Possibilities of increasing the dimensional accuracy of nodular cast iron castings

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Abstract. This paper is devoted to influence of the size and number of graphite inclusions in high-strength cast iron on pre-shrinkage expansion and, as a result, on linear shrinkage and dimensional accuracy of castings. It was established that influencing the number and size of graphite inclusions it is possible to increase the dimensional accuracy of high-strength cast iron castings by two accuracy classes and significantly reduce mechanical processing allowances of cast iron in order to save metal.

1. Introduction

High-strength cast iron has a significant advantage over gray cast iron in the manufacture of equipment for rolling mills, steam turbine housings, crankshafts, wheel hubs and other parts operating under cyclic loads and under heavy wear. This material has high mechanical properties. However, along with the advantages it also has disadvantages. It is well known that high-strength cast iron has a large pre-shrinkage expansion affecting metal shrinkage.

The works [1, 2, 7] demonstrate that modification during crystallization provides a larger number of spherical graphite small-sized inclusions and improves the degree of spherical shape thus reducing the tendency to the linear shrinkage. The growth of graphite inclusions occurs throughout the entire casting crystallization process and has a significant effect on pre-expansion and final shrinkage. This process is explained by the fact that tensile stresses arise in the body of a casting.

Based on a planar model of the stress distribution in a solid during graphite grain growth the difference was shown in the dependence of the pre-shrinkage expansion on the size and number of inclusions (Figure 1) [3].

In this case, the assumptions are made that:
– the number of pressed solid bodies in the first sample is three, and in the second sample they are six;
– the degree and speed of indentation are the same;
– the volume of pressed solid bodies is the same;
– total internal stresses (σ₁) at the boundary “solid - metal” directed outward the sample are the same;
– total internal stresses (σ₂) directed to the centre of the sample depend on the area of graphite inclusions facing inward.
According to Hooke’s law, the relative elongation of the sample (L) is described by the formula [4]:

\[ L = \frac{\sigma}{E}, \]

where $\sigma$ is the internal voltage, Pa;
$E$ – Young’s modulus, Pa.

As soon as the internal stresses exceed the elastic limit of the material the elastic deformation becomes plastic deformation. Since the Young's modulus is the same in the cases under consideration, it can be assumed that the pre-preservation expansion (linear elongation of the sample) will be directly proportional $\sigma$.

According to the theory of elasticity [4], stresses of different signs inside the body are mutually balanced.

As can be seen from the above model in figure 1, for cast iron with three spherical inclusions, 1/6 of the tensile stresses are mutually balanced while for a sample with six spherical inclusions 1/3 of the tensile stresses are mutually balanced.

In this case, the elongation of the sample will be described by the formula:

\[ L = \frac{(\sigma - \sigma_{in})}{E} = \frac{\sigma_s}{E} \]

Based on a flat mathematical model, it has been shown that the various pre-shrinkage expansions in high-strength cast iron castings are determined by the number and size of spherical graphite inclusions with the same volume which can significantly affect the internal tensile stress in the region of plastic deformation of the alloy. Thus, the component of pre-expansion and, accordingly, linear shrinkage in addition to speed degree of graphitization and shape properties [10] will be determined by the difference in internal tensile stresses.

In the production of high-strength cast iron castings with spherical graphite due to the peculiarity associated with large pre-shrinkage expansion there is a difficulty in forming dimensions of castings. An analysis of the literature review showed that at present there is no complete idea of the mechanism of all shrinkage processes in the aggregate including pre-shrinkage expansion and its effect on the dimensional accuracy of casting.

The purpose of this work is to study the dimensional accuracy of cast iron samples with spherical graphite inclusions depending on the size and number of inclusions, to conduct a comparative analysis
of the influence of size and number of inclusions on the shrinkage and dimensional accuracy of casting.

2. Objects and methods of research
The object of research was high-strength cast iron with spherical graphite inclusions. For research, a technological sample was proposed in the form of two simultaneously filled in samples 400 × 40 × 40 in size located in the upper flask of 500 × 300 × 100 in order to reduce the influence of the hydrostatic alloy pressure of the on the pre-shrinkage of a sample and ease of moulding. To conduct the research for all heat amounts cast iron of the same chemical composition was selected (Table 1).

Table 1. Chemical composition of cast iron

| Items | Item content, % |
|-------|-----------------|
| C     | 3.2             |
| Si    | 0.83            |
| S     | 0.07            |
| Mn    | 2.59            |
| Fe    | 94.69           |

The chemical composition of cast iron was determined using a high-performance scanning electron microscope equipped with an energy dispersive spectrometer JED-2300 Analysis Station.

Five castings of cast iron were carried out on the IST 0.16 furnace. The charge load was 45 kg per heat. The release temperature was 1420 °C; the pouring temperature of the samples was 1370 °C. The size and amount of graphite inclusions were controlled by the exposure time after modification [5] and addition of 0.5% FS 75 ferrosilicon. In the first and second melting the modification was carried out in a ladle of 3% Sferomag® modifier 611 manufactured by Ltd “Technologiya” LLC, Chelyabinsk. The third heat was modified with 3% cerium modifier. In the next two meltings 0.5% FS 75 ferrosilicon and 3% Spheromag®611 were added. Table 2 shows composition of the modifier.

Table 2. Chemical composition of the modifier

| Modifier  | Mg   | Ca  | Ce   | Al  | Si   | P3M  | Fe    |
|-----------|------|-----|------|-----|------|------|-------|
| Spheromag® 611 | 6.30 | 1.41 | -    | 1.19| 50.3 | 0.87 | Rem.  |
| Cerium    | -    | 1.5-2| 12-13| -   | 50   | -    | Rem.  |

After cooling and knocking the samples were numbered and the linear size was measured with an accuracy of ± 0.05 mm. To determine the size and number of graphite inclusions a LIM 305 microscope was used. Samples were prepared according to the standard metallographic method.

3. Results of the experiments and discussion
The results of the investigation are presented in Table 3 taking into account [6].

Table 3. Summary of the results of field experiments

| № of melting | № sample | The exposure time after modification, min | Length, mm | Linear shrinkage, % (mm) | Graphite size Ø, mm | Number of inclusions, pcs / mm² | Shrinkage, % |
|--------------|----------|----------------------------------------|------------|--------------------------|-------------------|-------------------------------|-------------|
| 1            | 13       | 1                                      | 394.5 ±0.1 | 0.9863 (5.5 mm)          | 0.100             | 21                            | 1.4         |
| 2            | 14       | 4                                      | 398.0 ±0.5 | 0.9950 (2 mm)            | 0.015             | 56                            | 0.06        |
The result of the experiment was mathematically evaluated to verify the randomness of the sample length deviation. To estimate the probable density of the normal distribution of a random variable and the percentage of its falling into segments equal to the standard deviation the “Three Sigma Rule” is used which states that almost all values of a normally distributed random variable lie in the range \((\bar{x} - 3\sigma; \bar{x} + 3\sigma)\) what is approximately from a probability of 0.9973 normally distributed random variable lies in the specified interval (\(\bar{x}\) is the true value not obtained as a result of the sample processing). Figure 2 clearly shows the probability density distribution area [8].

![Graph of the probability density of the normal distribution and the percentage of the random variable falling on the segments equal to the standard deviation](image)

**Figure 2** Graph of the probability density of the normal distribution and the percentage of the random variable falling on the segments equal to the standard deviation

To find out how much on average the actual measurements deviate from their average value the standard deviation of the sample distribution of the obtained data was determined by the example of samples 13 and 15. Mathematical processing of experimental results:

\[
\sigma_{13} = \sqrt{\frac{(394.5 - 394.4)^2 + (394.5 - 394.6)^2}{2}} = 0.1
\]

(3)

\[
\sigma_{15} = \sqrt{\frac{(399.5 - 400.4)^2 + (399.5 - 398.6)^2}{2}} = 0.9
\]

(4)

When combining the obtained results, the scatter interval is shown in Figure 3.

![Interval for finding sizes of samples 13 and 15](image)

**Figure 3.** Interval for finding sizes of samples 13 and 15

The general accuracy class for the length of 400 mm is: 400.4 - 394.2 = 6.2 mm. Comparing with [9], such dimensional tolerances correspond to accuracy class 12. If we conditionally divide the schedule into the first and second half of the modifier and take the average size equal to 397.3 mm we
get that the first half \((397.3 - 394.2 = 3.1 \text{ mm})\) corresponds to the 11th class, and the second half \((399.5 - 397.3 = 2.2 \text{ mm})\) corresponds to class 10.

According to table 3, the dependence of the final sizes of the samples on the size of graphite inclusions and their quantity is shown in Graphs 1 and 2.

**Graph 1.** Dependence on the size of graphite inclusions

**Graph 2.** Dependence on the number of graphite inclusions

Therefore, pre-shrinkage expansion, linear shrinkage and the accuracy class depend on the range in which graphite inclusions are located. Using the experiment and obtaining high-strength cast iron with spherical graphite with various inclusions and amounts of inclusions from the time of modification it
is shown that by dividing the effective time of the modifier into the first or second halves of the modifying effect it is possible to increase the dimensional accuracy of casting according to [9] by 2 classes, which will significantly reduce the volume of the profitable part of the casting and the irreversible waste of high-stress-iron with spherical graphite during further machining.

4. Conclusion
Based on the above mentioned information, we can conclude:
– It was established that the linear shrinkage of nodular iron castings substantially depends on their size and quantity;
– It is shown that if it is possible to stabilize the size and number of graphite inclusions within a narrow framework, it is possible to increase dimensional accuracy by 2 classes with metal saving of linearly extended castings up to 2% of the casting weight.

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