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REVEALING THE SIGNIFICANCE OF THE INFLUENCE OF VANADIUM ON THE MECHANICAL PROPERTIES OF CAST IRON FOR CASTINGS FOR MACHINE-BUILDING PURPOSE

The object of study in this work is cast iron with lamellar graphite, modified with two types of modifiers – FeSi75 and FeSi40V7. In this work, the influence of vanadium on the mechanical properties of cast iron used for castings for engineering purposes was determined.

The existing problem lies in the fact that ignorance of the influence of the alloying element on the mechanical properties of the alloy does not allow determining its consumption rates during the melting process. This can lead to unnecessary costs for materials for melting and casting, and not be justified in terms of the expected improvement in properties.

To determine the effect of vanadium on properties, three indicators of the quality of cast iron are considered: tensile strength, stiffness, and a generalized quality index for mechanical properties. A decision is proposed on the procedure for checking the significance of the influence of vanadium within the considered range of variation V=0.04–0.078 % on these indicators.

It has been established that the introduction of vanadium into cast iron as part of the FeSi40V7 modifier leads to a decrease in the tensile strength by 4 %, but to an increase in rigidity by 2 %. A significant influence of vanadium with a probability of 95 % was also established with respect to the generalized quality indicator for mechanical properties – the introduction of vanadium contributes to a drop in this indicator by about 5 %.

As a result, it was concluded that the use of vanadium in the composition of FeSi40V7 within the final content in cast iron at the level of 0.04–0.078 % can be expedient only if it is necessary to increase the hardness of cast iron due to the promotion of carbide formation during alloy crystallization.

The presented study will be useful for machine-building enterprises that have foundries in their structure, where cast iron is smelted for the manufacture of castings.

Keywords: *cast iron for machine-building castings, modifier, alloying, vanadium, mechanical properties.*

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1. Introduction

The quality of cast iron for shaped castings for machine-building purposes is determined by many factors, most of which are extremely difficult to take into account. However, the defining group of factors is those associated with the metallurgical features of the process. The most attractive is melting in induction furnaces, as it allows getting pure cast iron in terms of harmful impurities, however, provided that the charge is not contaminated. At the same time, the quality of the alloy is formed during the melting process under the influence of temperature and the dynamics of the movement of the melt in the crucible, which form the course of the redox processes occurring in the bath. The works [1, 2] describe studies devoted to revealing the patterns of carbon transformations at high temperatures, which are typical for the melting of ferrous alloys in induction furnaces. Based on the results of these studies, which made it possible to reveal the regularities of the process of carbon oxidation in a carbon dioxide medium at various temperatures, kinetic equations for melt control were obtained. The same approach was used in [3], where the parameters of the kinetic equations were estimated for melts doped with vanadium. Alloying and modification performed at the stages of melting or out-of-furnace treatment have a significant effect on the formation of the alloy structure; however, it should be taken into account that this effect is also determined by the temperature regime of the process [4, 5]. All this together forms the mechanical properties of cast iron. A number of studies are focused on the formalization of the description of such an influence for different types of cast irons:

– gray with lamellar graphite [6–9];
– aluminum [10, 11];
– special wear-resistant [12].

This approach is promising, but requires the use of a minimum number of influencing factors to build an adequate mathematical model. In turn, this requires procedures to reduce the number of influencing factors, leaving only the most significant of them in consideration. In addition, it is necessary to correctly choose the area of variation of the input variables, which should be as close as possible to the optimum area. The appearance of new modifiers, as a rule, complex, stimulates the need for research devoted to assessing the significance of the influence of each new element in the composition of modifiers. In this case, when setting the problem of constructing models of the «composition-properties» type, it is possible at the first stage to evaluate the potential influence of each factor, if to choose the composition of the modifier and alloying additives as their composition. To do this, it is also possible to choose the chemical composition of the alloy, the elements of which are formed, among other things, by these modifiers and alloying complexes. Vanadium is one of the most important alloying elements that affects not only mechanical, but also special (wear resistance, heat resistance, heat resistance, corrosion resistance, etc.) properties of cast iron.

The object of study in this work is cast iron with lamellar graphite, modified with two types of modifiers – FeSi75 and FeSi40V7.

The aim of study is to determine the effect of vanadium on the mechanical properties of cast iron used for shaped castings for machine-building purposes.

2. Research methodology

Serial melting was carried out in the iron foundry of JSC «Kremenchug plant of road machines» (JSC «Kredmash», Ukraine), where castings for automotive and road equipment are made from cast iron grade SCH20 according to GOST 1412-85 (DSTU EN 1561, EN-GJL-200).

Melting was carried out in an IST 1/0.8-M5 induction crucible furnace (USSR) with an acid lining (Fig. 1).

Fig. 1. Melting process

Charge materials:

– return of own production;
– breakage of graphite electrodes with a fraction of 1–10 mm;
– steel scrap 1A (St3) with a maximum overall size of 350 mm, a thickness of 3.9 mm, a minimum weight of 15–18 kg.

The charge was preheated. The charge materials were loaded after the charge was deposited in the crucible. The process was controlled from the control panel. The control of the correctness of the melting process, the state of the crucible and the insulation of the inductor was carried out according to the readings of the control panel instruments.

The slag was induced by the addition of dry sand, liquid slag was provided by the introduction of lime or limestone with a fraction of up to 30 mm. The melt was adjusted to the specified chemical composition and temperature after complete melting by heating the melt for 5 minutes and turning off the furnace with holding in order to more fully redox processes in the melt.

The temperature of cast iron before inoculation was in the range of 1400–1450 °C. The use of two modifiers was tested: FeSi75 (Series I heats) and FeSi40V7 (Series II heats). In both cases, the fraction was up to 10 mm, the amount of the modifier was 0.3 % of the mass of the liquid metal, the modifier was introduced into the ladle after filling it by 100–150 mm. The results of combined modification with doping with the FeSi40V7 ferroalloy were compared with the results of the modification of FeSi75, taking into account the correction of the silicon content. Thus, the influence on the mechanical properties of vanadium was checked.

Correction of the chemical composition and bringing it to the specified values for manganese, chromium, nickel was carried out, respectively: ferromanganese FeMn70, ferrochrome FeCr100, FeCr200, ferronickel FeNi70, in accordance with the norms of consumption of charge materials adopted at the enterprise.

In each series, 59 melts (N=59) were carried out and the following characteristics of cast iron were determined, taken as quality indicators:

– ultimate tensile strength (σ_b, MPa);
– hardness (HB);
– generalized quality index for mechanical properties ($GQI=\sigma_b/HB$).

Statistical data processing was carried out according to the formulas:

$$M(Y)=\frac{\sum_{i=1}^{N}Y_i}{N}, \quad (1)$$

$$s(Y)=\sqrt{\frac{\sum_{i=1}^{N}\left(Y_i-M(Y)\right)^2}{N-1}}, \quad (2)$$

where Y_i – mechanical properties (σ_b, MPa; HB; GQI); $s(Y)$ – the standard deviation of mechanical property; N – the number of experimental points for which the calculation of statistical characteristics is carried out.

The decision on the significance of the effect of vanadium on the mechanical properties and GQI was made on the basis of testing the statistical hypothesis that the mathematical expectation of a property in series II is equal to the mathematical expectation of a property in series I:

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$$H:\ M(Y_I)=M(Y_{II}), \qquad (3)$$

where Y_I is the value of the mechanical property and the *GQI* in series I; Y_{II} is the value of the mechanical property and *GQI* in series II; $M(Y_I)$ is the mathematical expectation of the value of the mechanical property and the *GQI* in series I; $M(Y_{II})$ is the mathematical expectation of the value of the mechanical property and the *GQI* in series II.

The hypothesis was considered rejected if the following condition was met:

$$t=\frac{\left(M\left(Y_I\right)-M\left(Y_{II}\right)\right)\sqrt{N}}{s(Y)}>t_{cv}, \qquad (4)$$

where t_{cv} – critical value of Student's distribution.

3. Research results and discussion

Table 1 shows the results of the chemical composition of the alloy in two series of melts – with the modification of FeSi75 (series I) and with the modification of FeSi40V7 (series II).

Table 1

The chemical composition of the alloy

Melting	Chemical composition, %			
	C	C_{eq}*	Cr	Ni
Series I	3.12–3.6	3.895–4.503	0.21–0.47	0.15–0.2
Series II	3.35–3.67	4.05–4.677	0.24–0.53	0.15–0.2
Melting	Ti		Cu	V
Series I	0.041–0.095		0.1–0.43	–
Series II	0.044–0.089		0.1–0.32	0.04–0.078

Note: * – carbon equivalent calculated by the formula C_{eq}=C+0.3Si+ +0.33P+0.4S–0.03Mn

Fig. 2–4 show the results of determining σ_b, *HB*, and *GQI*.

Fig. 5–7 show histograms of the distribution of σ_b, MPa, *HB*, and *GQI* values in series I and series II. Color designations correspond to those adopted in Fig. 2–4.

Table 2 shows the results of calculations of statistical characteristics and testing of the hypothesis about the equality of the values of mechanical properties and *GQI* in series I and series II.

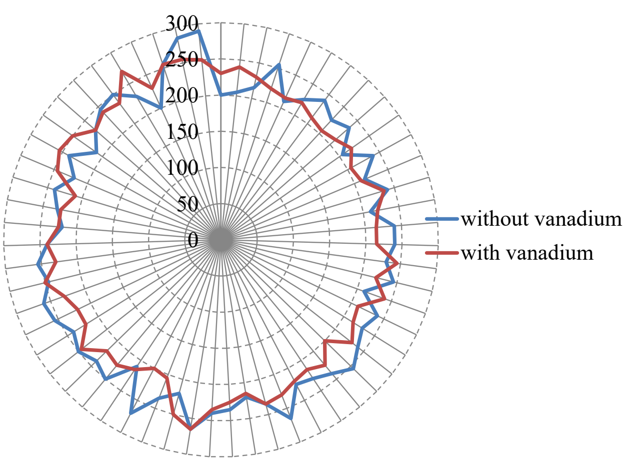

Fig. 2. Results of experimental-industrial heats in terms of σ_b

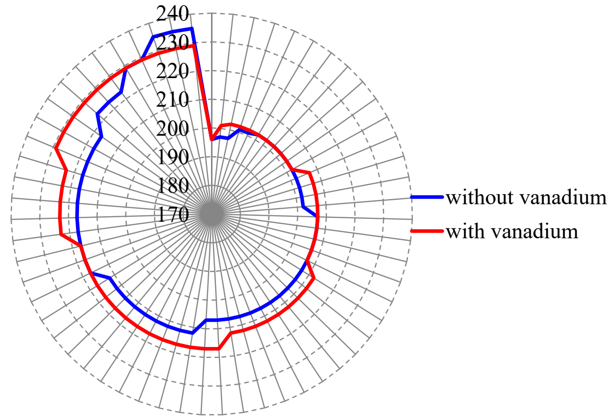

Fig. 3. Results of experimental-industrial meltings according to *HB*

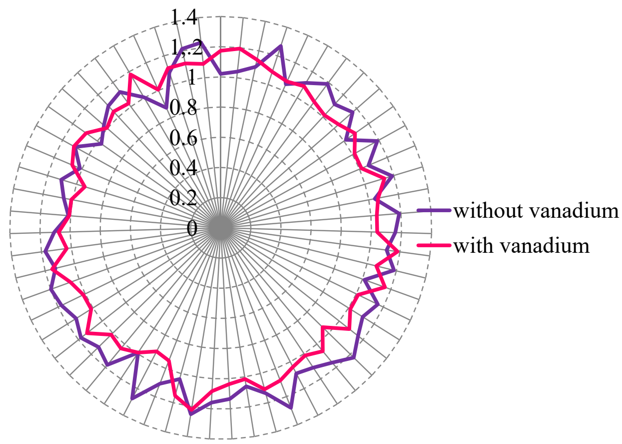

Fig. 4. Results of experimental-industrial meltings according to the defense industrial complex

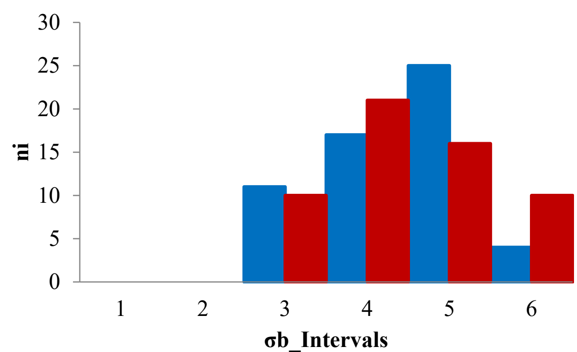

Fig. 5. Histogram of the distribution of the value σ_b: ■ – in series I; ■ – in series II

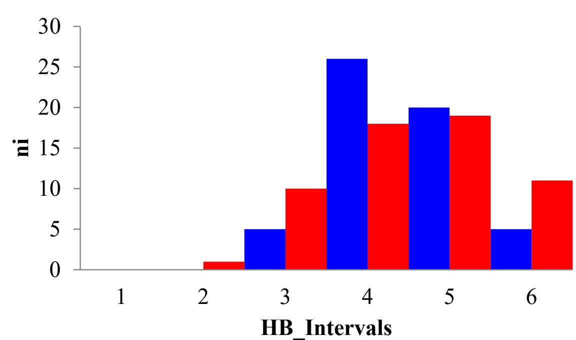

Fig. 6. Histogram of the distribution of the *HB* value: ■ – in series I; ■ – in series II

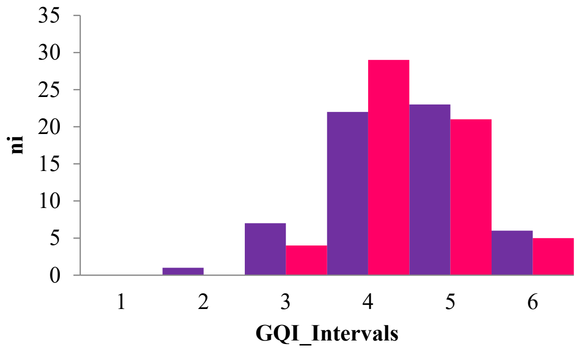

Fig. 7. Histogram of the distribution of the *GQI* value: ■ – in series I; ■ – in series II

Table 2

Statistical characteristics of mechanical properties and *GQI*

Proper-ties	Series I		Series II		
	$M(Y_I)$	$s(Y_I)$	$M(Y_{II})$	$s(Y_{II})$	t
σ_b, MPa	236	19.5	228	16.4	3.12
HB	211	9.4	215	9.5	3.24
GQI	1.118	0.1	1.063	0.1	4.19

Note: t_{cr}=2.66, P=0.95

Data in Table 2 shows that the hypothesis of equality of mathematical expectations should be rejected, that is, the introduction of vanadium is a significant factor influencing all the considered properties.

From Fig. 1 and Table 2 it follows that the effect of vanadium on the tensile strength does not correspond to generally accepted ideas – with the introduction of vanadium, σ_b decreases. An explanation for this fact should be sought in the study of the considered range of variation in the content of vanadium. The revealed fact can take place only within this interval; therefore, outside this interval, the quality of the effect of vanadium on σ_b may be different. For example, with a decrease in the content of V below the value of V=0.04 % or above the value of V=0.078 %, σ_b starts to grow or continues to fall. This requires further research.

With regard to the effect of vanadium on hardness, the trend is different – with an increase in the vanadium content, the hardness of cast iron increases. This is due to the strong carbide-forming effect of V, which corresponds to generally accepted ideas.

The generalized quality index for mechanical properties decreases with increasing vanadium content (Fig. 3, Table 2), which is explained by the principle of determining this quality index – a decrease in the numerator and an increase in the denominator leads to a decrease in the *GQI*.

The results of the study are limited by the ranges of variation of the elements of the chemical composition given in Table 1, when choosing the same modifiers.

Based on the results obtained, it is of interest to study in the direction of going beyond the ranges of variation in the content of elements of the chemical composition considered in this study. It is also interesting to study the microstructure of cast iron with a chemical composition in the ranges given in Table 1. The results of such studies can help in further identification of the mechanism for the formation of properties and their control by purposefully regulating the process of structure formation.

4. Conclusions

It has been established that the introduction of vanadium into cast iron as part of the FeSi40V7 modifier leads to a decrease in the ultimate strength by approximately 4 % – from σ_b=236 MPa to σ_b=228 MPa, but to an increase in hardness by approximately 2 % – from HB211 to HB215. Such quantitative values do not fall within the error, which is proved by statistical testing of the hypothesis of equality with the probability P=0.95 of the mathematical expectations of the mechanical properties of cast iron modified with FeSi75 and FeSi40V7. This means that the effect of vanadium on both σ_b and *HB* is significant. The same conclusion can be drawn in relation to the generalized quality index for mechanical properties – the introduction of vanadium leads to a drop in the *GQI* by about 5 % – from *GQI*=1.118 to *GQI*=1.063. Thus, the use of vanadium in the composition of FeSi40V7 within the limits of its final content in cast iron at the level of 0.04–0.078 % can be expedient only if it is necessary to increase the hardness of cast iron due to the promotion of carbide formation during alloy crystallization.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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