Study of the effect of differentiated cooling modes on the structure and mechanical properties of gray cast iron

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Abstract. The effect of the differential cooling regime on the structure and mechanical properties of gray iron castings is investigated. A technical solution has been developed for the differentiated change in the cooling rate of cast iron castings. An increase in the cooling rate during dendritic crystallization was achieved by blowing the mold with compressed air. To slow down the cooling rate in the interval of eutectic transformation, an exothermic carbon-containing additive, fuel oil M-100, was used. It is shown that the use of controlled cooling can significantly increase the tensile strength of cast iron without introducing additional alloying elements into the composition of cast iron.

1. Introduction

Among the structural materials used in mechanical engineering, an important place still belongs to iron-carbon alloys, improving the quality characteristics of which is an urgent problem of foundry. Existing methods for solving this problem with the use of alloying and improving the technology of metal smelting have already largely exhausted the possibilities at ever-increasing requirements for strength properties.

It is well known that the cooling rate of a casting affects the formation of a particular cast iron structure. It is believed that with an increase in the cooling rate of the casting, the content of cementite in cast iron increases; and with a decrease in the cooling rate of the casting, the content of graphite in cast iron increases. [1-5]. However, the influence of the cooling rate in the local temperature-time ranges of cast iron crystallization is completely ambiguous; it conceptually differently affects the formation of the structure, and hence the mechanical properties of gray cast iron [6-8].

If we look at the cooling curve of gray cast iron (figure 1), then the first structurally sensitive interval is the interval of dendritic growth from the onset of crystallization until it reaches the eutectic transformation temperature. It is the interval where primary austenite dendrites are formed, and an increase in the cooling rate will lead to an increase in the dispersion of the formed structure, which will positively affect the strength characteristics of cast iron.
Figure 1. Cast iron cooling curve: $T_L$ – dendrite crystallization onset temperature; $\Delta T_{eut}$ – eutectic temperature range in which crystallization of the eutectic occurs; $T_S$ – end solidification temperature; $V_1$ – liquid phase cooling rate; $V_2$ – dendritic crystallization rate; $V_3$ – eutectic crystallization rate; $V_4$ – cooling rate of the solidified cast iron; $\tau_d$ – dendritic crystallization duration; $\tau_{eut}$ – eutectic crystallization duration.

The next structurally sensitive interval is the eutectic transformation. The composition of the eutectic and the temperature of the eutectic transformation depend on which system (stable or metastable) it occurs. When converted through a stable system, a eutectic consists of a mixture of austenite and graphite. In a metastable system, eutectic transformation occurs at higher cooling rates and eutectic - ledeburite consists of a mixture of austenite and cementite [1-6].

After the eutectic transformation, the slowdown or acceleration of cooling of the cast iron in the temperature range of recrystallization inevitably affects the ratio of perlite and ferrite in the structure of the metal base. With an increase in the cooling rate, the amount of perlite in the structure increases and its dispersion also increases. With a decrease in the cooling rate, the amount of ferrite increases, and perlite becomes first medium plate and then coarse plate, substantially losing its hardness and strength [8-11].

Moreover, despite the presence of at least three structurally sensitive intervals during crystallization and cooling — dendritic crystallization, eutectic crystallization, pearlite transformation — the main quality characteristics of cast iron are formed in the first two, that is, in the interval of dendritic and eutectic crystallization [6]. Therefore, to achieve the guaranteed structure of gray cast iron, it is necessary to increase the cooling rate in the pre-eutectic temperature range, and in the eutectic transformation interval, the solidification process should be slowed down. Differentiated cooling modes of castings in these structurally sensitive intervals are excluding the unidirectional thermokinetic effects on the metal and can solve the problem of optimizing the structure and improving the quality of cast iron castings.

2. Materials and methods
Testing the production mode of castings with differential cooling in the mold was carried out on pre-eutectic iron, crystallizing with chilling effect in a wedge sample. In such castings, mottled structures are formed [1, 5]. The experimental melts were carried out in the IPP-15 induction melting furnace in the VSTU laboratory. The chemical composition of cast iron is presented in table 1.
Table 1. The chemical composition of cast iron, wt%.

| C    | Mn | Si  | P   | S   | Cr  |
|------|----|-----|-----|-----|-----|
| 3.48 | 0.77 | 2.73 | 0.055 | 0.039 | 0.055 |

To regulate the cooling of the casting in the mold, an experimental tooling was developed and manufactured that allows simultaneously pouring of the experimental and control castings.

To slow down the cooling rate, it was decided to add an exothermic carbon-containing additive - fuel oil M-100 in the amount of 3% into the facing molding mixture. The composition of the filling mixture is sand of the Oryol quarry 2K2O202 and bentonite clay BS1T2. The moisture content of the mixture was 3%.

Two cylindrical models (control and experimental) with a diameter of 15 mm and a height of 120 mm equidistant from the riser of the sprue-feed system were formed into the lower flask. The complete assembly was sealed on a pallet (receiver). Inside the pallet was divided into two halves, one of which was supplied with compressed air. Air flow control was carried out by a reducer. The second half remained insulated from the purge by an insulating partition, which allowed the control cast to solidify in the usual way. The exothermic additive was activated by compressed air, which, when it entered the mold cavity at the initial moment, cooled it, increasing the cooling rate of the casting in the dendritic crystallization interval, and then excited the combustion reaction of the additive, accompanied by heat emission. The temperature was recorded using a platinum-alloy of platinum and rhodium (10% Rh) thermocouples. Metallographic studies of the samples were carried out using an OLYMPUS BX51M microscope. Samples were etched in a 4% HNO3 solution. Next, the mechanical properties of the control and experimental castings were investigated. The temporary resistance $\sigma_B$, N mm$^{-2}$ was determined in accordance with GOST (State Standard) 1497-84 on the test universal machine IR 5082-100. To determine the hardness of the samples under the Brinell method (GOST 9012-59), the TB 5004 hardness tester was used.

3. Results and discussion

Cooling curves control and experimental castings are shown in figure 2. As seen from the figure, it was possible to increase the cooling rate of the experimental castings 9% using a blowing chilled air in the temperature range of pouring molten metal up to the eutectic. This affected the dispersion of the dendritic structure of cast iron. The activation of the carbon-containing additive of the molding sand of the experimental casting with compressed air at the beginning of the eutectic transformation allowed to reduce the cooling rate in this structurally sensitive interval by 18%. This affected the formation of austenite-graphite eutectic, see figure 3.
Figure 2. Cooling curves of experimental (with cooling control) and control castings.

Slowing down the cooling rate in the interval of eutectic transformation, increasing the graphitizing ability of cast iron, significantly reduced the formation of eutectic carbides in its structure, respectively, reducing chilling defect formation. This is the positive effect of slowing down the cooling rate in this structurally sensitive interval by heating the mold, which is implemented without increasing the degree of eutectic of cast iron with an unchanged number of graphitizing elements of chemical composition.

Microstructure control and experimental castings shown in figure 3.

Figure 3. Microstructures of the experimental (a) and control castings (b).

Mechanical properties of experimental and control castings are shown in table 2.
Table 2. Mechanical properties of cast iron castings.

| Casting       | tensile strength, σв, N mm⁻² | hardness, HB | Index of quality σв/HB = K |
|---------------|-------------------------------|--------------|---------------------------|
| Control       | 240                           | 229          | 1.05                      |
| Experimental  | 270                           | 229          | 1.18                      |

The mechanical tests showed that the tensile strength of the metal of the experimental casting is 11% higher than the strength of the control sample and does not impair the machinability of the casting due to the absence of eutectic carbides, which in turn affects the increase in cast iron index of quality.

4. Conclusion

It is possible to increase the cooling rates of cast iron castings in the dendritic crystallization interval by blowing the mold with compressed air.

It is possible to slow down the eutectic transformation by introducing into the facing layer of the molding mixture a carbon-containing exothermic additive fuel oil M-100.

Thus, the differentiable cooling of cast iron in a sand-clay casting mold can significantly increase the tensile strength of cast iron without introducing additional alloying elements into its composition.

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