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Structure formation and properties of overheated steel depending on thermokinetic parameters of crystallization

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ABSTRACT

Purpose: The aim of the proposed research is to investigate the mutual influence of the temperature of an overheated melt and its cooling rate during crystallization on the formation of the cast structure and mechanical properties of structural steels.

Design/methodology/approach: Two structural medium-carbon steels were melted in induction furnace and poured from temperatures 1520-1670°C into casting moulds with different heat removal ability. This ensured the crystallization and structure formation of the studied steel castings at cooling rates (V_c) of 5°C/sec (sand-clay mould), 45°C/sec (steel mould), 350°C/sec (water cooled copper mould). It was studied a change of structure formation, mechanical characteristics depending on the temperature-kinetic conditions of the processing of the melt. Based on the processing of the array of obtained experimental data using linear regression analysis and a software package, interpolation models and their graphic images obtained allow a quantitative assessment of the established patterns of structural characteristics and mechanical properties of the studied steels depending on melt temperature (T, °C) and its cooling rate (V_c, °C/sec) during crystallization and structure formation.

Findings: Among the technological factors that determine the formation of the cast structure and the mechanical properties of steels, the dominant role is played by the intensity of heat removal during the solidification of castings. The high cooling rate of the melt during crystallization determines an increase in the number of crystallization nuclei due to an increase in the degree of supercooling of the melt, eliminates the negative effect of the high overheating temperature of the metal before casting.

Research limitations/implications: In the future, the results can be complemented by studies of the influence of the duration of isothermal exposure of the melt at different temperatures of superheating and cooling conditions.

Practical implications: The obtained mathematical models (regression equations) that determine the mutual influence of the cooling rate and the temperature of the melt overheating on the structure and mechanical properties of the studied steels make it possible to obtain steel castings with predetermined properties at the level of properties of wrought steel of similar chemical composition.

Originality/value: Interpolation models that allow a quantitative assessment of the established patterns of structural characteristics and mechanical properties of the studied steels depending on the melt temperature (T, °C) and its cooling rate (V_c, °C/sec) during crystallization and structure formation are obtained.

Keywords: Steel, Overheating, Structure, Crystallization, Cooling rate

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MATERIALS

1. Introduction

Currently, the extensive use of foundry technologies in mechanical engineering is due to the ability to quickly obtain castings of various shapes and sizes close to finished products, low production costs and significant reduction in the volume of machining and metal waste. However, in some cases, cast products are inferior to rolled products due to the presence of segregations, transcrystallinity, heterogeneity and porosity in certain zones of the ingots. Also, high requirements for uniformity and dispersion of the cast structure, strength, viscosity and brittle fracture resistance are not always ensured.

The solution to the problem of improving the properties of cast steel products is possible by developing means of technological influence on liquid, crystallizing and solid metal. In particular, providing the necessary nonequilibrium and structural microheterogeneity of the melt before casting, controlling the processes of nucleation and growth of the solid phase, as well as structure formation at the stages of liquid-phase and solid-phase transformations.

The optimal temperature range for casting steels into foundry moulds is 30-50°C above the temperature of their equilibrium liquidus. At higher temperatures of melt overheating during casting, the grain size in steel castings increases significantly, causing a decrease in their resistance to brittle fracture.

Based on modern ideas about the processes of melting, crystallization and structure of microheterogeneous melt, it becomes possible to control the phase-structural state and properties of steel castings by optimizing the thermokinetic parameters for processing liquid, crystallizing and solid metal. In this case, the main technological means for controlling the structure and properties of cast steel products are the melt temperature and the cooling rate during crystallization and solid-phase transformations [1-4].

The aim of the proposed research is to investigate the mutual influence of the temperature of the overheated melt and its cooling rate during crystallization on the formation of the cast structure and mechanical properties of structural steels.

2. Experimental procedures

As an object of study, two structural medium-carbon steels were used, one of which (45HGSTFL) has an experimental chemical composition (additionally alloyed with chromium, titanium and vanadium). Complete chemical composition of the used steels is listed in Table 1.

The steels were melted in a 30 kg induction furnace. The melted steels were poured from temperatures 1520-1670°C into casting moulds with different heat removal ability. This ensured the crystallization and structure formation of standard clover-shaped samples (ISO 4990:2015) of the studied steels at cooling rates (V_c) of 5°C/sec (sand-clay mould), 45°C/sec (steel mould), 350°C/sec (water cooled copper mould).

Metallographic analysis was performed on a light microscope with a 100-fold magnification. Grain size number of steels was determined according to the ISO 643:2012 [5].

Table 1.
The chemical composition of steels

Steel	Weight fraction of elements, %							
	C	Mn	Si	Cr	Ti	V	P	S
45L	0.46	0.80	0.45	-	-	-	0.035	0.025
45HGSTFL	0.46	1.12	1.30	1.50	0.18	0.43	0.035	0.025

The density of the dendritic structure and the dispersion of the dendritic structure were determined using quantitative metallography methods [6], which guaranteed satisfactory reproducibility of the results and the possibility of estimating measurement errors.

The dispersion of the dendritic structure is the number of axial and interaxial sections that fit into the unit length of the sample. It was calculated by the formula:

$$D = \frac{n}{\sum L} \quad (1)$$

where n – the number of axial and axial sections on the secant line drawn perpendicular to the direction of the axis of the dendrites; $\sum L$ – secant line length, mm.

The density of the dendritic structure is the ratio between the areas that occupy the axial and interaxial sections of the primary cast structure. It was calculated by the formula:

$$P = \frac{\sum Lo}{\sum Lm} \quad (2)$$

where $\sum Lo$ – the number of axial sections on the secant line drawn perpendicular to the direction of the axis of the dendrites; $\sum Lm$ – the number of interaxial sections on the secant line drawn perpendicular to the direction of the axis of the dendrites.

Physical extension of X-ray lines and fine crystalline structure of cast steels was determined by the methods of X-ray analysis.

Tensile strength and yield strength were determined by the methods described in ISO 6892:2016. The average hardness was obtained by using a Vickers hardness tester (ISO 6507:2018). Toughness of steels was determined on samples with U-shaped incision according to the ISO 83:1976.

Based on the processing of the array of obtained experimental data using linear regression analysis [7,8] and a software package (Statgraphies, Mathcad), interpolation models and their graphic images were attained, which allowed a quantitative assessment of the established patterns of structural characteristics and mechanical properties of the studied steels depending on the melt temperature (T, °C) and its cooling rate (V_{c}, °C/sec) during crystallization and structure formation.

3. Results and discussion

A metallographic analysis showed (Figs. 1, 2) that, depending on the temperature-kinetic conditions of the processing of the melts and the crystallization of steels, the characteristics of their cast structure changed correlatively. At a low cooling rate of the molten steel during crystallization (V_c = 5°C/sec) and overheating in the limit of the studied temperature range 1520-1670°C, the grain size of steel 45L increases from number -1 to -2 and of steel 45HGSTFL from number 2 to -1.

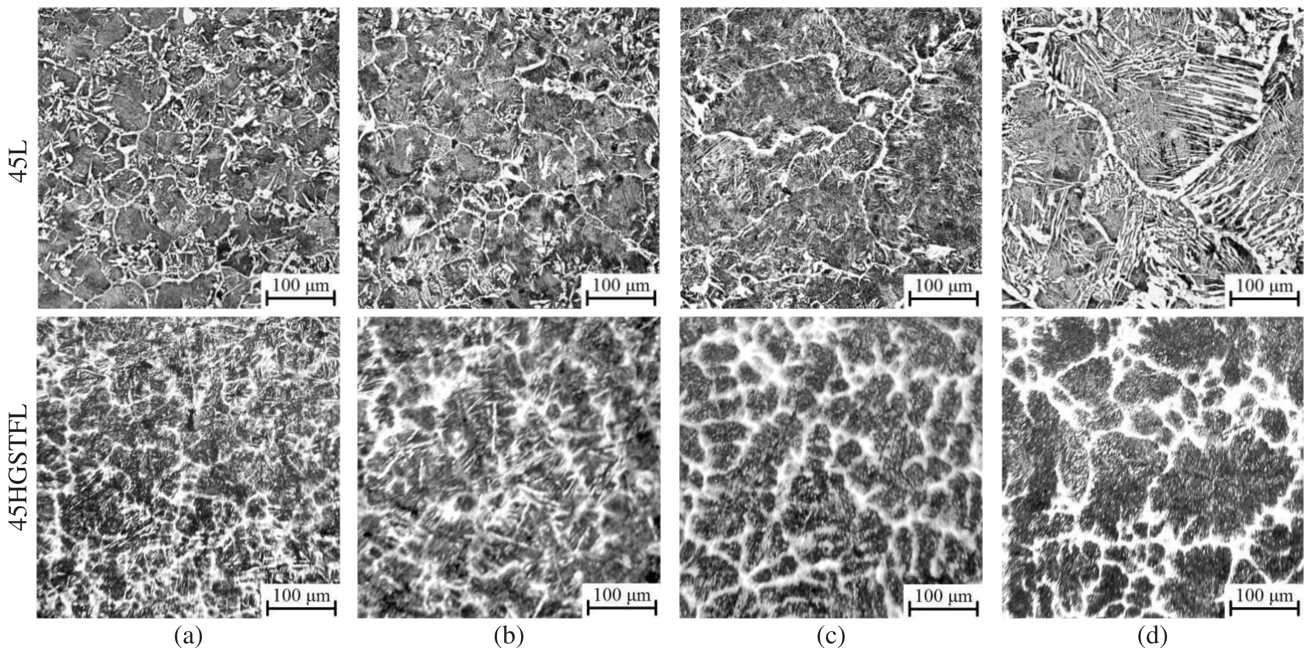
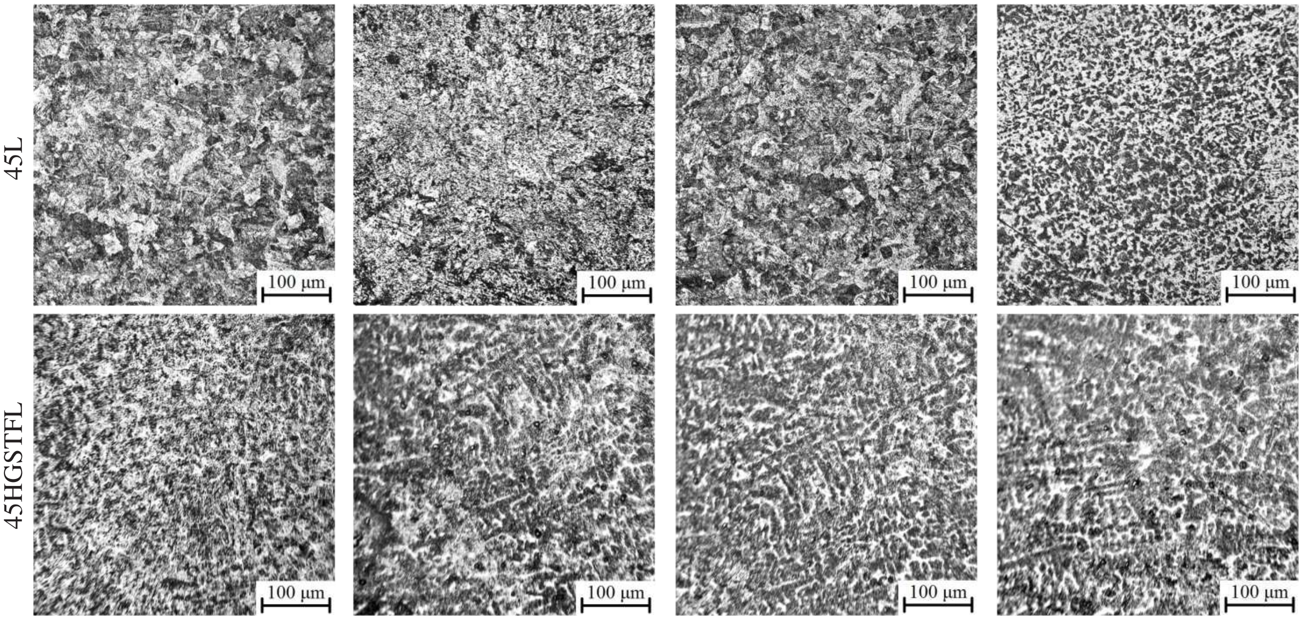


Fig. 1. Structure transformation of the steel depending on cooling rate of crystallization (5°C/sec) and melt overheating temperature: a – 1520°C; b – 1570°C; c – 1620°C; d – 1670°C



(a) (b) (c) (d)

Fig. 2. Structure transformation of the steel depending on cooling rate of crystallization (350°C/sec) and melt overheating temperature: a – 1520°C; b – 1570°C; c – 1620°C; d – 1670°C

a) b)

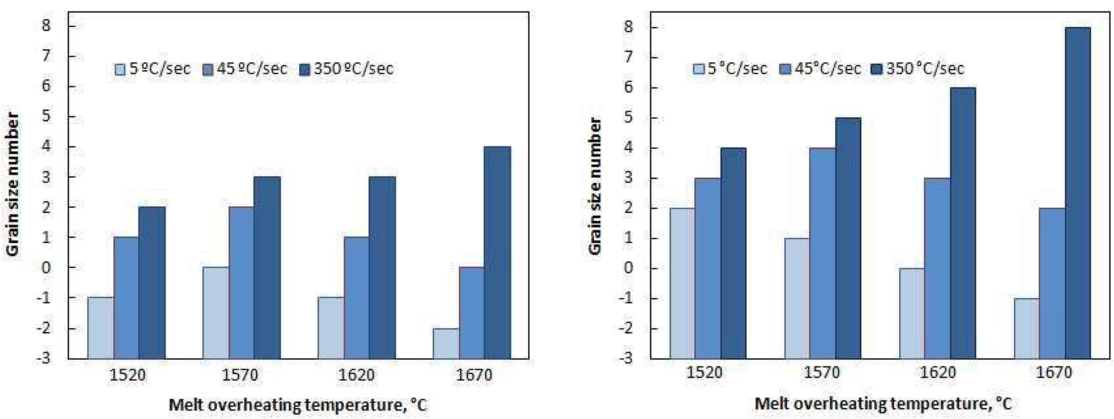


Fig. 3. Grain size number of steels depending on cooling rate of crystallization and melt overheating temperature: a – 45L steel; b – 45HGSTFL steel

With an increase in the cooling rate to 45°C/sec and 350°C/sec, a correlative change in the nature of crystallization and structure formation processes is observed, causing the corresponding grain refinement of the superheated steel due to the dominant influence of the temperature gradient of the liquid and the solid phases and the degree of supercooling of the superheated melt. Accordingly, within the limits of the experiments, the maximum increase in the dispersion of the cast structure is achieved at 350°C/sec and overheating of the melt 1670°C. Under such conditions, the grain size of steel 45L decreases to number 4, and of steel 45HGSTFL to number 8.

The graphical interpretations of the obtained regression equations (3, 4) shown in Figure 3 of the grain size changes of the studied steels indicate a significant effect of the cooling rate. An increase in the cooling rate of the melt makes it possible to neutralize the negative effect of significant overheating on the dispersion of the cast structure. The obtained mathematical models allow us to determine the optimal ratio of the melt temperature and its cooling rate during crystallization to obtain the predicted high structure characteristics in steel castings.

Grain size number (45L) = -329.856 + 0.418861 × T + 0.000038546 × T × V_c - 0.000133333 × T^2 - 0.000139811 × V_c^2;

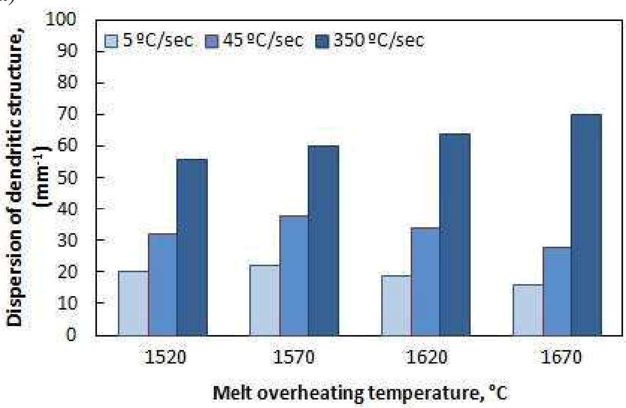
R^2 = 95.2332% (3)

Grain size number(45HGSTFL) = 14.0242 - 0.129383 × V_c + 0.000125163 × T × V_c - 0.00000544592 × T^2 - 0.000155025 × V_c^2;

R^2 = 97.4836% (4)

Changes in the temperature-time conditions of melt processing and its cooling rate during crystallization cause not only a change in grain size, but also a change in the morphology of the cast structure – the dendritic structure of castings (dispersion (Fig. 4) and density (Fig. 5) of the cast structure).

a)



b)

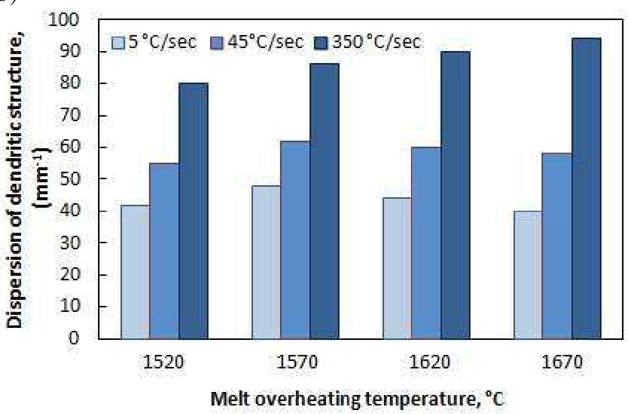
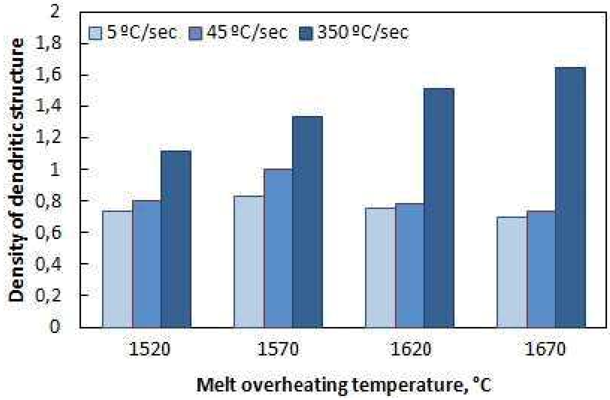


Fig. 4. Dispersion of dendritic structure depending on cooling rate of crystallization and melt overheating temperature: a – 45L steel; b – 45HGSTFL steel

a)



b)

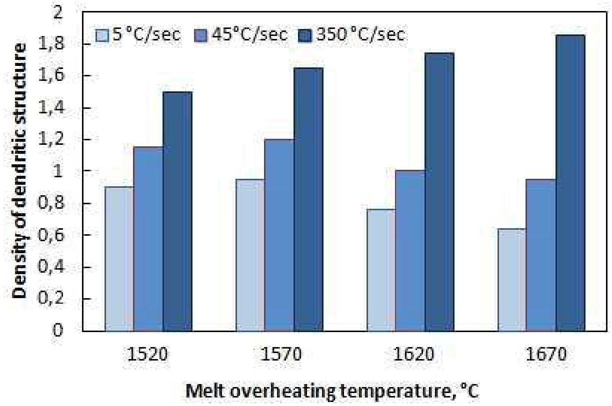


Fig. 5. Density of dendritic structure depending on cooling rate of crystallization and melt overheating temperature: a – 45L steel; b – 45HGSTFL steel

It has been established that an increase in the melt temperature from 1520°C to 1670°C leads to a decrease in the dispersion of the dendritic structure of steels by an average of 25-50% at the usual intensity of heat removal during crystallization (V_c = 5°C/sec). In this case, density of the dendritic structure in the studied range of temperatures of the melt overheat decreases by only 10-15%.

With an increase in the cooling rate of the molten steel, which crystallizes from 5°C/sec to 350°C/sec with a minimum superheat of 1520°C, its determining influence on the characteristics of the dendritic structure of the steel is realized, ensuring an increase in its dispersion by 1.5-2 times.

At the maximum overheating of the melt, the dispersion of the dendritic structure increases by 2.5-3 times in accordance with the chemical composition of the steels. The density of the dendritic structure also naturally increases with increasing heat removal during crystallization of the castings.

Changes in the temperature-time conditions of melt processing, crystallization, and solid-phase $\gamma \rightarrow \alpha$ transformations also lead to a change in the fine crystalline structure of cast steels. This is confirmed by the results of X-ray analysis (Tab. 2).

Table 2.
Physical extension of X-ray lines (110), rad$\cdot 10^{-4}$ depending on cooling rate of crystallization and melt overheating temperature

Melt overheating temperature, °C	Cooling rate on crystallization, °C/sec	45L	45HGSTFL
1520	5	45.0	72.5
	45	48.4	76.5
	350	60.2	94.0
1570	5	53.2	80.3
	45	66.0	88.4
	350	74.5	120.0
1620	5	48.5	70.5
	45	50.2	80.0
	350	70.4	110.2
1670	5	43.6	65.4
	45	48.0	73.0
	350	65.2	105.0

It was experimentally shown that an increase in the cooling rate during the crystallization of castings causes an increase in the characteristic of the physical line width (110). At all of the melt overheating temperatures, this indicates a decrease in the size of the substructure elements of the studied steels – coherent scattering zones and an increase in the dislocation density, which is most significant at 350°C/sec. The increase in the width of the (110) line in 45L steel is associated with an increase in the curvatures of the crystal lattice and the formation of martensitic structures. With additional alloying of steel with a complex of elements Cr-Mn-Si-Ti-V (steel 45HGSTFL), an increase in the physical expansion of the (110) line is due to the following features of their influence on the fine crystalline structure of steels.

Thus, silicon completely dissolves in the matrix without creating new phases, which causes the expansion of the (110) line at all cooling rates and melt overheating temperatures. When doping with titanium under conditions of slow cooling of the melt during crystallization (5°C/sec), the expansion of the line (110) increases due to the refinement of the structure, and upon rapid cooling, titanium is fixed in the solid solution and leads to additional distortions of the steel crystal lattice. With an increase in the cooling rate in the solid solution of complex alloy steels, the amount of carbon, chromium, and manganese increases substantially. Slow cooling also determines the precipitation of vanadium carbides [9], and with rapid cooling, an increase in the (110) line width is associated with its dissolution in the steel matrix. As for the melt temperature before crystallization, the largest values of the line width (110) are observed at a temperature of 1570°C, which corresponds to the practical recommendations of the foundry for normal cooling conditions. The high heat removal during crystallization of steels predetermines a significant expansion of the (110) line under all conditions of melt overheating.

Thus, it was found that, depending on the temperature and time parameters of the melt processing, crystallization and structural formation processes, cast steel structures are formed, which differ significantly in dispersion, grain size, and dendritic and fine crystalline structure characteristics. This determines corresponding changes in the mechanical properties of steel castings. So, with slow cooling (5°C/sec) and slight overheating of the melts (1520°C), the level of mechanical properties of carbon steels is quite low (Fig. X). The tensile strength for steel 45L is 420 MPa, the yield strength is 250 MPa, and Vickers hardness is 200 HV.

Overheating of the molten steel to 1670°C determines an increase in these characteristics by an average of 6-10%, due to a slight increase in the temperature gradient during crystallization, and a decrease in the level of toughness due to an grain increase in the cast structure. Under conditions of intensive cooling during crystallization (350°C/sec), the levels of mechanical properties of steel under all conditions of melt overheating increase significantly: tensile strength by 20%, yield strength by 26% in average for steel 45L. Simultaneously with the increase in the characteristics of mechanical properties, the ductility and toughness characteristics increase up to 2-3 times with the increase in the cooling rate of the melt.

With additional alloying of steel with a complex of elements Cr-Mn-Si-Ti-V the level of mechanical properties of steel increases due to an increase in the degree of alloying of a solid solution [10,11], the formation of carbide phases and nonequilibrium structures. The graphical interpretations of the obtained regression equations (5-12) shown in Figure 6 of changes in mechanical properties depending on the temperature of the melt and its cooling rate during crystallization and structure formation.

Tensile strength, MPa (45L) = $131.365 + 0.188 \times T + 1.26951 \times V_c - 0.00289024 \times V_c^2$;
$R^2 = 98.5996$ % (5)

Yield strength, MPa (45L) = $- 6451.76 + 8.256 \times T + 0.803078 \times V_c - 0.00253333 \times T^2 - 0.00168656 \times V_c^2$;
$R^2 = 96.8881$ % (6)

Toughness, J/cm^2 (45L) = $11.9218 + 0.00011774 \times T \times V_c - 0.000369948 \times V_c^2$;
$R^2 = 93.7555$ % (7)

Hardness, HV (45L) = $-98.0218 + 0.188667 \times T + 0.778138 \times V_c - 0.00168775 \times V_c^2$;
$R^2 = 96.1903$ % (8)

Tensile strength, MPa (45HGSTFL) = $12385.8 - 14.7186 \times T - 3.89427 \times V_c + 0.00273667 \times T \times V_c + 0.0047 \times T^2$;
$R^2 = 96.963$ % (9)

Yield strength, MPa (45HGSTFL) = $556.085 + 0.000495273 \times T \times V_c + 0.0000596952 \times T^2 - 0.00160093 \times V_c^2$;
$R^2 = 97.3903$ % (10)

Toughness, J/cm^2 (45HGSTFL) = $-1378.36 + 1.78003 \times T - 0.428558 \times V_c + 0.0002923 \times T \times V_c - 0.000566667 \times T^2$;
$R^2 = 97.3382$ % (11)

Hardness, HV (45HGSTFL) = $321.58 - 1.61999 \times V_c + 0.00196435 \times T \times V_c$;
$R^2 = 99.4636$ % (12)

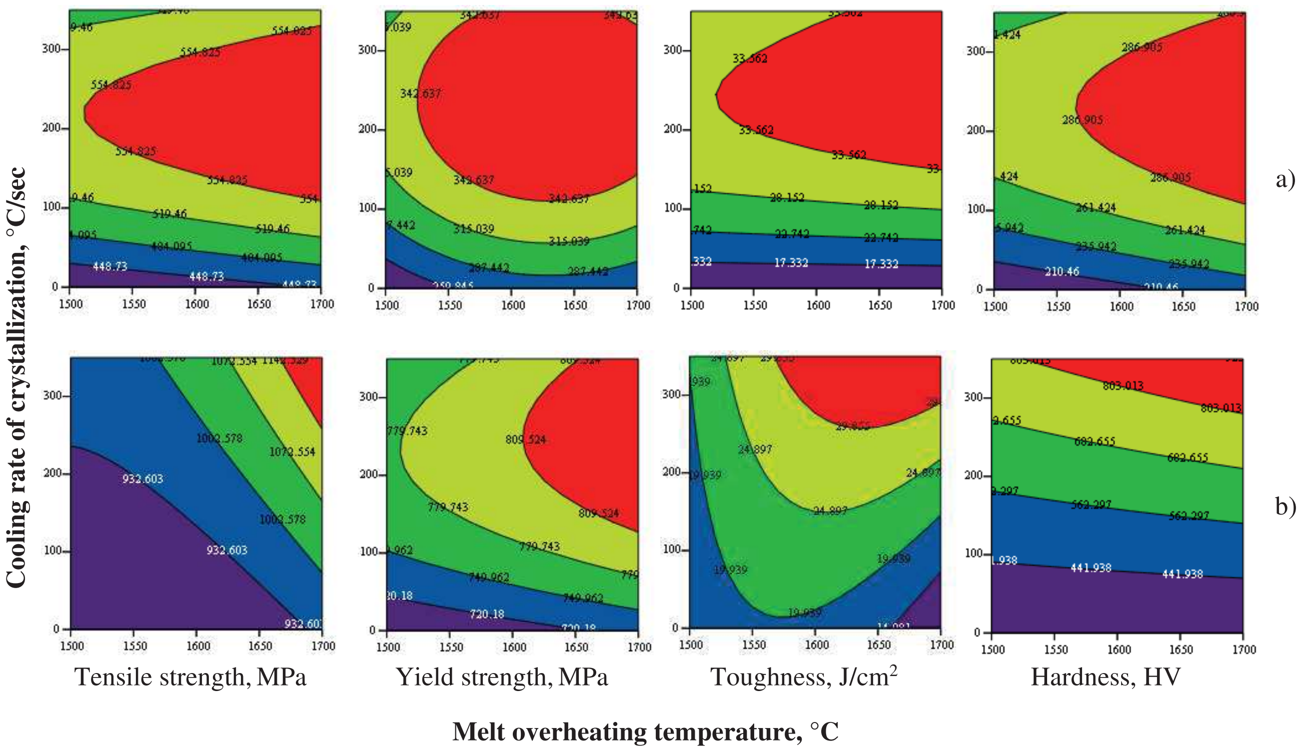


Fig. 6. The mechanical properties of carbon steels depending on the temperature-time conditions of crystallization

In this case, there is a slight increase in the hardness of steel upon overheating of the melt to 1670°C by 32 HV with a decrease in toughness by 14%.

With an increase in the cooling rate of the steel melt during crystallization, the strength, ductility, and toughness indicators for all studied melt overheating modes increase accordingly. The most significant increase in these indicators is observed at a cooling rate of the steel melt 350°C/sec. Moreover, the values of tensile strength, yield strength and hardness of steels show significant increase by 20, 25 and 65%, while simultaneously increasing their toughness by 2-3 times.

4. Conclusions

Summarizing the research results, we note that among the technological factors that determine the formation of the cast structure and the mechanical properties of steels, the dominant role is played by the intensity of heat removal during the solidification of castings. The high cooling rate of the melt during crystallization determines an increase in the number of crystallization nuclei due to an increase in the degree of supercooling of the melt, eliminating the negative effect of the high overheating temperature of the metal before casting. This ensures the formation of a more dispersed and uniform structure in steel castings, a decrease in grain size, an increase in the dispersion, density and branching of the dendritic structure, and the fine crystalline structure of steel. This achieves a significant increase in the mechanical properties of cast steels, a combination of high characteristics of strength, ductility and toughness. The obtained mathematical models (regression equations) that determine the mutual influence of the cooling rate and the temperature of the melt overheating on the structure and mechanical properties of the studied steels make it possible to obtain steel castings with predetermined properties at the level of properties of wrought steel of similar chemical composition.

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