INVESTIGATION OF STRUCTURAL CAST IRON HARDNESS FOR CASTINGS OF AUTOMOBILE INDUSTRY ON THE BASIS OF CONSTRUCTION AND ANALYSIS OF REGRESSION EQUATION IN THE FACTOR SPACE «CARBON (C) – CARBON EQUIVALENT (C_eq)»

The object of research is structural cast iron for commercial castings for automotive castings, in which the carbon

with a maximum tensile strength and a minimum hardness. With regard to hardness, it is necessary to take into account that the lower level of the hardness should provide the specified performance properties in case the surface is contacting. The upper level of hardness should ensure the possibility of high-quality machining and do not cause a reduction in the reliability of the metalworking tool. It is also important to take into account that sudden increase in hardness indicates changes in the microstructure and the formation of carbides. In particular, we can talk about the most dangerous for structural iron carbon carbide – Fe₃C. Thus, hardness as a regulated quality indicator of structural iron is important from the technological point of view, and with information – as an indirect indicator, indicating undesirable changes in the microstructure. Therefore, the research areas devoted to the study of the effect of physical, chemical, technological and structural factors on the hardness of structural iron are relevant.

1. Introduction

In the technologies of foundry production, priority is given to the quality management of obtained castings. Taking into account the fact that the quality of castings is formed by two components of technological processes – the metallurgical component and the technology of the mold – there are basically two main approaches to research. The first of them is based on a comprehensive study of the design and manufacture of casting technology, the second on the study of melting and out-of-furnace processing [1–3].

Among the considered quality criteria, the surface cleanliness, the presence of surface defects, the correspondence of dimensional and geometric accuracy specified in the design documentation, mechanical and special properties can be distinguished. And if the first are formed by the technological components of the process – the mold technology, the latter is formed by the metallurgical component, which depends on the melting and out-of-furnace processing. It is the mechanical properties – the ultimate tensile strength and hardness – that are controlled by government standards. At the same time, it should be noted that when comparing samples of constructional cast iron with general machine-building design, preference should be given to those

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with a maximum tensile strength and a minimum hardness. With regard to hardness, it is necessary to take into account that the lower level of the hardness should provide the specified performance properties in case the surface is contacting. The upper level of hardness should ensure the possibility of high-quality machining and do not cause a reduction in the reliability of the metalworking tool. It is also important to take into account that sudden increase in hardness indicates changes in the microstructure and the formation of carbides. In particular, we can talk about the most dangerous for structural iron carbon carbide – Fe₃C. Thus, hardness as a regulated quality indicator of structural iron is important from the technological point of view, and with information – as an indirect indicator, indicating undesirable changes in the microstructure. Therefore, the research areas devoted to the study of the effect of physical, chemical, technological and structural factors on the hardness of structural iron are relevant.

2. The object of research and its technological audit

The object of research is structural cast iron for commercial castings for automotive castings, in which the carbon
importance of evaluating the effect of hardness studies. This production need is caused by the
impact of the specified range of hardness (HB) in cast iron microstructure. The
subsequent study of the mechanisms of the formation of carbon equivalent on hardness as an
optimum composition of the charge for the minimum cost.

The influence of the modifier composition in the mold on the microstructure and fatigue strength of castings made
from cast iron EN GJS 700-2 is described in [7]. In this paper, the authors talk about the possibility of managing
properties through effective modification. In this case, efficiency is considered in the sense of a specified targeted
effect on the microstructure of the alloy. However, the problem is investigated primarily on the basis of a material
science, rather than a technological approach.

In a number of works, for example, [8, 9], it was noted that regression analysis or modified Griffiths and Hall-
Petch equations can be used to study the formation of a metal matrix. Here it should be noted once again that if
the strength of cast iron depends mainly on the amount, shape, size and distribution of graphite, then the hardness
is determined mainly by the metal matrix.

The influence of the alloying parameters, together with the regulation of the C/Si ratio in cast iron, on the
microstructure and the mechanical properties of cast iron, is described in [10]. In this work, it is established that the
output characteristics of the cast iron modifier in combination with antimony (Sb) influence the data. However,
the results described in this paper refer to high-strength cast iron and the possibility of spreading the findings in
it to cast iron with plate graphite requires additional studies. The problem of globular graphite formation during
the modification of cast iron by magnesium is given attention in [11], and the choice of the modifier type and the
development of modifying technology as technological factors for controlling mechanical properties are discussed in
[12-14]. Among the most highly developed modifiers, for example, the Superseed® Extra Inoculant [12], Reseed®
Inoculant [13] and SMZ® Inoculant [14] modifiers can be noted. The Superseed® Extra Inoculant modifier
minimizes bleaching in cast iron castings, promotes the formation of evenly distributed graphite, neutralizes the
harmful effects of nitrogen and promotes the formation of small graphite inclusions, reducing the graphite chipping
during machining. This effect of the modifier is explained by the authors in the presence of zirconium and strontium
in its composition, which improve the nucleation with a minimum degree of supercooling and reduce the
risk of formation of supercooled graphite and ferrite. The Reseed® Inoculant modifier is designed for high-strength
and gray cast iron with low sulfur content and contributes, in particular, to the formation of globular graphite with a good degree of globularity in the thick sections of castings from high-strength cast iron. Also, this modifier helps to prevent the formation of micro-shrinkage porosity in the castings. This effect is ensured by the presence in the modifier of a balanced number of active elements – calcium and cerium. Obviously, due to these effects, one should expect an increase in the cast iron hardness. The SMZ® Inoculant modifier can be used for graphitizing modification of gray cast iron and vermicular graphite cast iron and is suitable for late modification in a metal stream (MSI process). This ensures stabilization of deviations in chemical composition and regulation of nitrogen content in cast iron. Such effect, as the authors of [12] note, can be explained by a carefully balanced amount of calcium and aluminum, which ensures maximum control over bleaching. Despite the qualitative assessment of the expected effects of the modification, the lack of quantitative estimates, which can only be made on the basis of an analytical description, does not allow making sound technological decisions. In particular, we can talk about the selection of the chemical composition that provides the specified properties, and allows the possibility of optimizing the charge by the criterion of minimum costs. Certain exceptions in considering the problem from this point of view have the works [15, 16], in which the accent is made precisely on the methods of quantitative evaluation. The authors of these works have investigated the use of methods for constructing «composition-properties» models under conditions of uncertainty, with hardness chosen as the output variable.

The described work allows to conclude that there are no ready solutions for the reasonable choice of the composition of cast iron from the point of view of ensuring a given hardness. As for the questions of the effect of the chemical composition of cast iron in a specific range of variation of the input C–CEQ on the hardness of structural iron, the corresponding work has not been found. Therefore, to solve the emerging practical issues on the choice of the chemical composition of cast iron, which provides the given values of its hardness and which allows further minimizing the cost of its production, special studies are necessary.

5. Methods of research

According to the results of industrial tests, described in detail in [4], a total of 12 samples were selected for further investigation.

Fig. 1 shows the hardness values of 12 samples selected for further investigation.

To estimate the vectors:

\[
A = (FF)^{-1} FY = CFY, \tag{2}
\]

minimizing the least-squares functional of the form:

\[
J = (FA - Y)^T (FA - Y), \tag{3}
\]

where \(F\) – the matrix of the experimental design, which has the form:

\[
\begin{bmatrix}
1 & x_{11} & x_{12} & x_{13} & x_{14} & x_{15} & x_{16} & x_{17} & x_{18} & x_{19} & x_{20} \\
1 & x_{21} & x_{22} & x_{23} & x_{24} & x_{25} & x_{26} & x_{27} & x_{28} & x_{29} & x_{30} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1 & x_{31} & x_{32} & x_{33} & x_{34} & x_{35} & x_{36} & x_{37} & x_{38} & x_{39} & x_{40}
\end{bmatrix}
\]

\[
Y = \begin{bmatrix}
y_1 \\
y_2 \\
\vdots \\
y_n
\end{bmatrix}
\]

– matrix of experimental hardness values.

6. Research results

Using the OLS, the values of the coefficients of the regression equations of the form (1) are calculated from (2):

\[
A = \begin{bmatrix}
216.934 \\
-11.7595 \\
1.057318 \\
2.341327 \\
4.389574 \\
-37.0113
\end{bmatrix}
\]
Considering the fact that the coefficients of the regression equations are estimated on the basis of a passive experiment that does not allow parallel measurements of the output variable at each point of the plan, the possibility of testing the homogeneity of the experimental plan is not available. The adequacy of the model, based on Fisher’s F-test, or testing the hypothesis that the variance of experimental errors is equal, and the model’s inadequacy, is not therefore possible. Therefore, the potential performance of the model is evaluated on the basis of checking the number of experimental points that fell within a given confidence interval (Fig. 2).

Fig. 2. Results of testing the model’s performance on the basis of the polynomial regression equation

From Fig. 2 it follows that 11 test points (92 %) fell into the confidence interval. Therefore, there is reason to believe that the regression equation of the form (1) is operable for further analysis.

Since the most interesting is the identification of stationary points and the description of the response surface in their vicinity, the canonical transformation of the response surface is performed, similarly to the procedure described in [4]:

1. Determination of the coordinates of the stationary point \( x^* \) by solving a system of linear equations:

\[
\begin{align*}
&\begin{pmatrix}
  a_{11} & \ldots & a_{1n} \\
  \vdots & \ddots & \vdots \\
  a_{n1} & \ldots & a_{nn}
\end{pmatrix} \begin{pmatrix}
  x_1^* \\
  \vdots \\
  x_n^*
\end{pmatrix} = \begin{pmatrix}
  a_1 \\
  \vdots \\
  a_n
\end{pmatrix}
\end{align*}
\]

2. Calculation of the target value at a stationary point:

\[ y^* = a_0 + 2a'x^* + Ax^* \]

3. Definition of \( n \) eigenvalues \( \lambda_1, \lambda_2, \ldots, \lambda_n \):

\[
\begin{pmatrix}
  a_{11} - \lambda & a_{12} & \ldots & a_{1n} \\
  a_{21} & a_{22} - \lambda & \ldots & a_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  a_{n1} & a_{n2} & \ldots & a_{nn} - \lambda
\end{pmatrix} = (-\lambda)^n + \ldots + P_1 \lambda^{n-1} + P_0 = 0.
\]

4. Description of the equation of the response surface in the canonical form:

\[ y - y^* = \lambda_1 \xi_1^2 + \lambda_2 \xi_2^2 + \ldots + \lambda_n \xi_n^2. \]

As a result of the transfer and rotation of the axes and the transition from the coordinate system \( (x_1, x_2) \) to the coordinate system \( (\xi_1, \xi_2) \), the initial equation of the response surface is transformed to:

\[ y(x) = a_0 + 2a'x + x'Ax, \]

the canonical form \( y - y^* = \lambda_1 \xi_1^2 + \lambda_2 \xi_2^2 + \ldots + \lambda_n \xi_n^2 :\)

\[ x = x^* + B\xi, \]

where \( B \) – the rotation matrix, \( B'B = I \), and the difference between the values of the output variable at an arbitrary and stationary point is described by the equation:

\[ y(\xi) - y^* = \xi'\xi_0, \]

The following values are obtained by the realization of the procedure 1–4: \( \lambda_1 = -15.1685, \lambda_2 = 21.89937 \). This means that the equation describing the response surface in the canonical form has the form:

\[ y - y^* = -15.1685\xi_1^2 + 21.89937\xi_2^2. \]

Since the ratio of the eigenvalues in magnitude and sign determines the form of the response surface, and:

\[ |\lambda_1| > |\lambda_2|, \lambda_1 < 0, \lambda_2 > 0, \]

the response surface, just as in the case of a tensile strength test [4], is a hyperbolic parabaloid. However, the position of the saddle point in it is not so pronounced (Fig. 3).

Fig. 4 is a top view of the response surface, from which it can be seen that with the increase in the carbon equivalent, the hardness of the cast iron is reduced. The effect of the carbon content on hardness is more complex – it is described by a parabolic dependence.
This means that the maximum hardness is reached at about the average level of carbon content (3.495%). Before this value, the hardness increases with increasing carbon content, and then decreases.

In other words, from the point of view of using carbon as a factor in reducing the hardness of cast iron, its allowable range is limited to an interval (3.42–3.495) %.

A more significant factor from this point of view is the carbon equivalent, which needs to be increased. This means that in order to reduce the hardness value it is necessary to increase the width of the $C–C_{eq}$ interval in the Fe–C state diagram.

Fig. 4. The response surface $HB = HB(C, C_{eq})$, top view, (the input variables are given in the normalized form)

To find suboptimal points, it is advisable to use the ridge analysis of the received response surface [17]. To do this, it is necessary to obtain a parametric description of the type:

$$
\begin{align*}
x'(\lambda) &= (\lambda I - A)^{-1}a,
\end{align*}
$$

where $a_0$, $a$, $A$ – estimates of the coefficients in the regression equation (1); $x'_i = \frac{a_i}{2\lambda}$ – suboptimal values of input variables;

$$
r(\lambda) = \sqrt{x'^2},
$$

$r^2 = \sum \left( \frac{a_i}{2\lambda} \right)^2$ – restrictions imposed on the values of input variables in the factor space ($C$ and $C_{eq}$); $y^2 = a_0 + \sum \frac{a_i^2}{2\lambda}$ – suboptimal values of the output variable (HB).

Fig. 5–7 shows a graphical solution to the problem of ridge analysis of the obtained response surface $HB = HB(C, C_{eq})$ (Fig. 3) analytically described by the regression equation of the form (1). If the range of the planning region is chosen as the imposed constraint, $C = (3.42–3.57)$ % and $C_{eq} = (4.2–4.4)$ % (in the normalized form [–1; 1]), which corresponds to the value of $r = \sqrt{2} = 1.414$. There may be several suboptimal solutions. They are defined as the intersection points of the ridges and the constraints $r = 1.414$. In this case, the tasks of minimizing hardness are not set and the range $HB = 180–250$ satisfies the quality requirements specified by the production conditions. If the priority is to minimize hardness, then the suboptimal solution is found as the point of intersection of the restriction $r = 1.414$ and the lower branch of the ridge line II–III. Consequently, the resulting results in the form of Fig. 7 allow to draw a number of important conclusions from the practical point of view concerning the satisfaction of different requirements for hardness. This indicates the multivariance of the obtained solutions, the choice of the most preferable of which is determined by the requirements of the production conditions.

Fig. 5. Dependence $r = r(\lambda)$

Electronic copy available at: https://ssrn.com/abstract=3691024
Obviously, there are many sub-optimal solutions given by the first equation of system (8). For the case when the requirements $HB = 180–250$ are sufficient, such solutions are shown in Fig. 8.

From a practical point of view, the transformation of the solutions obtained in a normalized form to a natural form is of special interest – obtained description is a nomogram. The nomogram, as is known, is a convenient tool in the hands of a technologist [18–20], and allows choosing rational modes of the technological process. Fig. 9 shows such nomogram for the investigated range of values of input variables.

As follows from the above description, in order to select the necessary correction value for the carbon or carbon equivalent, it is possible to estimate the distance between the point of the factor space corresponding to the actual values of $C$ and $C_{eq}$ and the nearest of the two curves.
Obviously, the best choice will be the one providing the minimum consumption of corrective additives, that is, one for which the distance from the current point (corresponding to the actual values of \( C \) and \( C_{eq} \)) to the corresponding curve will be minimal.

7. SWOT analysis of research results

**Strengths.** Among the strengths of this research, it is necessary to note the possibility of using the resulting regression equation to solve two key problems:
- predicting the hardness by the actual chemical composition, obtained during the melting process;
- selection of the composition providing a given level of hardness. In the first case, it becomes possible to reduce the number of laboratory hardness tests by reducing the corresponding costs. In the second case, the prospect of minimizing the cost of the burden opens, that is, reducing the cost of 1 ton of good casting. It should also be noted that the possibility of an indirect evaluation of the appearance of undesirable carbides in the microstructure, in particular cementite, is possible. This can contribute to the selection of more rational solutions with regard to the technological regimes of secondary treatment. Finally, a targeted choice of chemical composition, which provides minimum, but acceptable from the standpoint of strength, hardness of structural iron should contribute to improving the reliability of the cutting tool.

**Weaknesses.** The weaknesses of this research are related to the fact that the regression equation is built on the basis of an arbitrary area of experiment planning. This means that the obtained estimates of the coefficients are far from optimal and there is a principal possibility of increasing the accuracy. This is possible, for example, by optimizing the experimental design. However, this desire to improve quality will require the need for additional fusions, which is associated with significant additional costs.

**Opportunities.** Additional opportunities for using the above results in industrial conditions are related to the optimization of the chemical composition of cast iron or the optimization of the charge composition. In the latter case, the initial data can be obtained suboptimal solutions. Additional opportunities are also opened during the off-furnace treatment – thanks to the use of obtained nomograms, the rational selection of corrective additives is simplified. In this case, there is a principal possibility to minimize costs precisely at the expense of the most acceptable option.

**Threats.** The obvious risks when using the results are due to the fact that consumers prefer to purchase castings from high-strength cast iron with nodular graphite or high-quality gray cast iron with vermicular graphite. This is completely justified, since the mechanical or special properties of such cast irons are much higher. From the point of view of the manufacturer of cast iron for castings, if the operating conditions of cast iron parts are non-rigid, typical, there is no need to spend extra money in pursuit of increasing mechanical properties. And if the manufacturer’s costs are one of the criteria for minimization, then they are not interested in the consumer. From the point of view of using the obtained solutions in production, there is a management risk – changing the composition of the charge requires a revision of the consumption rates, and possibly suppliers of charge materials. This, in turn, requires the presence of progressive management and especially the corresponding level of top managers of production.

8. Conclusions

1. It is shown that a polynomial regression equation can be used to obtain a workable analytical description of the effect of carbon (\( C \)) and the carbon equivalent (\( C_{eq} \))

![Nomogram describing the set of suboptimal solutions for the investigated range of values of input variables satisfying the requirements of HB=180–250](https://ssrn.com/abstract=3691024)
on the hardness value. The solutions obtained in the construction of the regression equation of the form $HB = HB(C, C_{eq})$ refer to the range of values of the input variables $C = (3.42–3.57)\%$ and $C_{eq} = (4.2–4.4)\%$. This structure of the equation and the corresponding estimates of the coefficients obtained by the least squares method ensure high accuracy of the forecast. Even with a small sample of data, this accuracy is 92%.

2. On the basis of the canonical transformation of the received response surface, the presence of a saddle point is revealed, which, however, is not as pronounced as for a response surface that describes the magnitude of the tensile strength in the same range of input variables. The ridge analysis of the described response surface shows that there is a principal possibility of satisfying different requirements for hardness. So, if the range of the planning area $C = (3.42–3.57)\%$ and $C_{eq} = (4.2–4.4)\%$ is chosen as the imposed constraint, then several suboptimal solutions are possible. This is the case if the task of minimizing the quality requirements specified by the production conditions. If the priority is hardness minimization, then the suboptimal solution is one. Thus, there are many suboptimal decisions, depending on the requirements of production. It is shown that such solutions, in fact, are a nomogram that allows to select in a rational way the technological regimes of out-of-furnace processing in the part concerning the correction of the chemical composition of the alloy.

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