Increasing the Strength Properties of Gray Iron Castings without Introducing Additional Modifying and Alloying Additives into Its Composition

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Abstract. The effect of the differential cooling regimes on the structure and strength properties of gray iron castings in sand molds was investigated. The experimental foundry equipment was developed and assembled in order to produce experimental and control castings. This equipment allows to investigate the crystallization of two castings under initially equal pouring conditions: chemical composition, temperature and speed of mold filling with molten metal. It was shown that due to the using of the differential cooling regimes the experimental castings tensile strength was increased by 13.8% and hardness reduced by 12.3% via excluding the formation of ledeburite in the structure, which leads to increase in the quality index of cast iron by 33%.

1. Introduction

Foundry is the procurement base of engineering, so obtaining high-quality castings with improved structure and mechanical properties is an urgent task. Due to ever-increasing demands of the consumer, the existing technologies for producing castings of high-carbon alloys using modification and alloying have mostly exhausted their capabilities. Therefore, the possibility of increasing the strength of cast iron without changing its chemical composition is of great interest. It is known that the formation of the structure, and hence the properties of cast iron during crystallization and subsequent cooling process occurs in several local structurally sensitive intervals, such as dendritic crystallization, eutectic transformation and eutectoid transformation. Many researchers believe that the strength characteristics of cast iron are directly related only to the secondary recrystallization structure [1–9]. However, the secondary recrystallization structure inherit the properties from structure of primary crystallization and determined by the parameters of the primary structure, enhancing their strengthening effect in some cases and weakening in others [10–12]. Depending on the cooling rate, cast iron can crystallize both in stable (with the formation of austenite-cementite eutectic) and metastable (with the formation of austenite-graphite eutectic) systems. At high cooling rates, common for thin-walled castings, in gray cast iron usually occur ledeburite formation which leads to chilling. At low cooling rates, cast iron loses its strength properties due to the presence of free carbon in the form of graphite in its structure and an increase in the proportion of ferrite component in the metal base [13–18]. Thus, unidirectional change in the cooling rate alone does not solve the problem of increasing the strength properties with preserving the nature of gray cast iron. Therefore, it is necessary to increase the cooling rate in the interval of dendritic crystallization for dispersed dendritic structure formation and then decrease the cooling rate in the interval of eutectic transformation for exclude ledeburite formation, thereby allowing...
reduce the degree of supercooling of cast iron and crystallization in accordance to stable system. The use of differential cooling regimes can solve this problem.

2. Materials and methods
To implement the application of differential cooling regimes of gray iron castings an experimental foundry equipment that allows to investigate the crystallization of castings, with the possibility of multidirectional exposure to external factors under the same pouring conditions (such as temperature and chemical composition) was developed and assembled at the “Casting Machines and Technology” department (Figure 1).

![Figure 1. Equipment for the study of castings crystallization.](image)

Foundry equipment for the study of castings crystallization is divided into two independent segments. The cooling of the studied castings in these segments takes place according to individual regimes. A dividing wall in the pallet 1 is installed for cooling gas supply to each of the segments. The supply and control of gas flow into the pallet is carried out through the fitting 3 with a built-in reducer 4. For uniform distribution the accumulated in the pallet gas rises under pressure into the mold through a perforated plate 5. The division of the lower half of the mold 6 by a heat-insulating partition 7 makes it possible to use various compositions of
filling and facing sands to change the thermal regime of the mold. Having two independent segments 2 for supplying with various gases allows to adjust the cooling rate of the castings in the desired directions (increase or decrease the cooling rate). To increase the efficiency of gas blowing of lower half of the mold 6 and to improve the conditions of heat removal from the casting in the upper half of the mold 8, the application of prickings 9 is provided. For the castings temperature and cooling rate control the thermocouples 15 was placed both in the mixture 12, 13 and the body of the castings 16 via technological holes. As a result, each of the castings are provided with individual cooling regimes under initially same pouring conditions (such as chemical composition, temperature and speed of mold filling with molten metal) due to the common gating and feeding system 10, 14. This allows you to obtain correct data for further comparison of experimental results.

To investigate the effect of the cooling rate on the structure and properties two castings were poured: one crystallized without additional impact of the cooling rate, and the second with cooling rate control in the intervals of dendritic crystallization and eutectic transformation. Pre-eutectic cast iron of composition: C – 3.47; Si – 1.73; Mn – 0.59; P – 0.072; S – 0.112; Cr – 0.174; Ni – 0.188; Cu – 0.162; Mo – 0.01; V – 0.013; S - 0.9; Fe – the rest (% wt) was chosen for research. The degree of eutecticity (Se) is – 0.9 [19]. Melting cast iron performed in the “IST-0.06” induction crucible furnace. The pouring temperature was recorded by a type A (“VR5/VR20”) tungsten-rhenium thermocouple display unit. Metal crystallization temperature was controlled by a “KSP-4” potentiometer. Metallographic studies of the samples were carried out on Olympus BX51M modular optical microscope with Olympus SC30 digital camera for microstructure photographing. Samples were etched in a 4% HNO3 solution. Etching of samples was carried out by wiping with a cotton swab or dipping into a container with the etching reagent. Static tension tests were performed on cylindrical samples (working part diameter of 6 mm and length of 36 mm) at room temperature in accordance with GOST 1497-84 on a “TsD-40” tensile testing machine. For each option 3-5 samples were tested. Obtained data was averaged. The determination of Brinell hardness (GOST 9012-59) was performed using a “TB 5004” hardness tester. The hardness was determined at a load of 3000 kg with the indenter diameter of 10 mm. The measurement error was not greater than 1% in both tests.

3. Results and discussion
A molten metal was poured at a given temperature into a common gating and feeding system, from which it simultaneously at the same speed entered two cavitys of the lower half of the mold, which are isolated from each other by a heat-insulating partition. Cylindrical specimens with a diameter of 12 mm and a length of 125 mm were cast. The filling and facing sands of the experimental mold consisted of 6% (wt) bentonite clay and 94% (wt) quartz sand. Water was added in an amount of 3.5% (wt). An exothermic carbon-containing additive was additionally introduced into the composition of the facing sand in an amount of 2.5% (wt). At the initial moment of pouring, the mold was blown with air under a pressure of 4 atm. Upon reaching the eutectic transformation temperature, the blowing was ceased and the cooling rate was slowed down due to destruction of the exothermic carbon-containing additive introduced into the facing sand. The control casting was cooled in the normal regime (without blowing with air and without regulating the cooling rate).

The cooling curves of the control and experimental castings are shown in Figure 2.

It can be seen from Figure 2 that, by blowing the mold of experimental casting with air under excessive pressure it was possible to increase the cooling rate by 1.17 times during the primary austenite dendrites precipitation. An increase in the cooling rate led to the formation of a strong reinforcing framework in the form of numerous dendrites of primary austenite in cast iron structure. Next, a mechanism for slowing down the cooling rate in the interval of eutectic transformation was triggered due to the release of heat by previously introduced into the composition of the facing molding sand of the exothermic carbon-containing additive. This led to a decrease in the degree of supercooling of the experimental casting and further crystallization of cast iron according to a stable system with the formation of austenite-graphite eutectic (Figure 3).
Figure 2. The cooling curves of the control and experimental castings.

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

The presence of ledeburite in the structure of the control casting led to the chilling which common for mottled cast iron. The mechanical properties of the control and experimental castings are shown in table 1.

The mechanical tests showed that the tensile strength of the experimental castings is 13.8% higher than the strength of the control one. The hardness of the experimental castings was reduced by 12.3%, which led to an increase in the quality index of cast iron by 33%.

Table 1. Mechanical properties of cast iron castings.

| casting       | tensile strength, $\sigma_s$, N mm$^{-2}$ | hardness, HB | Index of quality $K^*$ |
|---------------|-------------------------------------------|--------------|------------------------|
| Control       | 232                                       | 246          | 0.9                    |
| Experimental  | 264                                       | 219          | 1.2                    |

*ratio between relative strength and relative hardness [20].
4. Conclusions

- An experimental foundry equipment has been developed and assembled in order to study the simultaneous crystallization of two castings under the same pouring conditions with obtaining different structure and properties due to an individual cooling regimes.
- It was shown that the use of a multidirectional cooling regime for experimental castings in the interval of dendritic crystallization and eutectic transformation led to an increase in the strength properties of gray cast iron without introducing additional modifying and alloying additives into its composition.

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