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Thermokinetic Parameters of Solidification and Gradient Structure of Steel Castings

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Systematic studies of the influence and interrelation of the temperature and physicotechnological factors on the crystallization and formation of structural zones in steel castings are carried out. Therefore, research aimed at determining the boundaries of the optimal influence of the thermal and technological factors on the processes of crystallization and structural formation of steels is important for further use of the regularities of the formation of structural zones in castings to optimize their macro- and microstructures and physical and mechanical properties. Changing the temperature–time conditions of crystallization and post-crystallization cooling allows for regulating the processes of forming the structure of steel castings. The phase-structural state and properties of steel in different structural zones of castings depend not only on the technological parameters of casting and crystallization, but can also be intentionally modified by regulating the conditions of solidification and structure formation. The study investigates the patterns of forming the main macrostructural zones across the section of castings of carbon hypoeutectoid steels and the quantitative changes of their length depending on the thermokinetic conditions of crystallization.

Key words: steel, crystallization, structure, structural zones, cooling, melt, castings.

Проведено системні дослідження щодо впливу та взаємозв'язку температурних і фізико-технологічних чинників на кристалізацію та формування структурних зон крицевих виливків. В зв'язку з цим важливими є дослі-

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дження стосовно визначення границь оптимального впливу теплофізичних і технологічних чинників на процеси кристалізації та структуроутворення криць із подальшим використанням закономірностей формування структурних зон у виливках для оптимізації їхніх макро- й мікроструктур і фізико-механічних властивостей. Зміна температурно-часових умов кристалізації та післякристалізаційного охолодження уможливлює реґулювати процеси формування структури крицевих виливків. Від технологічних параметрів лиття та кристалізації залежать не тільки фазово-структурний стан, але й властивості криці у різних структурних зонах виливків, які можна змінювати, цілеспрямовано реґламентуючи умови тверднення та структуроутворення. В роботі досліджено закономірності формування основних макроструктурних зон по перерізу виливків вуглецевих доевтектоїдних криць і кількісних змін їхньої протяжности залежно від термокінетичних умов кристалізації.

Ключові слова: криця, кристалізація, структура, структурні зони, охолодження, розтоп, виливки.

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1. INTRODUCTION

During the production of cast engineering products, the formation of macrostructural zones of different morphology, dispersion, and length is observed in steel castings as the distance from the surface of the cast product increases.

Despite the usual attempts to ensure the formation of a homogeneous fine-grained structure throughout the volume of castings, similar to products made of rolled steel, in some cases, it is expedient to create differentiated (gradient) structures in castings to enhance special properties and working lifespan of cast products. The gradient nature of the structure of castings and its changes, depending on the thermokinetic conditions of crystallization, determine corresponding changes in mechanical properties in different sections of the castings, opening up new possibilities for engineering the structure and properties of cast products and increasing the competitive capacity of foundry technologies in engineering [1–6].

Based on the absence of systematic studies in this area, the aim of this work was to establish the patterns of formation of the main macrostructural zones across the section of castings of carbon hypoeutectoid steels and quantify changes in their length depending on the thermokinetic conditions of crystallization.

2. EXPERIMENTAL/THEORETICAL DETAILS

The study was conducted on rectangular castings of 20Л, 45Л, and

TABLE 1. The chemical composition of steels.

Steel	Weight fraction of elements, %				
	C	Mn	Si	P	S
20Л	0.21	0.52	0.25	0.025–0.030	0.028–0.032
45Л	0.46	0.60	0.23	0.025–0.030	0.028–0.032
У7Л	0.69	0.45	0.31	0.025–0.030	0.028–0.032

У7Л steels (Table 1) with dimensions of 115×130×200 mm and a weight of over 25 kg. The castings were designed to ensure one-sided predominant cooling of the end part of the castings with different intensity of heat removal V during solidification: 5°C/s (sand mould), 60°C/s (cast iron mould), 300°C/s (copper water-cooled mould). The steels were melted in an induction furnace with acidic lining using the same technically clean raw materials (ISO 4990:2015). The steel was poured at standard temperatures ($T_L + 50$°C). The investigated castings were removed from the moulds after cooling to room temperature.

The liquidus and solidus temperatures in the work were determined by a calculation method based on the chemical composition of the steels [7]. The critical points of the investigated steels were also determined by a calculation method [8] (Table 2).

When choosing the steels for experimental castings, the aim was to investigate the influence of not only the heat transfer conditions (V, °C/s) but also the temperature interval of steel crystallization (ΔT, °C) in a wide range of its changes, on the processes of structure formation, as determining parameters (Table 2).

The studies were carried out on specimens taken from the central longitudinal part of the castings, which were crystallized under conditions of directed one-sided heat transfer.

Interpolation models and their graphical representations were attained through the processing of experimental data using linear regression analysis [9, 10] and software (Statgraphics, Mathcad), allowing for a quantitative assessment of the established patterns of structural gradient of the studied steels dependent on the temperature range of crystallization (ΔT, °C) and cooling rate (V, °C/s) during crys-

TABLE 2. Temperature characteristics of the studied steels.

Steel	T_L, °C	T_S, °C	ΔT, °C	Ac_1, °C	Ac_3, °C
20Л	1510	1470	40	726	841
45Л	1485	1415	70	724	768
У7Л	1470	1357	115	735	746

tallization and structure formation.

3. RESULTS

Metallographic analysis (Fig. 1) revealed that the macrostructure of the investigated castings consists of four main structural zones: a chill zone of small equiaxed grains, a zone of columnar grains formed by transcrystallization oriented in the direction of the main prevailing heat removal, a transition zone of branched dendritic-like grains, and a zone of large equiaxed grains in the central volumes of the castings.

The chill zone, which is formed under the conditions of a significant temperature gradient and rapid cooling during the very short period of the beginning of solidification, up to the formation of the casting gap, changes according to the increase in carbon content in steels and ranges from 0.25–0.35 mm (for sand moulds) and 0.5–1.0 mm (for copper water-cooled moulds), and is not considered in our further research.

The zone of columnar crystals during solidification in the sand mould ($V = 5$°C/s) is most developed in the casting of low-carbon steel

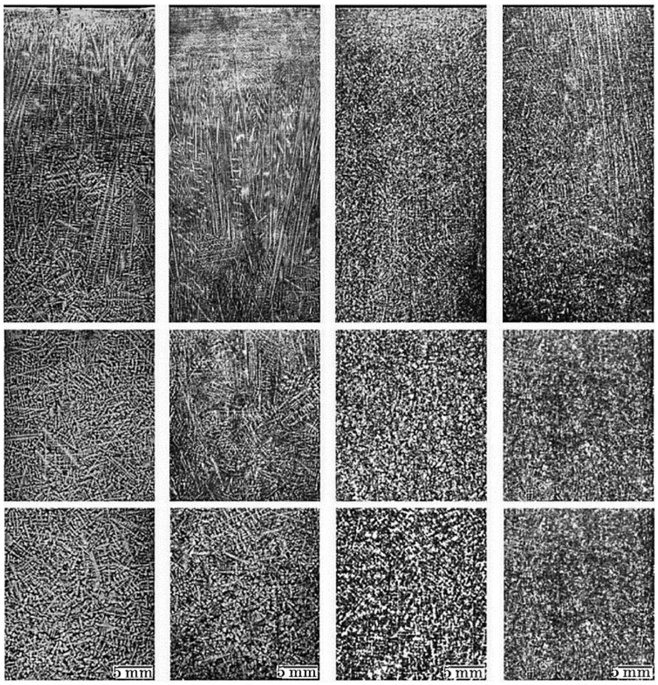

Fig. 1. Structural changes across the cross section of steel ingots under different conditions of crystallization: normal cooling, 20Л (*a*), intensive cooling 20Л (*b*), normal cooling, У7Л (*c*), intensive cooling У7Л (*d*).

20Л and is of 64 mm; for steel 45Л, it is of 49 mm; for steel У7Л, it is of 31 mm (Fig. 2). Under conditions of more intense heat removal in the cast iron mould ($V = 60°C/s$), the zone of columnar crystals increases to 75 mm (steel 20Л). When the cooling rate increases to 300°C/s, the columnar zone reaches maximum values for steel 20Л 90 mm, steel 45Л and steel У7Л, of 85 and 72 mm, respectively.

The transition structural zone of branched dendrite growth during solidification in sand form has a maximum length of 88 mm in the casting of steel 20Л, of 79 mm in steel casting 45Л and of 38 mm in steel casting У7Л. Increasing the cooling rate of the melt to 60°C/s and 300°C/s leads to a reduction in the length of this zone to 80 and 70 mm, respectively (steel 20Л), to 70 and 48 mm (steel 45Л), to 35 and 32 mm (steel У7Л).

The length of the zone of equiaxed crystals in the deeper volumes of castings is mainly determined by the thermal conductivity of the steels, which is associated with their carbon content, as well as the width of their temperature interval of crystallization. It changes during solidification in a sand mould from 48 mm to 72 mm and 131 mm in the castings of steels 20Л, 45Л and У7Л, respectively, and during solidification in ironmould, it changes from 45 mm to 70 mm and 121 mm. Under conditions of high-speed heat removal (copper water-cooled mould), the length of this zone increases with the increase in carbon content in the studied steels and amounts to 40 mm, 67 mm and 96 mm, respectively.

Interpolation equations and their graphical interpretations (Fig. 2) were obtained using regression analysis of experimental results, which allows for a quantitative assessment of the influence of the investigated thermokinetic parameters on the gradient of the structure across the cross-sections of steel castings. The dependence of the length of struc-

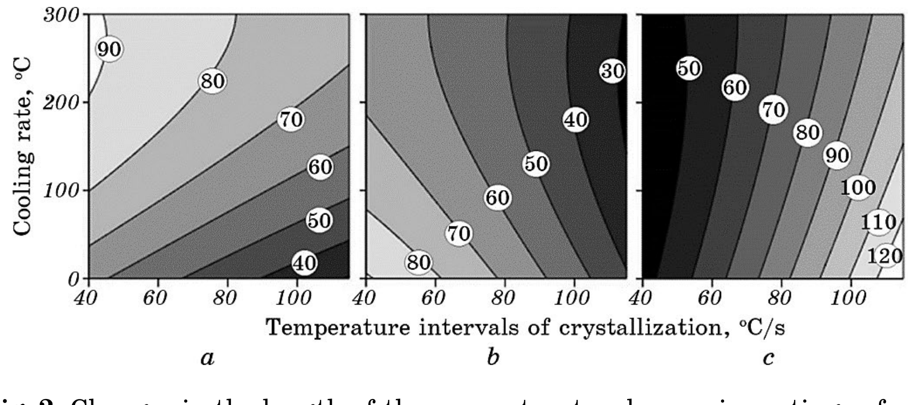

Fig. 2. Changes in the length of the macrostructural zones in castings of carbon steels depending on the temperature–kinetic conditions of casting: columnar zone (*a*), transition zone (*b*), equiaxed crystal zone (*c*).

tural zones (L, mm) on the surface cooling rate of castings (V, °C/s) and the width of the temperature interval of crystallization (ΔT, °C) for carbon hypo-eutectoid steels is described by Eqs. (1)–(3):

$$L_1 = 103.6345517681 - 0.1824172167V - 0.1975353794\Delta T + \\ +0.0002461051V^2 + 0.0006027768V\Delta T - \\ -0.0030123457\Delta T^2,\ R^2 = 0.97, \tag{1}$$

$$L_2 = 103.6345517681 - 0.1824172167V - 0.1975353794\Delta T + \\ +0.0002461051V^2 + 0.0006027768V\Delta T - \\ -0.0030123457\Delta T^2,\ R^2 = 0.97, \tag{2}$$

$$L_3 = 13.4093769999 - 0.0058261552V + 0.7269747596\Delta T + \\ +0.0001527992V^2 - 0.0012668651V\Delta T + \\ +0.0024691358\Delta T^2,\ R^2 = 0.99, \tag{3}$$

where L_1 is length of the columnar zone (mm), L_2 is length of the transition zone (mm), L_3 is length of the equiaxed zone (mm), V is surface cooling rate of castings (°C/c), ΔT is temperature interval of crystallization (°C), R^2 is correlation coefficient.

4. DISCUSSION

The experimental results indicate systematic changes in the morphology and extent of macrostructural zones in castings depending on the determining parameters of crystallization such as cooling intensity and temperature range of solid-liquid state of the melt.

The maximum values of the columnar zone length (Fig. 1, *a*) and the transition zone length (Fig. 1, *b*) are observed in low carbon steel (0.21% C) with the smallest temperature range of crystallization (40°C) during solidification under conditions of rapid melt cooling ($V = 300$°C/s). When crystallizing at a low cooling rate of the melt ($V = 5$°C/s), the transition zones in 20Л steel and equiaxed crystal zones in У7Л steel show the greatest development, respectively, with a narrow ($\Delta T = 40$°C) and wide ($\Delta T = 115$°C) temperature range of crystallization.

Graphic interpretations of the obtained regression equations (Fig. 2) allow estimating the degree of influence of the main parameters of crystallization (the cooling rate of the melt and the temperature range of steel crystallization) on the length of the investigated macrostructural zones in castings.

Thus, an increase in the length of the columnar zone is associated with a decisive influence of the increase in the cooling rate of the melt, while the widening of the temperature range of steel crystallization leads to a predictable reduction in this zone in castings.

The zone of transition crystals acquires the greatest length under conditions of slow cooling of the melt in steels with a narrow temperature range of crystallization. The widening of the crystallization interval in high-carbon steels leads to a significant reduction in the length of this zone and a weakening of the influence of the cooling rate on it.

The formation of a zone of equiaxed crystals is associated with a decisive influence of the temperature range of steel crystallization on its length for all investigated modes of cooling the melt during the solidification of castings. The widening of the crystallization interval in the given range of its changes (40–115°C) leads to a significant increase in this macrostructural zone in the central volumes of carbon steel castings.

5. CONCLUSION

Formation of macrostructural zones in steel castings is an integral part of the crystallization process and is mainly determined by cooling conditions. Although the formation of macrostructural zones in steel castings is an undesirable phenomenon, and many scientific studies are devoted to combating it and striving to create a homogeneous cast structure, we have demonstrated the possibility of controlling the process of gradient structure formation in order to enhance the special properties across the cross-section of steel castings.

As part of the research, the influence of thermokinetic parameters on the gradient structure across the cross-section of steel castings has been established. It has been shown that the length of the columnar zone is mainly determined by the rate of cooling of the melt, while the zones of transition and equiaxed crystals are determined by the temperature interval of crystallization. Moreover, the zone of equiaxed crystals is almost independent of the degree of heat dissipation from the surface of the casting.

Our study proposes both qualitative and quantitative methods for controlling the gradient structure and requires further research to determine the properties across the cross-section of castings depending on the cooling conditions. Overall, the obtained results of the study regarding the influence of thermokinetic parameters on the processes of crystallization and formation of gradient structures in steel castings open up new possibilities for predicting and purposefully influencing the structure formation and mechanical properties of cast steel castings.

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