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Assessment of the effect of the steels structure dispersion on its magnetic and mechanical properties

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ABSTRACT

Introduction: The control of the mechanical properties of structural steels is one of the main processes that regulate the service life of equipment. In most technical processes (pressure treatment, welding, rolling, thermal exposure), structure changes both in local areas and in the entire volume. Changes in the steel structure entail changes in its properties and as a result in local areas, at various stages of operation, the likelihood of the occurrence and development of critical defects increases. Its presence significantly affects the performance of the equipment, and leads to premature aging of the material and its failure. Precisely because the control of the mechanical properties of steel remains one of the urgent problems, new control methods are being developed. It is known that all properties of steel depend on the structure of the substance, however, studies on the effect of the dispersion of the structure under consideration on the mechanical properties are presented in an insignificant amount. **Purpose:** to analyze from a mathematical point of view the influence of the factor of different grain size, as a parameter reflecting the dispersity of the system, on the mechanical properties of structural steel. **The paper studies** a heat-treated planar samples of steels *15KhSND*, *09G2S* and *St3*. **Methods of research:** scanning electron and optical microscopes are used to study the grain structure and grain boundaries; *SIAMS 700* software package is used for finding the boundaries and average data of the grain structure; portable X-ray fluorescence analyzer of metals and alloys *X-MET 7000* is used to determine the chemical composition of the test samples in percentage; tensile testing machine *IR-50* is used for measuring the tensile strength of samples; Vickers hardness tester is used to determine the hardness of samples. **Results and discussion:** it is found that there is a satisfactory correlation for the mechanical properties of structural steels (hardness and ultimate strength) and the grain size factor, which can be used to predict the hazardous states of structures and the operating time. The analysis of variance and regression of the detected dependencies is carried out. It is noted that the dropout of some values from the general regression dependence can most likely be associated with a decrease in the value of internal stresses as a result of a decrease in the distortions of the crystal lattice of steel occurring during heat treatment. It should be noted that the processes occurring and the degree of its influence on the properties of the structural steels under consideration can be different due to the presence of different amounts of alloying elements in the composition of the studied steels.

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Introduction

There is a need to determine the value of the steel mechanical properties to predict the residual life in the practice of operating the hazardous production facilities. Mechanical properties are the main characteristics to which strict control requirements should be imposed. They directly determine the service life of equipment and metal structures.

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As is known, the properties of alloys in the solid state are determined by its crystal structure, chemical composition and by all types of structural disorders manifested in the form of inhomogeneities [1]. The structure inhomogeneities or chemical composition leads to a deviation of the material properties in the local part. This significantly affects the reliability and service life of the equipment.

Considering that the operation of equipment and structures made of structural steels occurs in most cases under constant external loads, which are of a multi-component nature, then there is a rapid intensification of material destruction processes, leading to emergencies.

A lot of research is being carried out on the development of methods for determining the mechanical properties of steels [2-6]. Nowadays there are methods of non-destructive testing based on the analysis of magnetic parameters. It allows determining the steel mechanical properties, in addition to destructive tests [7, 8]. It is proposed to use the steel coercive force as a diagnostic criterion for the hardness and tensile strength in the study [7]. However, this approach has its own nuances. There is no uniform dependence of mechanical properties and coercive force for different grades of steel [7]. It indicates a difference in the structure and properties of the phase components, which significantly affect the formation of mechanical properties and coercive force. There are methods for monitoring mechanical properties. They are based on the analysis of the ultrasonic vibration propagation by the controlled object [9].

The connection of the diagnostic criteria with the mechanical properties and structural features of the steel has been considered for a long time. The diagnostic criteria show the magnitude of the steel mechanical properties.

There are research works that consider the influence of the structure dispersion (inhomogeneity) on the mechanical properties. Inhomogeneity is the presence of different grains in the structure at the same time. For example, the influence of an ultra-fine-grained or fine-grained structure of simple carbon steel on the yield strength is considered. [10]. The process of accumulation and occurrence of dislocations and its effect on the steel strength is analyzed in [11] from a statistical point of view for eutectic steel with an ultra-fine-grained or fine-grained structure. The study of changes in plastic deformation for austenitic steel with a high manganese content and different average grain size is reflected in [12]. The influence of substructure development on deformation hardening of steel *(Fe*-17.5*Mn*-8.3*Al*-0.74*C*-0.*14Si)* is evaluated in [13]. It is noted that substructures during refinement make significant changes in the strength properties.

The intragrain orientation inhomogeneity and inhomogeneity of the stress state are highlighted as important areas for the future studies in [14].

There are works [15, 16], in which the samples being studied are obtained by an additive method, in addition to the works, in which the study is carried out on alloys, obtained by conventional metallurgical methods. In these works, the influence of microstructural features, namely mesostructure descriptors, which describe the features of mesostructural inhomogeneity on mechanical properties from the point of view of quantitative evaluation, is considered.

Despite the fact that in the works listed above, some statistical analysis of the effect of structural heterogeneity on mechanical properties was carried out, there is no verification of the dependencies put forward as the results.

In this study, the influence exerted by the structure dispersion not only on the value of the ultimate strength, but also on the value of the coercive force and internal stresses of structural steels *15KhSND*, *09G2S*, *St3* is considered. The influence is assessed by the analysis of correlation dependencies between the ultimate strength, coercive force, the value of internal stresses and the uneven-grained factor, acting as a criterion for the structure dispersion.

The studied structural steels are widely used for the manufacture of various metal structures, pipeline transport, storage tanks for oil and petroleum products.

To determine the relationship between the considered values, it is necessary to analyze the effect of heat treatment on the value of coercive force, tensile strength, internal stresses and the uneven-grained factor; and to determine the correlation relationship between these parameters and to explain changes of these parameters during heat treatment.

Research methodology

Samples of *09G2S*, *St3*, *15KhSND* steels with a size of 4.0 x 70.0 x 25.0 mm were laser-cut from the sheets along the direction of its rolling. The chemical composition was determined by the *X-MET 7000* analyzer. Table 1 shows the average values obtained during 10 measurements.

The heat treatment strongly affects the structural and phase composition of steel. The inhomogeneities in the mechanical and magnetic properties of rolled steel, from which samples are made, usually do not exceed 15 % [17]. It is necessary to conduct heat treatment of experimental samples to create distinct variations of the structure and the grain composition. Therefore, before the study conducting, the samples were quenched and then tempered at different temperatures (Table 2). This is done to create variations of the structural-phase state.

Table 1

Chemical composition of the studied steels

Steel grade	Element content, wt. %							
	C	*Si*	*P**	*S**	*Cr*	*Mn*	*Ni*	*Cu*
09G2S	0.11	0.15	0.05	<0.028	0.07	1.91	0.11	0.22
St3	0.16	0.15	0.05	<0.02	0.03	0.45	0.03	0.04
15KhSND	0.16	0.71	0.06	<0.02	0.84	0.79	0.34	0.20

* He indicators of the content of carbon, sulfur and phosphorus are given according to the information specified in the quality certificates on the steel from which the samples are made.

Table 2

Heat treatment of the test samples

Steel grade	Heat treatment
09G2S	Heating up to 930 ± 20 ^{o}C quenching in water. Tempering at 200, 350, 500, 650 ^{o}C for 1 hour, air cooling
St3	Heating up to 930 ± 20 ^{o}C quenching in water. Tempering at 200, 350, 500, 650 ^{o}C for 1 hour, air cooling
15KhSND	Heating up to 930 ± 20 ^{o}C quenching in water. Tempering at 200, 300, 350, 400, 500, 550, 650 ^{o}C for 1 hour, air cooling

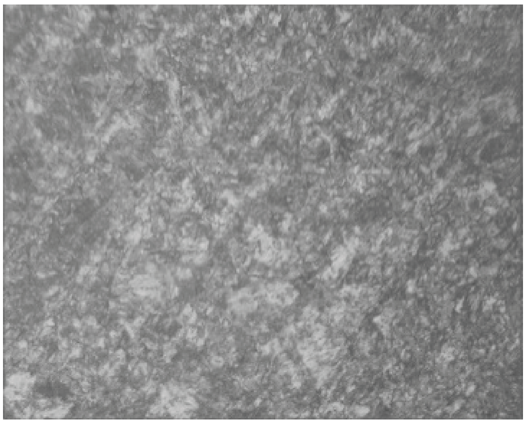
The microstructure of the samples being investigated was studied by the *JEOL 6008A* scanning electron microscope using a 3% solution of nitric acid as an etchant.

The value of the uneven-grained factor is determined by the formulas presented in [18, 19]. The distribution of grain severities observed on the micrograph is used.

The microphotographs were processed (Figure 1) in the *"SIAMS 700"* metallographic research software package (Figure 2) to calculate the uneven-grained factor. As an example, Figure 3 shows the distribution of the grain severity of the *15KhSND* steel sample. The distributions of the remaining samples have a similar character.

The grain severity is determined in accordance with *GOST* 5639-82 [21]. The calculation of the uneven-grained factor F_z is performed by the formula:

$$F_z = \frac{f_{\max} Z_{\max}}{\sum f_i Z_i}, \tag{1}$$



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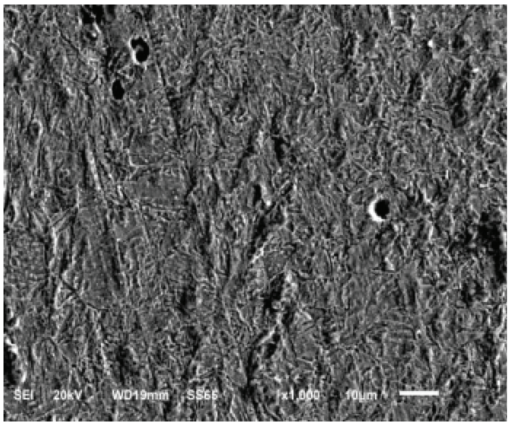

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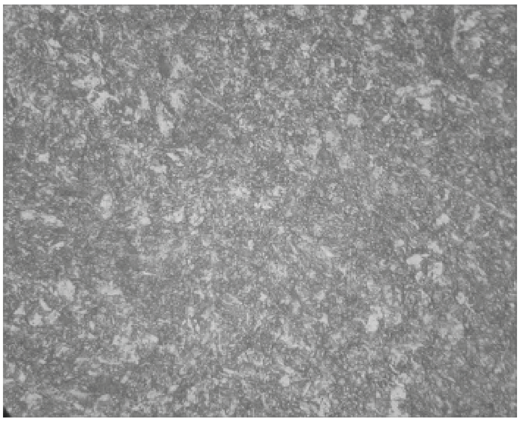

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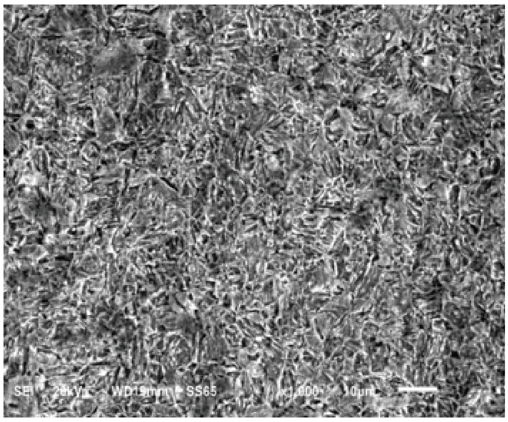

d

Fig. 1. Structure of heat-treated steel samples *09G2S* at 1,000x magnification in optical and scanning electron microscopes:

a – the structure of the sample quenched at a temperature of 950 °C, studied using an optical microscope; *b* – the structure of the sample quenched at a temperature of 950 °C, studied using a scanning electron microscope; *c* – the structure of the sample after tempering at 350 °C, studied using an optical microscope; *d* – the structure of the sample after tempering at 350 °C, studied using a scanning electron microscope

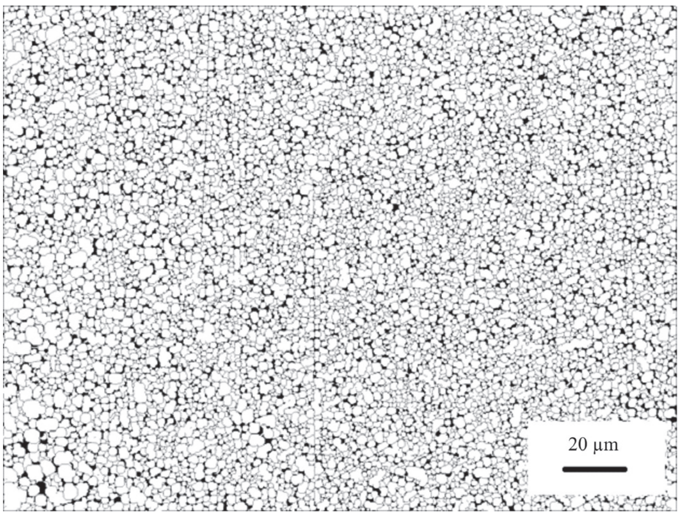

Fig. 2. Microstructure of a sample heated to 930 °C and quenched in water, made of rolled steel *09G2C*, obtained by processing microphotographs in the *SIAMS 700* software package

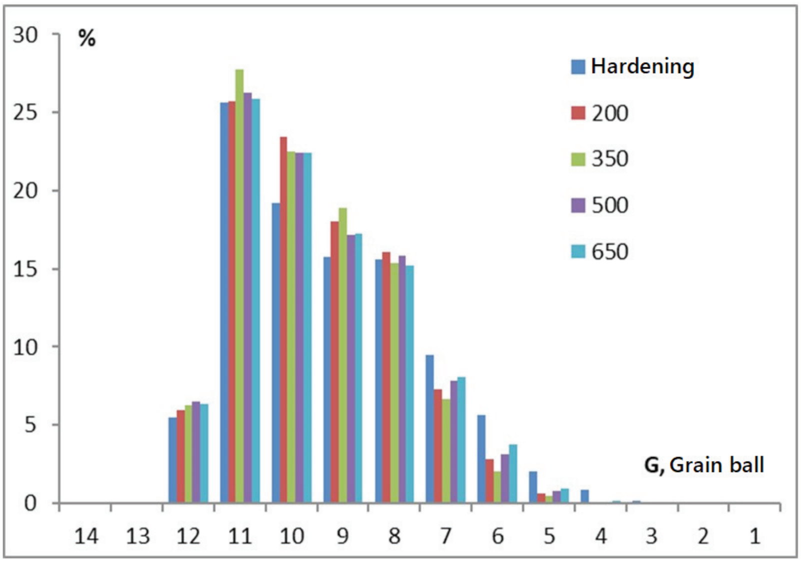

Fig. 3. Histogram of the percentage distribution of grains by points for micro-sections of heat-treated samples made of *15KhSND* steel by grain size [20]

where f_i – is the proportion of grains with a certain severity, %; f_{max} – is the proportion of grains that occupy the maximum part on the cross-section, %; Z_i – is the grain severity; Z_{max} – is the grain severity that occupies the maximum part on the cross-section.

Results and discussion

The values of the uneven-grained factor obtained in the study [20] are shown in Figure 4. It can be noted that the highest value in the magnitude of the uneven-grained factor is observed in a sample tempered at temperature of 200 °C. This is due to the beginning of the process of violation of the coherence of the lattice of martensite and cementite [22–24], as a result of the beginning of carbon separation processes [24, 25]. During these processes, a region with a carbon-depleted phase with low hardness is formed in the material, as well as a new phase in the form of ferrite and cementite. The fragmentation of the martensite phase occurs, which leads to an increase in the number of grains with a higher severity.

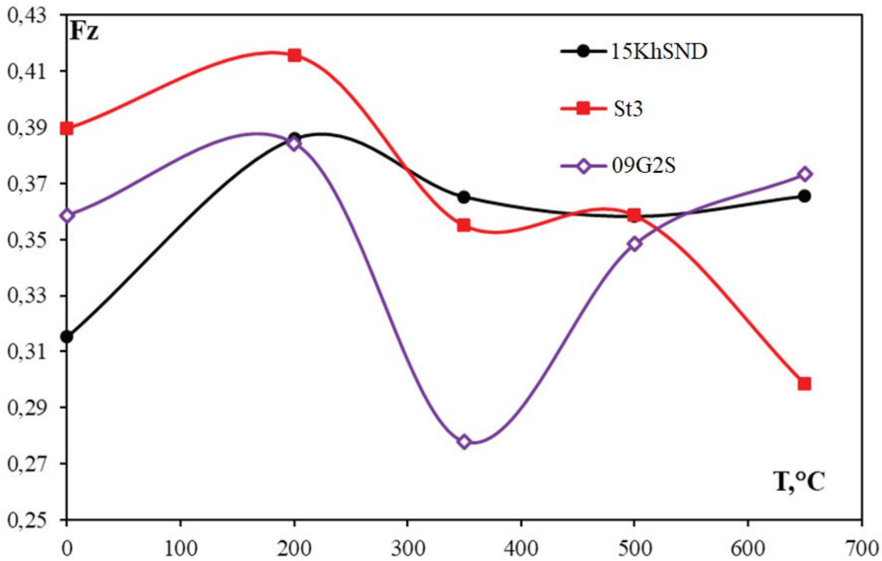

Fig. 4. Change in the value of the factor of different grain size F_z for samples made of *15KhSND* steel with different heat treatment [20]

The magnitude of internal stresses was determined according to the method [26]. It is made by comparing the data obtained on the samples under study with the data of the reference sample, which was an annealed one. The results are shown in Figure 5 [25]. A general-purpose automatic X-ray diffractometer *DRON-7* was used to take X-ray diffraction patterns.

Stress-strain diagrams were obtained with the help of an *IR-50* tensile testing machine. During the analysis, the data on the magnitude of the ultimate strength of the investigated materials subjected to different heat treatment were specified (Figure 6).

The magnitude of coercive force was determined by the *KRM-C-K2M* structurescope (Figure 7). It steadily decreases with increasing tempering temperature. This is due to the changes in the structural and phase composition of steels. It is noted in [27] that changes in the coercive force are associated with the

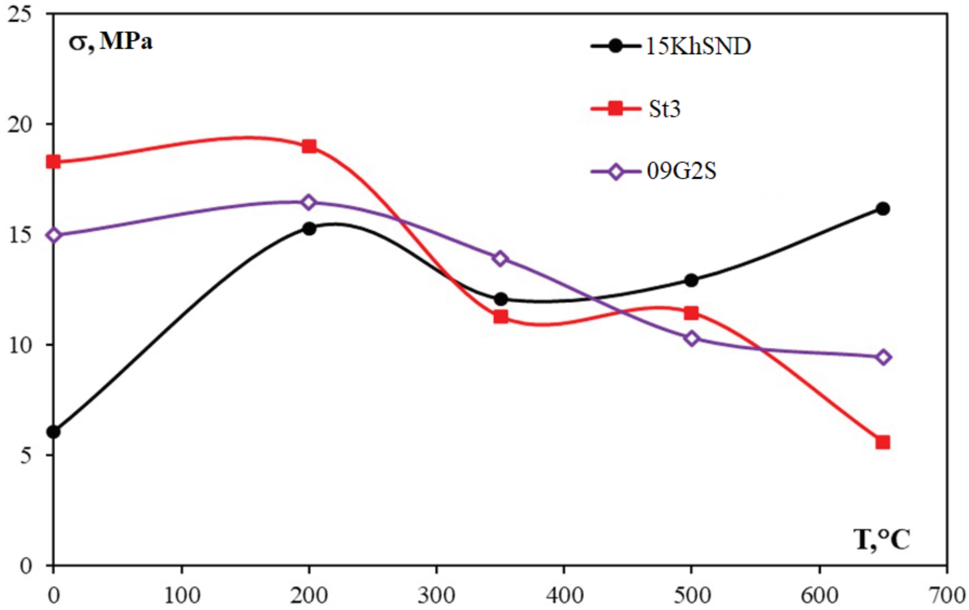

Fig. 5. Dependence of the change in the magnitude of internal stresses on the tempering temperature of structural steels

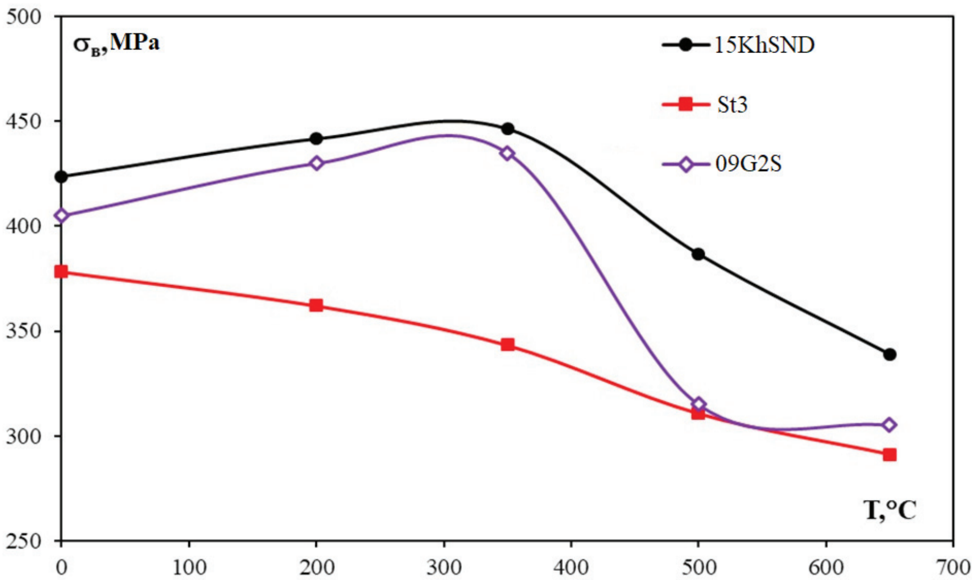

Fig. 6. Dependence of the change in the value of the ultimate strength on the tempering temperature of structural steels

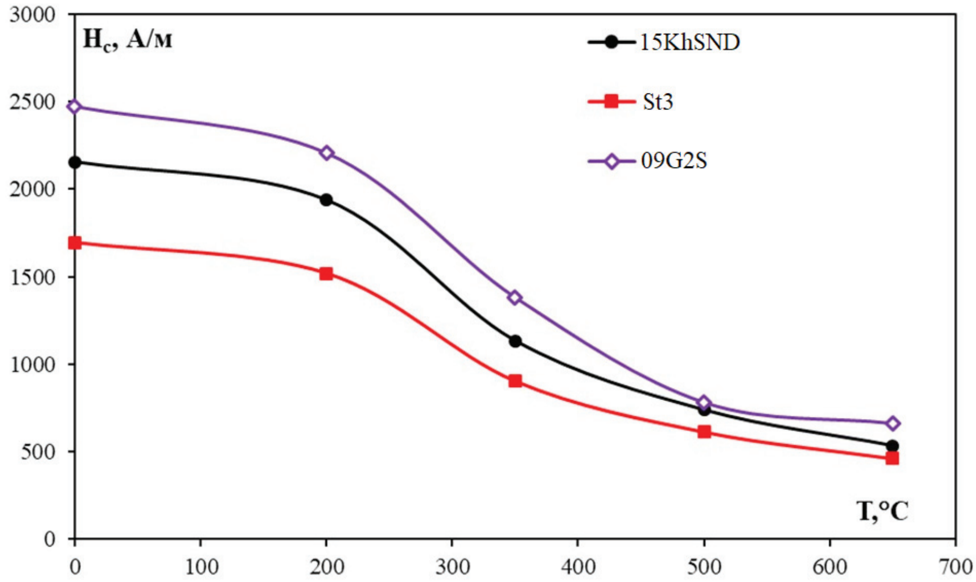

Fig. 7. Dependence of the coercive force on the tempering temperature of the investigated steels

processes of decay for the martensitic structure and the presence of cementite components in various magnetic states.

There are known works [28, 29], in which the magnetic parameters of steel were used to determine structural changes: coercive force, magnetic permeability, relaxation coercive force, differential magnetic permeability, etc.

The experimentally established correlation between the magnetic properties of a ferromagnet, the structure and mechanical properties is shown in [30]. However, it should be noted that regularities of this kind are determined only for a certain class of steels, for example, carbon steels *30*, *35*, *45*, *U8*, *U10*, *U12* subjected to quenching and tempering at different temperatures [31]. The significant influence of heat treatment on the structure and properties of steel, which can be considered on the coercive force and hardness, is shown in [29].

When analyzing the relationship, correlation dependences of magnetic and mechanical properties for steels belonging to different groups, the dependences cease to be of a general direct nature, and it is often difficult to determine the properties of interest. This is due to the fact that the structures formed during heat treatment and their characteristics (the amount, distribution and properties of martensite, retained austenite, carbides) are more dependent on the interaction of alloying elements that are part of the steel, their percentage content, including carbon, the nature as well as magnitude of temperature influences [32].

It is necessary to make an assessment by statistical and regression analysis to understand the influence of the structure dispersion on the magnetic and mechanical properties of steel. Figures from 8 to 10 show the dependences of the uneven-grained factor on various parameters characterizing the steel properties. They are obtained in laboratory conditions. In addition, these graphs show the predicted values for the *Y*-value of the uneven-grained factor calculated from the magnitude of internal stresses.

The regression analysis for the data in Figure 8 [33, 34] allows obtaining the information about regression statistics. Its main indicators are shown in Table 3.

The *R*-squared or the determination coefficient in the analysed model is 0.885. It suggests that the used parameters have a relationship that with a probability of 88.5% can be explained using the proposed model. Because the determination coefficient is greater than 0.5, then the relationship is considered satisfactory.

ε is the standard error for the regression model. This value shows how much the predictions of the values for the parameter *Y* do not correspond to the true value. Usually, the permissible limits defined on the base of ε lies within +/- 2-3 values.

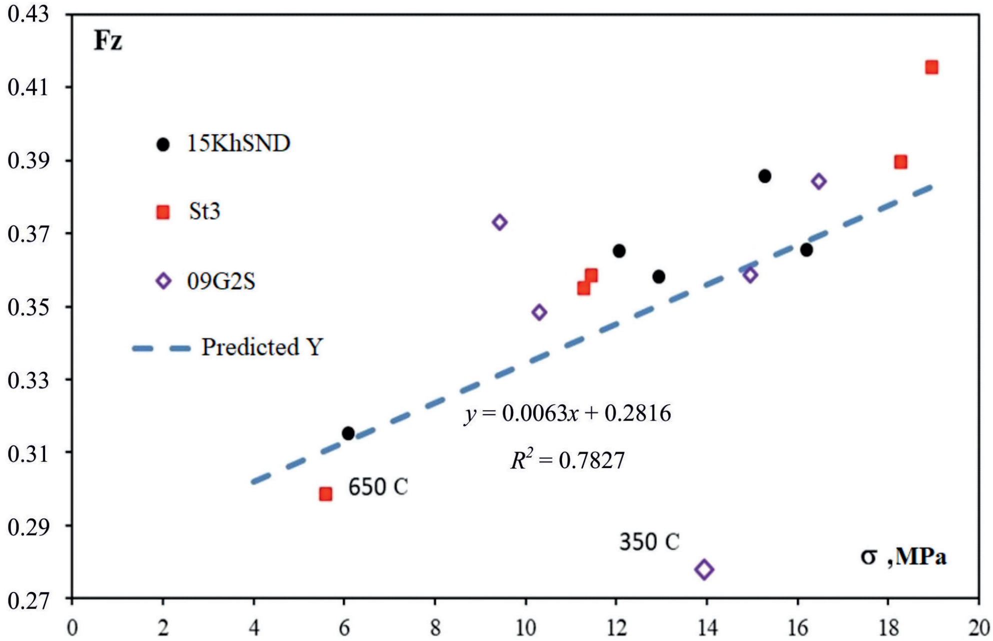

Fig. 8. The value of the grain size factor *Fz* depending on the value of internal stresses (stresses of the second kind) for heat-treated samples made of structural steels

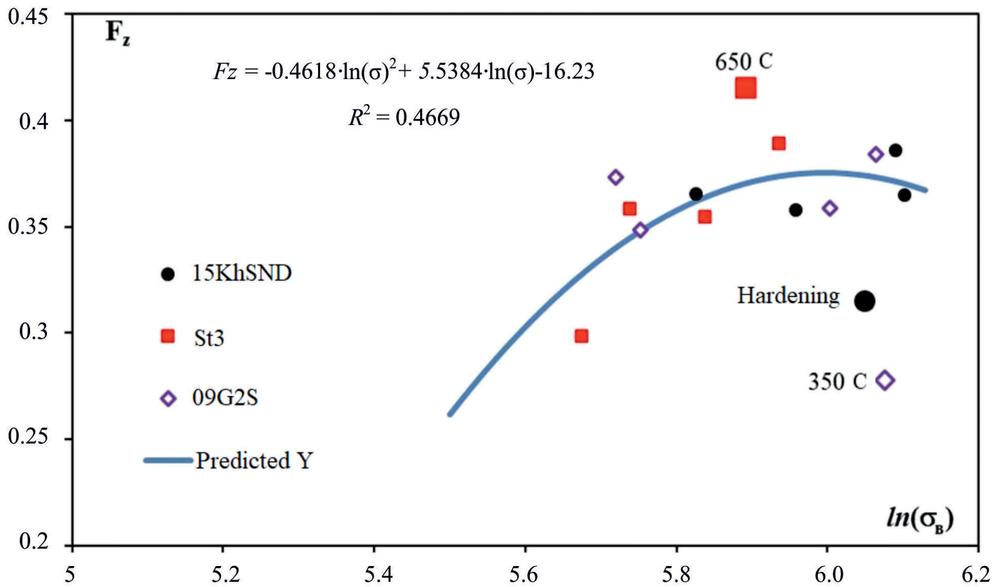

Fig. 9. The value of the factor of different grain size *Fz* depending on the logarithm of the ultimate strength value for heat-treated specimens made of structural steels

In this case, the equation characterizing the linear regression model is:

$$Y = aX + \beta \pm \varepsilon. \qquad (2)$$

In this case, $\varepsilon = 0.014$. ε shows how large the error of predicting one value from another is. In the diagram, the prediction limits based on the ε-value are defined as:

$$G = \widehat{Y}_i \pm 2\varepsilon, \qquad (3)$$

where $\widehat{Y}_i$ is the predicted value of Y.

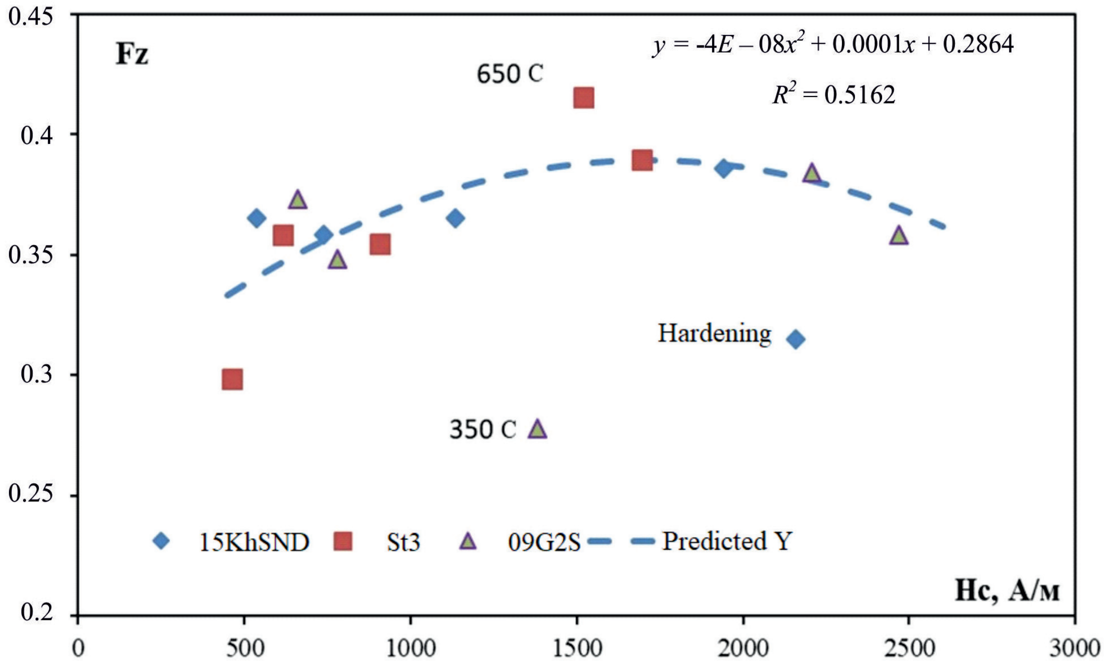

Fig. 10. The value of the factor of different grain size *Fz* depending on the value of the coercive force for heat-treated specimens made of structural steels

Table 3

Regression statistics

Multiple *R*	0.885
R-square	0.783
Normalized *R*-square	0.765
Standard error	0.014
Observations	14

With a value of $\pm 2\cdot\varepsilon$, 95 % the data points are located within these defined limits.

The adequacy of the proposed linear regression model can be verified by examining the residuals of the model, which are determined for each X as:

$$U_i = Y_i - \widehat{Y}_i. \tag{4}$$

The graph of the dependence of the residuals on the predicted values of *Y* is shown in Figure 11. There is a necessary condition that characterizes the adequacy of the analysed dependence for such graphs. It is the absence of characteristic “patterns” for the nonequilibrium distribution, depending on the *Y* values. For the dependence shown in the figure 11 in the location of the point cloud, there are no obvious patterns, which can tell us about the correctness of the found linear regression.

Table 4 shows the values required for the regression analysis. The Y_p coefficient corresponds to the *Y* value, provided that all parameters in the model are equal to 0. It means that the model does not introduce the other factors effects on the analysed parameters. X_{p1} shows the weightage of the parameter *X* over *Y*. The internal stresses within this model affect the uneven-grained factor with a weight of 0.0063. The sign before the number indicates the influence exerted on the uneven-grained factor: the greater the internal stress, the greater the value of the uneven-grained factor.

In addition, the values for the parameter *Y* at the intersection of the *X* axis with a confidence interval of 0.95 are presented.

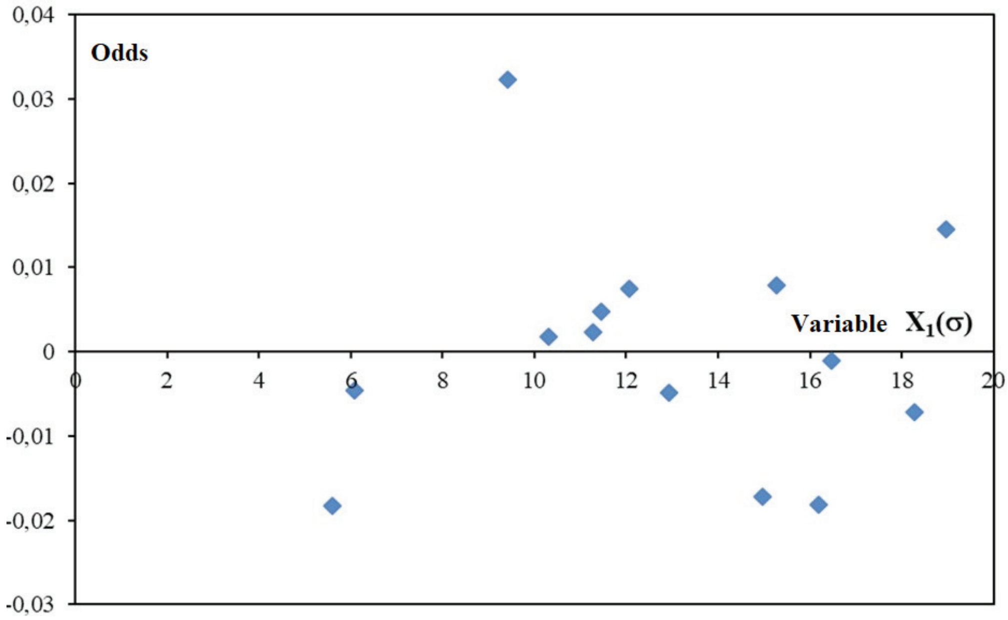

Fig. 11. Dependence of the residuals for the magnitude of the internal stresses obtained for steels of different grades on the hardness at different heat treatment of samples

Table 4

Data obtained from regression analysis

	Coefficients	Standard error	*t*-statistics	*P*-value
Y_P	0.282	0.013	21.908	4.8E-11
X_{P1}	0.006	0.001	6.574	2.64E-05
	Low 95%		High 95%	
Y-intersection	0.254		0.309	
Variable X_1	0.004		0.008	

The results of the one-way analysis of variance for the obtained data [35–37] are presented in Table 5. Where "*SS*" is the sum of squares of deviations, "*df*" is the degree of freedom, the graph "*MS*" is the mean-square value, "*F*" is the criterion of the actual *F*-distribution.

A statistical significance was tested by comparing variance due to between-group variation and variance due to intra-group variation. The obtained intra-group variances are compared using the *F*-test. It determines whether the difference between the average values is statistically significant and whether the ratio of variances is greater than 1. The *F*-significance shows the difference between the average values. This value is insignificant. It is concluded that there is a null hypothesis. Here is a dependency correlation between the grain size factor and the surface hardness of steel.

Table 5

Results of one-way analysis of variance

ANOVA					
	df	*SS*	*MS*	*F*	Significance of *F*
Regression	1	0.009	0.009	43.214	2.64E-05

The hypothesis about the influence of the considered parameters on each other is tested by the dispersion analysis. Several values of the grain size factor are analysed. They are obtained for samples with different heat treatment mode. The samples contain an equal number of elements.

Figure 12 shows the statistical characteristics of the studied data. Samples 1 and 2 are a set of values of the grain size factor obtained during several processing of microstructure images for different values of ultimate strength. Sample 3, in contrast to 1 and 2, was obtained when determining the grain severity by its area.

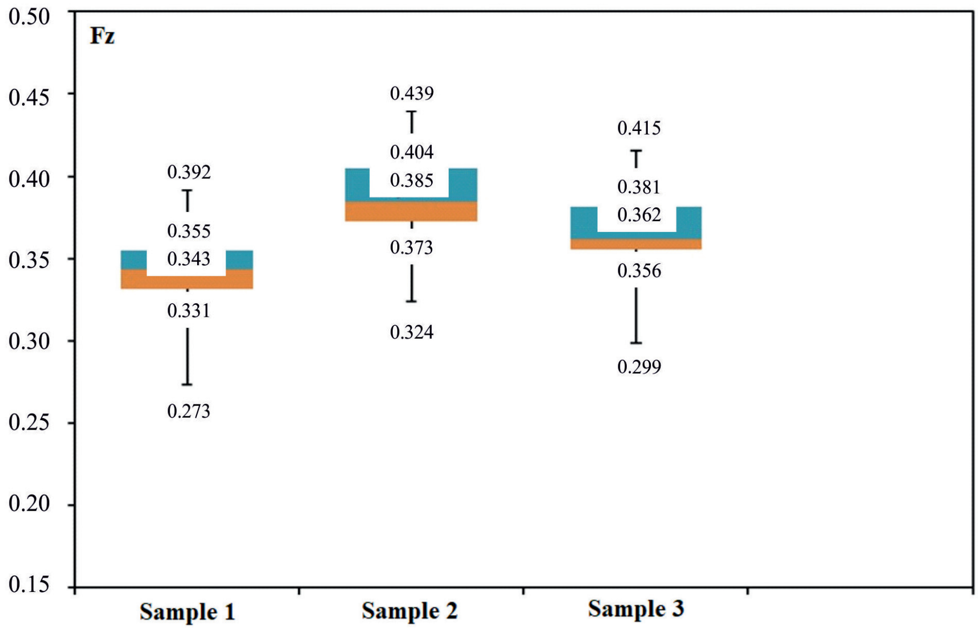

Fig. 12. A block diagram obtained by analyzing samples of the value of the grain size factor obtained with different estimates of the grain size

The choice of the method for calculating the grain size factor does not have a significant effect on the presence of a relationship between this value and the value of internal stresses. It is shown in the block diagram. However, the difference in the average values of the samples can be unexpected. Therefore, a statistically proved conclusion about the unambiguous influence of the factors on each other cannot be made.

The variance amount (data spread) for the samples has approximately the same value. It is the main condition determining the correctness of the method application for the variance analysis.

Analysis of test statistics, which in this case has the form of F-distribution or Fisher distribution, is shown in Figure 13.

The average value of the F-distribution obtained for the analysed dependence is 1.08. It is characterized by 13 and 28 degrees of freedom. The criterion for rejecting or accepting the null hypothesis is the value of $F0$, which is 4.915. The probability p has a value of 5.3358 or more is 0.00034 with a random magnitude having a Fisher distribution for the analysed dependence. When compared with the significance level of 0.05, it can be seen that p is significantly less than it, which indicates that the null hypothesis is rejected, and the difference in the average values for the analyzed samples cannot be explained only by chance.

The analysis described above is carried out for the dependencies presented in Figures 8 and 9.

Figures 14 and 15 show the Fisher distributions obtained by analysing the dependencies of $\ln(\sigma)$ and H_c.

It can be concluded that the average values for the samples are statistically significantly different from each other and the considered model (dependence) is statistically proved.

The dependences can be described by a linear (with the internal stresses) and a polynomial curve in the figures from 8 to 10. The presence of such dependences suggests that the dispersion of the system (the

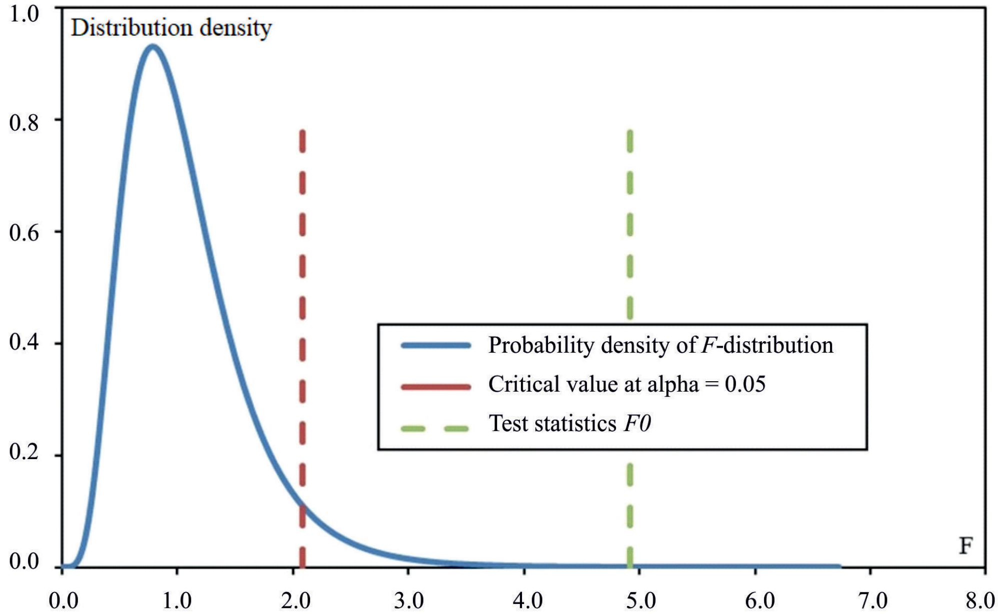

Fig. 13. Test statistics obtained from the analysis of the samples under consideration

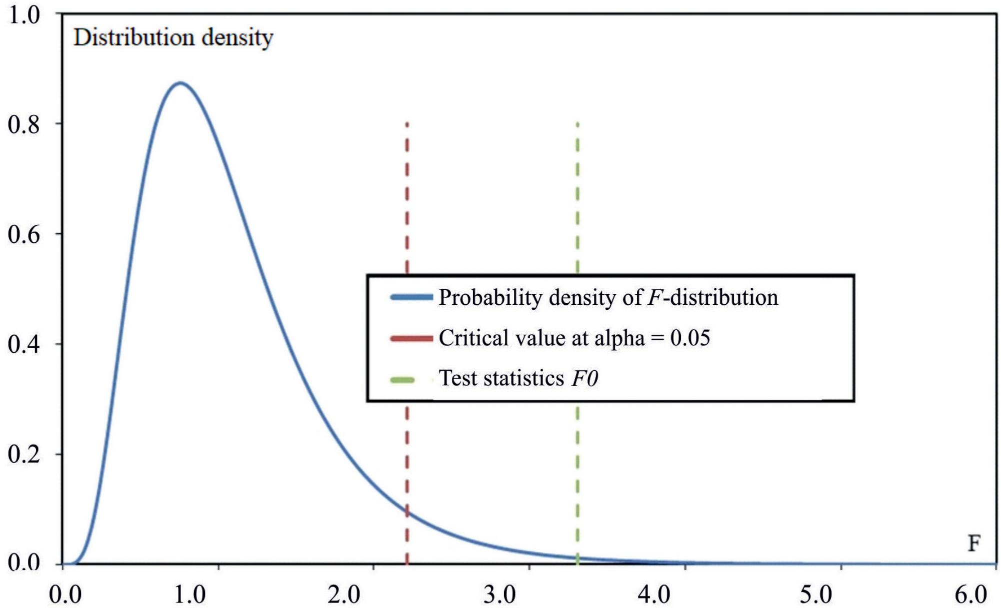

Fig. 14. Test statistics obtained from the analysis of the considered samples obtained for ln(σ)

factor of grain size) plays a significant role in the mechanism of formation of the ultimate strength, internal stresses, and the coercive force of the steels under consideration. The observed dropouts of points from the dependences found for the studied steels occur for samples with different heat treatment modes. This is due to the sharp changes in the structural and phase composition of steels. It is worth noting that the dropout of points from the revealed dependences occurs at the same temperatures: for samples made of steel 15KhSND – a sample with quenching in water; for samples of steel St3 – a sample with tempering at 650 ^{o}C; for samples made of steel 09G2S – a sample with tempering at 350 ^{o}C, which may indicate the presence of the influence of the structure dispersion on the properties under consideration.

The observed dropouts of experimental values from the found regression dependencies can be explained by the influence of other parameters into the structure and phase on the considered values.

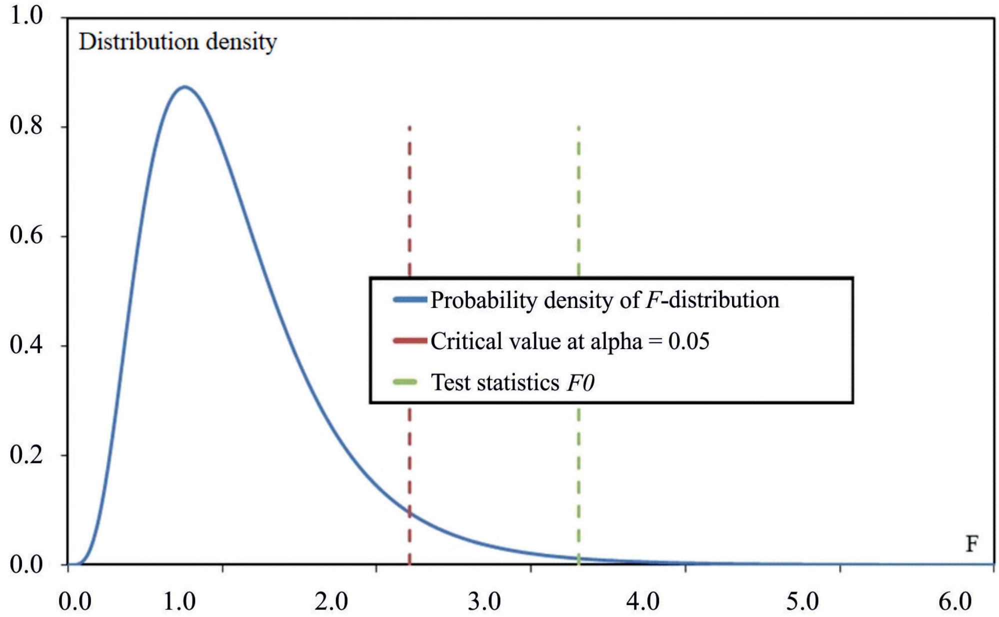

Fig. 15. Test statistics obtained from the analysis of the considered samples obtained for H_c

The microstructure research of the samples under study and the information analysis about the values of internal stresses allow to explain the observed phenomena. The dropout of a hardened sample made of 15KhSND steel is apparently associated with the formation of such a state of the structure in which the violation of the coherence of the lattices of martensite and cementite is not observed [23, 38-41]. Being in this state, both phases have a low density of defects in the structure of the crystal lattice [39, 42–45], which affects the value of internal stresses, making it sufficiently low compared to the internal stresses observed during a similar heat treatment for steels 09G2S and St3.

The dropout in the values of the analyzed parameters for a sample made of 09G2S steel tempered at a temperature of 350 °C can be explained by the processes of steel softening arising from a decrease in the density of dislocations and various structural defects that accumulate on carbide inclusions, which are the compound of manganese with carbon [23, 43–47], and leading to a decrease in internal stresses. In addition, it reduces the magnitude of internal stresses and the process of decomposition of martensite into ferrite and cementite, which occurs during medium tempering, and diffusion of carbon from carbon-enriched martensite regions [42, 45]. The phases of ferrite and depleted martensite formed during such a process have a lower hardness compared to the initial phase of martensite, which causes a decrease in the magnitude of internal stresses and, as a consequence, softening [38, 47].

The deviation from the found dependencies may be due to the process of the cementite particles coagulation and an increase in the average grain size for a sample made of St3 steel tempered at 650 °C. These processes lead to the equilibrium state of the structure [23, 38–42]. An increase in the average grain size and a decrease in the number of grains observed on a microsection leads to an increase in the length of high-angle boundaries, which leads to a decrease in the magnitude of internal stresses, and therefore, the distortions of the crystal lattice that they cause. The process of grain enlargement stops when the "critical size" is reached. The steel softening and the softer phases formation significantly affect the values of the coercive force and the ultimate strength. The processes occurring during this heat treatment also lead to a decrease in the value of the grain size factor.

Conclusions

1. The general satisfactory correlations are observed for the ultimate strength, internal stresses, coercive force and the grain size factor for steels 09G2S, 15KhSND and St3. The mathematical analysis of the obtained dependencies is carried out. Its results indicate the relationship between the analysed parameters.

It shows that the determining of the grain size factor value according to various criteria (area or grain diameter) does not significantly affect the relationship between this value and the ultimate strength, the internal stresses value and the coercive force.

2. The obtained research results show that the observed dropouts of points corresponding to characteristic thermal effects lead to certain structural and phase changes. They affect the steel structure homogeneity and the distortions in the crystal lattice that are caused by the large-angle boundaries and other factors. The difference in the processes taking place in the steels under consideration is associated with the percentage of alloying elements in it.

3. The analysis performed can be regarded as a concept for the development of the structural definition of the internal mechanisms of a multiphase system, which affect the mechanical and magnetic properties of steels. The use of the given data on the effect of the structure dispersion on steel parameters will allow predicting the dangerous states of structures arising under mechanical loads, as well as developing the most effective diagnostic methods.

References

1. Novikov V.F., Neradovskii D.F., Sokolov R.A. Ispol'zovanie kvazistaticheskikh petel' magnitnogo gisterezisa dlya kontrolya struktury stali [The using of quasi-static magnetic hysteresis loops to control steel structures]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Mashinostroenie, materialovedenie = Bulletin PNRPU. Mechanical engineering, materials science*, 2016, vol. 18, no. 2, pp. 38–49. DOI: 10/15593/2224-9877/2016.2.03.

2. Brnic J., Turkalj G., Canadija M., Niu J. Experimental determination and prediction of the mechanical properties of steel 1.7225. *Materials Science and Engineering: A*, 2014, vol. 600, pp. 47–52. DOI: 10.1016/j.msea.2014.01.097.

3. Zambrano O.A., Coronado J.J., Rodríguez S.A. Mechanical properties and phases determination of low carbon steel oxide scales formed at 1200° C in air. *Surface and Coatings Technology*, 2015, vol. 282, pp. 155–162. DOI: 10.1016/j.surfcoat.2015.10.028.

4. Nie B., Xu S., Zhang Z., Li A. Surface morphology characteristics and mechanical properties of corroded cold-formed steel channel sections. *Journal of Building Engineering*, 2021, vol. 42, p. 102786. DOI: 10.1016/j.jobe.2021.102786.

5. Chen M., Xing Sh., Liu H., Jiang Ch., Zhan K., Ji V. Determination of surface mechanical property and residual stress stability for shot-peened SAF2507 duplex stainless steel by in situ X-ray diffraction stress analysis. *Journal of Materials Research and Technology*, 2020, vol. 9, iss. 4, pp. 7644–7654. DOI: 10.1016/j.jmrt.2020.05.028.

6. Zhao M.H., Han X.C., Wang G., Xu G.T. Determination of the mechanical properties of surface-modified layer of 18CrNiMo7-6 steel alloys after carburizing heat treatment. *International Journal of Mechanical Sciences*, 2018, vol. 148, pp. 84–93. DOI: 10.1016/j.ijmecsci.2018.08.021.

7. Sandomirskii S.G. Korrelyatsionnye zavisimosti mezhdu mekhanicheskimi svoistvami i magnitnym parametrom stali 40Kh [Correlation dependences between mechanical properties and magnetic parameter of the 41CR4 steel]. *Mekhanika mashin, mekhanizmov i materialov = Mechanics of Machines, Mechanisms and Materials*, 2019, no. 3 (48), pp. 43–50.

8. Gorkunov E.S., Mitropolskaya S.Yu., Osintseva A.L., Vichuzhanin D.I. Issledovanie deformatsii i otsenka napryazhenii v materialakh s uprochnennym poverkhnostnym sloem magnitnymi metodami [Magnetic methods for deformation investigation and stress estimation in surface-hardened materials]. *Fizicheskaya mezomekhanika = Physical Mesomechanics*, 2009, vol. 12, no. 2, pp. 95–104. (In Russian).

9. Poletika I.M., Egorova N.M., Kulikova O.A., Zuev L.B. Ob ul'trazvukovom kontrole neodnorodnosti mekhanicheskikh svoistv goryachekatanoi stali [Supersonic testing of mechanical property uniformity in hot-rolled steel]. *Zhurnal tekhnicheskoi fiziki = Technical Physics Journal*, 2001, vol. 71, no. 3, pp. 37–40. (In Russian).

10. Zheng Ch., Li L., Yang W., Sun Z. Relationship between microstructure and yield strength for plain carbon steel with ultrafine or fine (ferrite+cementite) structure. *Materials Science and Engineering: A*, 2014, vol. 617, pp. 31–38. DOI: 10.1016/j.msea.2014.08.050.

11. Zheng Ch., Li L. Effect of microstructure on mechanical behavior for eutectoid steel with ultrafine- or fine-grained ferrite+cementite structure. *Materials Science and Engineering: A*, 2017, vol. 688, pp. 83–91. DOI: 10.1016/j.msea.2017.01.082.

12. Ueji R., Tsuchida N., Terada D., Tsuji N., Tanaka Y., Takemura A., Kunishige K. Tensile properties and twinning behavior of high manganese austenitic steel with fine-grained structure. *Scripta Materialia*, 2008, vol. 59, iss. 9, pp. 963–966. DOI: 10.1016/j.scriptamat.2008.06.050.

13. Abedi H.R., Zarei Hanzaki A., Ou K.-L., Yu C.-H. Substructure hardening in duplex low density steel. *Materials and Design*, 2017, vol. 116, pp. 472–480. DOI: 10.1016/j.matdes.2016.12.020.

14. Bhattacharyya J.J., Nair S., Pagan D.C., Tari V., Lebensohn R.A., Rollett A.D., Agnew S.R. Elastoplastic transition in a metastable β-Titanium alloy, Timetal-18 – An in-situ synchrotron X-ray diffraction study. *International Journal of Plasticity*, 2021, vol. 139, p. 102947. DOI: 10.1016/j.ijplas.2021.102947.

15. Motaman S.A.H., Haase Ch. The microstructural effects on the mechanical response of polycrystals: a comparative experimental-numerical study on conventionally and additively manufactured metallic materials. *International Journal of Plasticity*, 2021, vol. 140, p. 102941. DOI: 10.1016/j.ijplas.2021.102941.

16. Motaman S.A.H., Roters F., Haase Ch. Anisotropic polycrystal plasticity due to microstructural heterogeneity: a multi-scale experimental and numerical study on additively manufactured metallic materials. *Acta Materialia*, 2020, vol. 185, pp. 340–369. DOI: 10.1016/j.actamat.2019.12.003.

17. GOST 6996–66. *Svarnye soedineniya. Metody opredeleniya mekhanicheskikh svoistv* [State Standard 6996–66. Welded joints. Methods of mechanical properties determination]. Moscow, Standards Publ., 2005. 62 p.

18. Grokhovskiy V.I. [Possibilities of digital microscopy in metallography]. *Tsifrovaya mikroskopiya: materialy shkoly seminara* [Digital microscopy. School-seminar materials]. Ekaterinburg, USTU-UPI Publ., 2001, pt. 1, pp. 18–20. (In Russian).

19. Pomazova A.V., Panova T.V., Gering G.I. Vliyanie raznozernistosti struktury na korrozionnuyu stoikost' naruzhnoi poverkhnosti trub iz uglerodistoi stali 20, primenyaemykh v teploenergetike [Influence of the uneven grain structure on the corrosion resistance of the outer surface of pipes made of carbon steel 20 used in heat power engineering]. *Vestnik YuUrGU. Seriya: Metallurgiya = Bulletin of the South Ural State University. Series: Metallurgy*, 2014, vol. 14, no. 4, pp. 37–44.

20. Sokolov R.A., Novikov V.F., Muratov K.R., Venediktov A.N. Opredelenie vzaimosvyazi faktora raznozernistosti i skorosti korrozii konstruktsionnoi stali [Determination of the relationship between the factor of grain size factor and the corrosion rate of structural steel]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2020, vol. 22, no. 3, pp. 106–125. DOI: 10.17212/1994-6309-2020-22.3-106-125.

21. *GOST 5639–82. Stali i splavy. Metody vyyavleniya i opredeleniya velichiny zerna* [State Standard 5639–82. Steels and alloys. Methods of detection and determination of grain size]. Moscow, Standards Publ., 2003. 45 p.

22. Syugaev A.V., Lomaeva S.F., Reshetnikov S.M., Shuravin A.S., Sharafeeva E.V., Surnin D.V. The effect of the structure-phase state of iron-cementite nanocomposites on local activation processe. *Protection of Metals*, 2008, vol. 44, no. 4, pp. 367–371. DOI: 10.1134/S0033173208040097. Translated from *Fizikokhimiya poverkhnosti i zashchita materialov*, 2008, vol. 44, no. 4, pp. 395–399.

23. Schastlivtsev V.M., Mirzaev D.A., Yakovleva I.L. *Struktura termicheski obrabotannoi stali* [Structure of heat treated steel]. Moscow, Metallurgiya Publ., 1994. 288 p.

24. Callister W.D. *Materials science and engineering: an introduction*. 6th ed. Hoboken, NJ, Wiley, 2020. 848 p. ISBN 978-0471135760.

25. Sokolov R.A., Novikov V.F., Muratov K.R., Venediktov A.N. Influence of surface treatment of construction steels on determination of internal stresses and grain sizes using X-ray diffractometry method. *Materials Today: Proceedings*, 2019, vol. 19, pt. 5, pp. 2584–2585. DOI: 10.1016/j.matpr.2019.09.015.

26. Gorelik S.S. *Rekristallizatsiya metallov i splavov* [Recrystallization of metals and alloys]. Moscow, Metallurgiya Publ., 1978. 568 p.

27. Chulkina A.A., Ul'yanov A.I. Vliyanie magnitnykh svoistv tsementita na koertsitivnuyu silu vysokouglerodistykh stalei posle zakalki i otpuska [Influence of the magnetic properties of cementite on the coercive force of high-carbon steels after quenching and tempering]. *Fizika metallov i metallovedenie = The Physics of Metals and Metallography*, 2009, vol. 108, no. 6, pp. 581–588. (In Russian).

28. Shcherbinin V.E., Gorkunov E.S. *Magnitnye metody strukturnogo analiza i nerazrushayushchego kontrolya* [Magnetic methods of structural analysis and non-destructive testing]. Ekaterinburg, Ural Branch of the RAS Publ., 1996. 266 p.

29. Mikheev M.N., Gorkunov E.S. Magnitnye metody nerazrushayushchego kontrolya strukturnogo sostoyaniya i prochnostnykh kharakteristik termicheski obrabotannykh izdelii (obzor) [Magnetic methods for non-destructive testing of the structural state and strength characteristics of heat-treated products]. *Defektoskopiya = Russian Journal of Nondestructive Testing*, 1985, no. 3, pp. 3–21. (In Russian).

30. Mikheev M.N., Gorkunov E.S. *Magnitnye metody strukturnogo analiza i nerazrushayushchego kontrolya* [Magnetic methods of structural analysis and non-destructive testing]. Moscow, Nauka Publ., 1993. 252 p.

31. Bida G.V., Nichipuruk A.P. *Magnitnye svoistva termoobrabotannykh stalei* [Magnetic properties of heat-treated steels]. Ekaterinburg, Ural Branch of the RAS Publ., 2005. 218 p.

32. Novikov I.I. *Teoriya termicheskoi obrabotki metallov* [Theory of heat treatment of metals]. Moscow, Metallurgiya Publ., 1978. 392 p.

33. Ryan T.P. *Modern regression methods*. 2nd ed. Hoboken, NJ, Wiley, 2008. 672 p.

34. Sprent P., Smeeton N.C. *Applied nonparametric statistical methods*. 3rd ed. London, UK, Chapman & Hall/CRC, 2001. 470 p.

35. Scheffe H. *The analysis of variance*. New York, Wiley, 1959. 267 p.

36. Faraway J.J. *Practical regression and anovausing R*. Available at: https://cran.r-project.org/doc/contrib/Faraway-PRA.pdf (accessed 24.09.2021).

37. The R Development Core Team, ed. *The R manuals*. Available at: https://cran.r-project.org/manuals.html (accessed 24.09.2021).

38. Babicheva R.I., Semenov A.S., Dmitriev S.V., Zhou K. Effect of grain boundary segregations on martensitic transformation temperatures in NiTi bi-crystals. *Pis'ma o materialakh = Letters on Materials*, 2019, vol. 9 (2), pp. 162–167. DOI: 10.22226/2410-3535-2019-2-162-167.

39. *Wollenberger H.J.* Point defects. *Physical metallurgy*. Ed. by R.W. Cahn, P. Haasen. Amsterdam, Elsevier, 1996, vol. 2, pp. 1621–1721. ISBN 978-0-444-89875-3. DOI: 10.1016/B978-044489875-3/50023-5.

40. Rohrer G.S. *Structure and bonding in crystalline materials*. Cambridge, Cambridge University Press, 2004. 552 p. ISBN 9780511816116. DOI: 10.1017/CBO9780511816116.

41. Novikov I.I. *Defekty kristallicheskogo stroeniya metallov* [Defects in the crystal structure of metals]. Moscow, Metallurgiya Publ., 1975. 208 p.

42. Kleiner L.M., Larinin D.M., Shatsov A.A., Spivak L.V. Fazovye i strukturnye prevrashcheniya v nizkouglerodistykh martensitnykh stalyakh [Phase and structural transformations in low-carbon martensitic steels]. *Fizika metallov i metallovedenie = The Physics of Metals and Metallography*, 2009, vol. 108, no. 2, pp. 161–168. (In Russian).

43. Gao F., Heinisch H., Kurtz R.J. Diffusion of He interstitials in grain boundaries in α-Fe. *Journal of Nuclear Materials*, 2006, vol. 351, pp. 133–140. DOI: 10.1016/j.jnucmat.2006.02.015.

44. Hart E.W. On the role of dislocations in bulk diffusion. *Acta Metallurgica*, 1957, vol. 5, iss. 10, p. 597. DOI: 10.1016/0001-6160(57)90127-X.

45. Courtney T.H. *Mechanical behavior of materials*. Singapore, McGraw Hill, 2000. 752 p. ISBN 978-1577664253.

46. Li M., Kirk M.A., Baldo P.M., Xu D., Wirth B.D. Study of defect evolution by TEM with in situ ion irradiation and coordinated modeling. *Philosophical Magazine*, 2012, vol. 92, pp. 2048–2078. DOI: 10.1080/14786435.2012.662601.

47. Noyan I.C., Cohen J.B. *Residual stress – measurement by diffraction and interpretation*. New York, Springer, 1987. 285 p. ISBN 978-1-4613-9570-6.

Conflicts of Interest

The authors declare no conflict of interest.