,n}$,, registered by the camcorder are entered into a personal computer in digital form, for further processing with the appropriate software.

In this research the images were recorded with monochromatic digital camera "Grasshopper 3" with Computar F25\2.8 lens. Camera and additional illuminators were placed on a platform mounted on the frame of the loading mechanism. The distance between the lens and studied sample was equal to 300 mm. Therefore, it was possible to identify changes in the shape of the entire drilled area of the sample. The force applied by the pressure machine was recorded using a digital converter E14-440 with PowerGraph software.

As the result, the stresses in the cross-section were identified and the stress-strain state diagram was formed (Blikharskyy et al., 2020a).

Previous studies (Blikharskyy et al., 2020a) were focused on the analysis of elastic-plastic properties of thermally-strengthened reinforcing bars, which contain different structural layers of the material. In this paper, instead, the inhomogeneity of the strength characteristics of thermally modified reinforcing steel along the cross section of the rebar is considered.

4.1. Statistical processing of the experimental data

The analysis is performed on the basis of data for 5 series of tests (for each series the yield strength was determined for different effective diameters with 1 mm step).

For each value of effective diameter, the main statistic parameters were identified:

- mathematical expectation (arithmetic mean, average):

$$\overline{\sigma_{0.2}} = \frac{\sum_{i=1}^{n} \sigma_{0.2i}}{n} \tag{1}$$

- standard deviation:

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\sigma_{0.2i} - \overline{\sigma_{0.2}})^2} \tag{2}$$

- coefficient of variation:

$$\nu = \frac{S}{\overline{\sigma_{0.2}}} \tag{3}$$

- dispersion:

$$\delta^2 = \frac{\sum_{i=1}^{n}(\sigma_{0.2i} - \overline{\sigma_{0.2}})^2}{n-1} \tag{4}$$

where $\sigma_{0.2i}$ -the strength value from certain series; *n*-the number of samples in the series.

The actual values of strength, as well as the results of their statistical processing are given in Table 1.

The series are checked for significant errors with the use of Student's criterion (Lychev et al., 1990). The check consists in comparison of the calculated value of the Student's criterion for each doubtful value with the tabular value:

$$t_{calc} = \frac{\left|\sigma_{0.2-doubt} - \overline{\sigma_{0.2}}\right|}{S} \le t_{table} \tag{5}$$

where $\sigma_{0.2-doubt}$ is the doubtful value of the parameter; t_{calc} - calculated value of the Student's criterion; t_{table} -tabular value of the Student's criterion.

From the tables of Student's distribution (Lychev et al., 1990), assuming the level of significance *q = 5%* and the number of degrees of freedom *f = 5-1 = 4*, the tabular value of the Student's criterion could be found. For each value of diameter, we check the largest and smallest values of parameter.

The results of the series` check for significant errors are given in Table 2.

Table 1. (begin). Initial experimental data of reinforcement strength and their statistical parameters

Effective diameter D, mm	Experimental data				
	$\sigma_{0.2i}$, MPa, for the sample №				
	1	2	3	4	5
1	2	3	4	5	6
20	581.0	585.0	578.0	591.0	590.0
19	549.0	552.0	547.0	558.0	556.0
18	557.0	562.0	554.0	558.0	562.0
17	554.0	557.0	548.0	552.0	561.0
16	561.0	567.0	559.0	562.0	565.0
15	490.0	491.0	485.0	490.0	497.0
14	477.0	481.0	472.0	474.0	483.0
13	466.0	469.0	461.0	471.0	472.0
12	448.0	450.0	444.0	449.0	453.0
11	442.0	448.0	442.0	450.0	450.0
10	439.0	440.0	439.0	437.0	443.0

Table 1. (end)

Effective diameter D, mm	Statistical processing				
	$\overline{\sigma_{0.2}}$ MPa	S , MPa	δ^2 MPa^2	ν	
				in p.	%
1	7	8	9	10	11
20	585.0	5.020	31.5	0.009	0.858
19	552.4	4.128	21.3	0.007	0.747
18	558.6	3.072	11.8	0.006	0.550
17	554.4	4.409	24.3	0.008	0.795
16	562.8	2.857	10.2	0.005	0.508
15	490.6	3.826	18.3	0.008	0.780
14	477.4	4.128	21.3	0.009	0.865
13	467.8	3.970	19.7	0.008	0.849
12	448.8	2.926	10.7	0.007	0.652
11	446.4	3.666	16.8	0.008	0.821
10	439.6	1.960	4.8	0.004	0.446
Average		3.633	17.3	0.007	0.715

Table 2 (begin). Results of the series` check for significant errors

Effective diameter D, mm	Experimental data				
	$\sigma_{0.2i}$, MPa, for the sample №				
	1	2	3	4	5
1	2	3	4	5	6
20	581.0	585.0	578.0	591.0	590.0
19	549.0	552.0	547.0	558.0	556.0
18	557.0	562.0	554.0	558.0	562.0
17	554.0	557.0	548.0	552.0	561.0
16	561.0	567.0	559.0	562.0	565.0
15	490.0	491.0	485.0	490.0	497.0
14	477.0	481.0	472.0	474.0	483.0
13	466.0	469.0	461.0	471.0	472.0
12	448.0	450.0	444.0	449.0	453.0
11	442.0	448.0	442.0	450.0	450.0
10	439.0	440.0	439.0	437.0	443.0

Table 2. (end)

Effective diameter D, mm	Check according to the Student's criterion		
	$\overline{\sigma_{0.2}}$, MPa	t_{calc}	
		for maximum value	for minimum value
1	7	8	9
20	585.0	1.07	1.25
19	552.4	1.21	1.17
18	558.6	0.99	1.34
17	554.4	1.34	1.30
16	562.8	1.32	1.19
15	490.6	1.50	1.31
14	477.4	1.21	1.17
13	467.8	0.95	1.53
12	448.8	1.28	1.47
11	446.4	0.88	1.07
10	439.6	1.55	1.19
Maximum t_{calc} ,			1.55

As can be noted, for all values the condition of results` reliability is fulfilled with the confidence probability of 95%. Namely, the maximum calculated value of the criterion for 5th sample and an effective diameter of 10 mm is within acceptable limits:

$$t_{calc-\max} = 1.55 < t_{table} = 2.78 \qquad (6)$$

As the requirement (5) is fulfilled there is no need in corrections and all the experimental data could be used for further analysis.

With the use of specialized software graphs of strength distribution along the cross-section are built and their statistical analysis is made. The corresponding graphs are shown in Fig. 1-2.

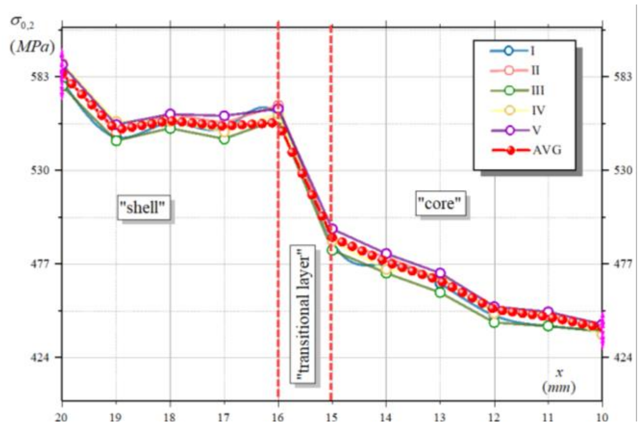

Fig. 1. Distribution of strength characteristics along the cross section of the rebar: I, II, III, IV, V, - the values for the samples № 1,2,3,4,5, respectively; AVG-averaged graph

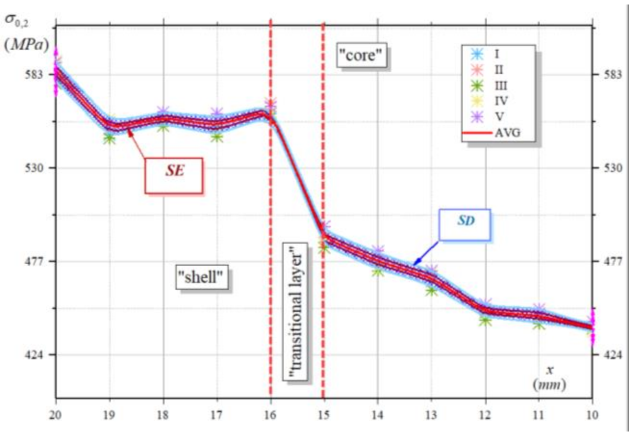

Fig. 2. Statistical analysis of strength distributions for series: I, II, III, IV, V, - values for samples № 1,2,3,4,5, respectively; AVG-averaged graph, SE-standard error, SD-standard deviation

4.2. Analytical strength model of thermally hardened rebar

As could be seen from the distribution of strength characteristics along the cross section (see Fig. 1, 2), 3 structural zones that have a significant difference in characteristics could be indicated:

- outer heat-strengthened layer with 2 mm thickness with the strength of $\sigma_{0.2i} \in [585; 560]$ MPa;
- transition zone with 0.5 mm thickness and $\sigma_{0.2i} \in [560; 490]$ MPa strength value;
- inner "core" with 15 mm diameter and strength equal to $\sigma_{0.2i} \in [490; 439]$ MPa.

The location of the structural zones of the steel bar cross section is shown in Fig. 3.

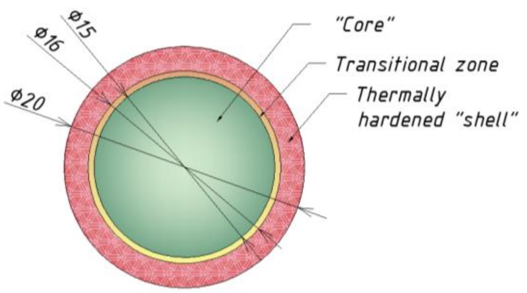

Fig. 3. The location of the structural zones along the cross section of thermally hardened steel bar

Modelling of such inhomogeneous characteristics envises formulation of analytical dependence that would most accurately describe the change in strength along the cross section in the form of function $\sigma_{0.2} = f(x)$. Choosing of such function is rather complicated and multistage process, as it is not known to which mathematical or physical laws it fits. In this study the function is chosen by approximation of graph AVG (see Fig. 1-2).

Statistical model`s conformity is checked according to the value of the coefficient of determination R^2, which indicates the extent to which the variation of the dependent variable is explained by independent variables in the regression model. Mathematically, the coefficient of determination can be determined by the formula:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \quad (7)$$

where SS_{res} -the sum of the squares of the regression residues, SS_{tot} -the total sum of the squares.

Let's consider the of values y_i belonging to the range $[y_1, y_n]$. In the statistical model these values correspond to $f_i \in [f_1, f_n]$. Then the sum of the squares of the regression residues and the total sum of the squares could be determined as:

$$SS_{res} = \sum_i (y_i - f_i)^2 \quad (8)$$

$$SS_{tot} = \sum_i (y_i - \bar{y})^2 \quad (9)$$

where $\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$ is the average of series` values.

The value of R^2 belongs to the range from 0 to 1. It is generally assumed that values of $R^2=1$ and $SS_{res} = 0$ correspond to the statistical model, which fits to actual data in the best possible way. In our case selection of function is iterative and multistage. Let's consider several variants of approximation by most common functions (see Fig. 4).

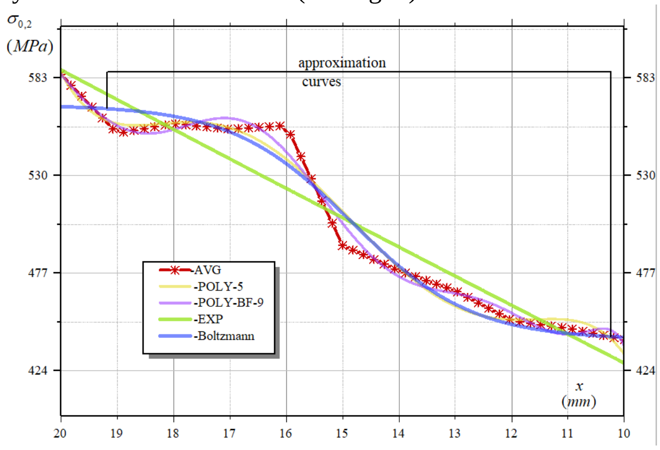

Fig. 4. Approximation curves, which correspond to the most common functions: AVG-averaged graph; POLY-5- approximation curve in the form of the 5th order polynomial, POLY-BF--approximation curve in the form of the 9th order polynomial; EXP--approximation curve in the exponential form; Boltzmann- approximation curve in the form Boltzmann function.

The best fit of the initial model could be obtained if the 9th order polynomial dependency is used (see Fig. 5):

$$f(x) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 + a_4 \cdot x^4 + a_5 \cdot x^5 + a_6 \cdot x^6 + a_7 \cdot x^7 + a_8 \cdot x^8 + a_9 \cdot x^9 \quad (10)$$

where a_i are randomly selected coefficients, which provide the best fit curve. Their actual values for our case are given in Fig. 5.

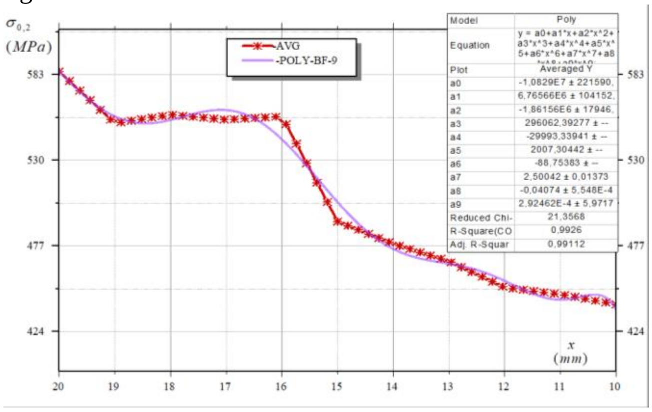

Fig. 5. Approximation curve in the 9th order polynomial form.

Although this variant of the approximation curve provides value $R^2=0.991$ and high correspondence with the initial statistical model, the 9th order polynomial function is rather complicated for practical usage in calculations. It is important to note, that in engineering calculations the error within 5% is permissible, therefore it is not optimal to use such compound mathematical apparatus.

For comparison, more simplified function could be considered. Figure 6 shows approximation curve in the form of the 5th order polynomial function:

$$f(x)=a_0+a_1\cdot x+a_2\cdot x^2+a_3\cdot x^3+a_4\cdot x^4+a_5\cdot x^5 \qquad (11)$$

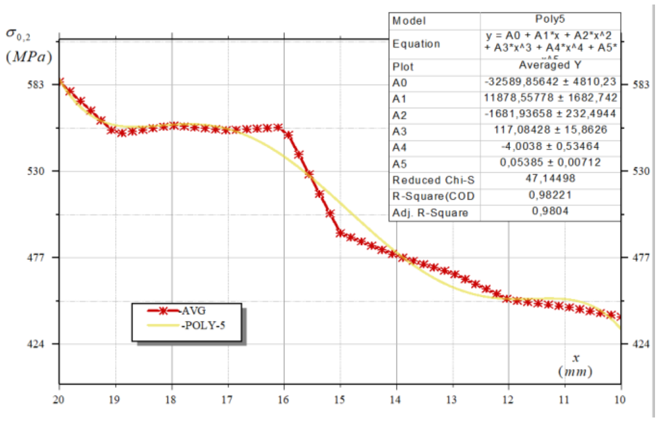

Fig. 6. Approximation curve in the 5th order polynomial form.

The value of $R^2=0.980$ reveals high regression of proposed function to the desired. Therefore, as such analytical representation is rather convenient, such statistical model is applicable for further usage.

It is important to note, that high values of the coefficients of determination for polynomial statistical models are explained by considerable flexibility of the polynomial function, because all the coefficients are randomly selected. Therefore, polynomial dependencies (10-11) have no explicit physical meaning and are completely empirical. It could be stated, that statistical model in the polynomial form can be used only to obtain partial solution for specific situation, rather than general solution, which is its significant drawback.

Another approximation model is the variant of exponential approximation curve (Fig. 7), according to dependency:

$$f(x)=y_0+A\cdot e^{Rx} \qquad (12)$$

where y_0, A, R -randomly chosen coefficients of eq. (12).

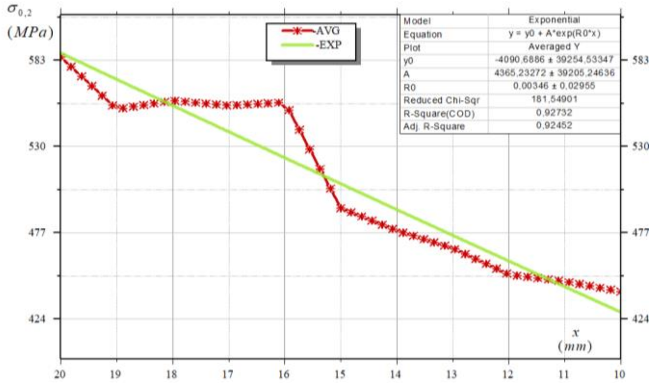

Fig. 7. Approximation curve in the exponential form.

Exponential dependency is often used for description of different engineering problems and physical phenomena, for example, corrosion processes, radioactive decay, in molecular kinetic theory, and so on. Except the better logical basis, this function has more simple and convenient form.

Despite all the above, as could be seen from Figure 7, exponential function does not provide reliable conformity with actual experimental data. Thus, coefficient of determination $R^2=0.924$ does not provide desired accuracy and function in the form (12) cannot be used for further analysis.

Interesting and promising variant for statistical model is the Boltzmann equation. In general, this function is commonly used to describe the particle distribution of an arbitrary non-equilibrium thermodynamic system by spatial coordinates and velocities. In addition, today Boltzmann equation underlies many diffusion and thermoelectric processes, in the laws describing the particles` movement in solids and is also used to describe kinetic and physical phenomena in crystalline and amorphous media.

As it is known, the strength distribution along the cross section of the rebar is the result of heat and mass transfer processes that took place in the material during its thermal hardening. Therefore, Boltzmann distribution is applicable for description of the statistical model:

$$f(x)=A_2+\frac{A_1-A_2}{1-e^{\frac{x-x_0}{dx}}} \qquad (13)$$

where x_0, A_1, A_2 , dx -randomly chosen coefficients according to Fig. 8.

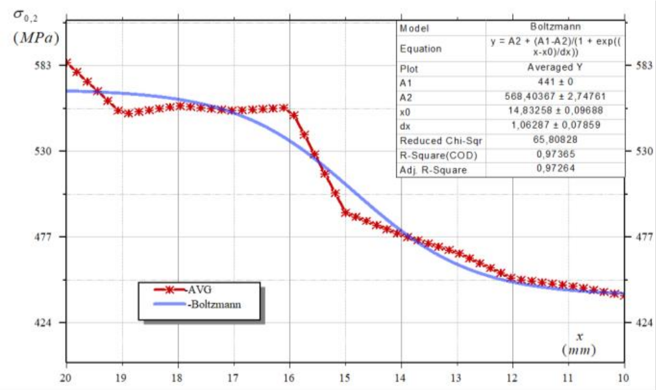

Fig. 8. Approximation curve according to Boltzmann distribution.

As could be seen from the graph (Fig. 8), approximation curve, described by Boltzmann equation is very close to the initial distribution of the strength characteristics. Therefore, with value of $R^2=0.973$, which is within the applicable limits, function (13) is highly prospective for further usage.

It could be summarized, that Boltzmann equation is the most appropriate for formulation of the analytical model of strength characteristics` distribution along the steel bar cross section. Finally, after substitution of actual values of random coefficients, strength characteristics of thermally hardened rebar could be described by formula:

$$f_{yk}(x) = 568.40 \pm 2.75 + \frac{441.00 \pm 0 - 568.40 \pm 2.75}{1 - e^{\frac{x - 14.83 \pm 0.09}{1.06 \pm 0.07}}} \quad (14)$$

5. Summary and conclusion

On the basis of experimental investigation, statistical processing and detailed analysis was made. Detailed statistical analysis of the experimental data has shown that procedures of thermal hardening have great influence on structural properties of the reinforcing steel on micro and macro levels. After microstructural changes the rebar could be considered as the complex system, rather than as the uniform material. As could be seen from Fig. 1-3, the strength characteristics differ greatly in different zones of the cross section. Strength of the reinforcing steel decrease when moving from the outer to the inner layer, forming three diverse structural areas with individual characteristics (Fig. 3).

It could be concluded, that rebar after thermal strengthening transforms into complex heterogeneous system with different strength characteristics along the cross section. Strength values for three distinct zones were indicated, which could be used for further theoretical investigation. In addition, an approach for analytical description of strength characteristics of the rebar is proposed. Analytical dependency that would most accurately describe the change in strength along the cross section was chosen by comparison of different approximation curves (Fig. 4). It was found, that Boltzmann equation (Fig. 8) is the most appropriate for formulation of the analytical model of strength characteristics` distribution. It is important to note, that the microstructural properties of the rebar could have the influence on the corrosion intensity. This aspect identifies perspectives for further research and development of the analytical model of strength characteristics of thermally-strengthened reinforcement.

Strength and deformation characteristics of thermally strengthened rebar is the complex indicator of reinforcement efficiency. Therefore, its understanding is decisive for reliable assessment of the of reinforced concrete structures in which hardened steels are used. It could be stated, that assessment of physico-mechanical characteristics of thermally hardened rebar is topical and important issue, which is the prospective area of further research.

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热硬化钢筋物理力学特性指标

關鍵詞
热强化
钢筋
钢筋混凝土结构
硬化

摘要
热硬化是当今广泛用于改变钢筋性能和获得有效增强材料的方法。热硬化钢筋的强度和变形特性是钢筋效率的复杂指标。因此，对热硬化钢筋的物理力学特性进行可靠评估是当前的热点和重要问题。本文旨在根据实验数据对热硬化钢筋的物理力学特性进行分析。对实验数据进行了彻底的统计处理，确定了强度参数的具体特征。提出了强度特性的分析模型，该模型能够考虑钢筋沿其横截面的不均匀强度特性。可以说，热硬化钢筋物理力学特性的评估是一个热点和重要的问题，是进一步研究的前瞻性领域。