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THE CAST IRON ROLLING ROLLS MANUFACTURING – BETWEEN THE MATHEMATICAL APPROACHES AND THE OPTIMISATION OF PROCESSES

Abstract:
The irons destined to these cast rolls belong to the class of low-alloyed irons, with reduced content of chrome, nickel and molybdenum. The technological instructions firmly state the elements required raising the quality of rolls, but the limits can be extensive or limited. Depending on the number of the technological parameters, it was chosen the analysis of multiple regressions studying the influence of the chemical composition upon the hardness, through the mathematical modeling.
The technical conditions, which are imposed to the cast iron rolls in the exploitation period, are very different and often contradictory. The obtaining of various physical and mechanical properties in the different points of the rolls meets difficult technological problems in the industrial condition. This supposes us to know many technological factors, which lead to the exploitation of this deformation equipment.
The experimented researches, as well as the optimization of the manufacturing technology, allow the conclusion of direct results for the rolls. The beneficiaries of these results are the unit in which the rolls are manufactured, as well as the unit that exploits them.

Keywords:
cast iron rolls, alloying elements, mathematical interpretations

INTRODUCTION

Poverty of detailed researches, theoretical and experimental, about the thermo-mechanical processes take place during the plastic deformations between the rolling mills rolls, represents a factor that reduces the possibility of rational exploitation of rolling mills. In the context of market economy is necessary a new evolution in the area of scientific researches, in the purpose of modernization of the equipments and metallurgical plants, using the most efficient solutions for obtaining aggregates with performances to the level of world technique. The technological processes of the rolls manufacture, as well as the quality of used materials have a quick extension, materialized in worldwide market competition, through exceptional qualities of rolls.

The technological manufacturing process of the rolling mills rolls, as well as the quality of material used in manufacturing them, can have a different influence upon the quality and the safety in the exploitation. Our proposal approaches the issue of quality assurance of the rolling mills rolls, from the viewpoint of the quality of materials, which feature can cause duration and safety in exploitation.

In these sense, our researches propose, on aside, to analyze the technological field of the rolling rolls manufacturing process – analysis materialized from prism of the foundry *experiments, including the metallurgical and mechanical aspects (casting process, moulding, iron melting, nodularization of graphite, hardness, durability and so others), and on another side, the optimization of the manufacturing technology of the cast rolls, especially those from cast-iron – using electronic calculus technique as the molding phenomenon and mathematical interpretation of the technological processes.*

The research on rolling mills rolls quality experimentally and teoretically defines an important chapter from the metallurgical, mechanical and mathematical aspects of these machines organs in the movement of rotation, in variable temperature mediums. Also, the mathematical modeling establishes a methodology for the determination of the technological parameters values, for which a mechanical characteristic (the hardness) has the desirable values. Because is disposed of real data, the optimization model is based on industrial data, obtained from cast-iron rolling rolls. Their analysis shall lead to the optimization pattern, through the prism of the multicomponent correlations, enounced by mathematical formulae.

Starting from the principle of molding process, used as necessary basic instrument, both in phase of conception, as well as in the industrial technologies analysis, is determined the optimum regimes of the cast rolls, from the view from chemical composition, as one as the most important parameters of disturbance of the manufacturing process. The enunciation of some mathematically molding results, described through a number of multicomponent equations determined for the spaces with 3 the and 4 dimensions, as well as the generation of some regression surfaces, of some curves of levels, of the volumes of variation, of the lines of outlines of the volumes of variation of surfaces and the areas of variation of these, can be represented and interpreted by technologists and can be considerate diagrams of correlation between the analyzed variables. From this point of view the project is inscribes in context of scientific capitalization of the process and the industrial technologies optimizations, on the way of the analysis and the mathematical experiment.

THE TECHNOLOGICAL APPROACHES

The nodular graphite cast iron is considered as one of the most versatile roll materials nowadays. This type of material may be used to produce large scale rolls in double pouring process, the barrel of rolls has high hardness while the neck has high toughness, so this type of rolls exhibits the properties of high thermal stability and resistance to wear. As the characteristics of any casting are influenced by the microstructure that is formed during the solidification in the cast form, and under the influence of the cooling speed, the main criteria, which determines the mechanical properties of the rolls is the structure. All structural components can be found in cast iron rolls, each of the components having its own well-determined hardness. One of the parameters, which are determined the structure of the irons destined for rolls casting, is the chemical composition. If we do not respect this composition, which are guarantied by the exploitation properties of the each roll in the stand of rolling mill, this leads to rejection. All FNS type rolls are alloyed especially with chrome, nickel and molybdenum, in different percentages. The irons destined to these cast rolls belong to the class of low-alloyed irons, with reduced content of these elements. The technological instructions firmly state the elements required to raise the quality of rolls.

The recommended hardness's for the working surfaces of the half-hard rolls are presented in Table 1, according with the hardness classes adopted by the Romanian Standard Regulations. Also, the recommended hardness for the rolls necks and the core are presented in same Table 1. The usual chemical composition of the irons destined for casting the half-hard rolls is presented in Table 2.

The quality of rolls is determined through hardness and through wear resistance, last index having a special importance for all modern rolling mills with a growth production. Of major importance for the rolls exploitation is not merely growth resistance, but also the ability to oppose to different types of wear. Thus, rolling mill rolls considerable influence the specific production and the qualitative level of laminates, reason for which they are given a special attention, in manufacturing, as well as in *usage. These requirements can't be completely fulfilled, compelling to the granting of priorities depending on the type of laminates, therefore to compromises. At large, the problem is reduced to the correct material choice, eased by the rich available experience in the current conditions of manufactured and burdened, in the same time, by the large diversity of material used.*

TABLE 1. The recommended hardness's of the half-hard rolls for the rolls working surfaces (body), the necks and the core

Rolls Type	Hardness Classes	Hardness: on the rolls working surface [HS]	Hardness: on the rolls working surface [HB]	Hardness: on the necks and in the core [HS]	Hardness: on the necks and in the core [HB]
FNS	0	33…42	218…286	30…40	195…271
FNS	1	43…59	294…347	30…40	195…271
FNS	2	69…75	499…550	35…45	218…309

TABLE 2. The usual chemical composition of the irons destined for casting the half-hard rolls

Rolls Type	Chemical Composition, [%]				
	C	Si	Mn	P	S
FNS	3,0..3,5	1,2..2,5	0,1..0,7	max. 0,15	max. 0,02

Rolls Type	Chemical Composition, [%]			
	Ni	Cr	Mo	Mg
FNS	1,5..2,5	max. 0,8	0,3…0,5	0,02…0,04

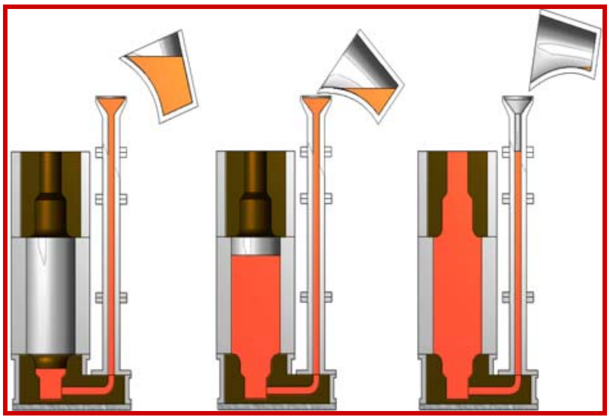

Fig. 1. Casting process of the half-hard iron rolls

Although the manufacture of rolls is in continuously perfecting, the requirements for superior quality rolls are not yet completely satisfied, in many cases, the absence of quality rolls preventing the realization of quality laminates or the realization of productivities of which rolling mills are capable.

To the selection of materials is considered the type of rolling mill, the sizes of rolls (in specially this diameter), the speeds of lamination, the stands from the train of lamination for which is achieved rolls, the working temperature in the lamination process, the module of cooling during work, the size caliber, the pressure on rolls, the rolled material hardness, etc.

The choice of material for rolls is the operation which takes into consideration the own solicitations of the lamination process afferent to the type of laminates (semiproduct or the finite laminate), and the features of different materials considerate optimum in the fabrication of different typo-dimensions of rolls.

Having abrading and dry friction wear resistance, as well as another mechanical characteristic superior to cast irons with lamellar graphite, the cast-irons with nodular graphite are successfully used to the cast of types of rolls. The main structural constituent of the cast-iron is the graphite, of the amount, form, sizes and module of allocation in basic metallic mass depends the physical and mechanical property of the cast-iron, inclusively of the rolls, as well as the wear resistance. For this reason, the amount and the module of distribution of the graphite separation in working surface of rolls it can be considered as main criterion of classification. The presents of graphite in working surface (body of rolls) assures the friction coefficient necessary to obtain quality laminate. From this point of view, the cast irons with nodular graphite is used to manufacture large types of rolls.

Having in view the complex solicitations in exploitation, another important characteristic imposed to the rolling mills rolls is the thermal shock resistance. The main cause of wear is the appearance of fissures on the working surface, due to thermal fatigue. The thermal wear, in principle, can be explained through the different behavior of the constituents that compose the basic metallic mass, in variations of temperature. The thermo-mechanical wear, due the crossing among the rolls of the laminates, warmed in the austenitic area, is direct influenced by the fineness of the basic metallic mass structure, as well as the form and size of graphite disjunctions. In order to obtained a good durability, it is needed a fine homogeneous structure, with a great degree of dispersion of the pearlite.

THE MATHEMATICAL APPROACH

The statistical methods of the analysis do not solve a whole series of appearances regarding to the decisions model to establish the management of the process. For this reason, in parallel with the statistical methods, was developed the methods of optimization.

As part as the basic experiment, through the regression analysis, it was aimed the determination of the mathematical functions form which connect the dependent variables u of the technological process with the free variables (the technological parameters) x, y, z,…, meaning u = f(x, y, z,…), on the strength of some experimental determinations, this after it accomplished a dispersion analysis of these correlation data. The determination of what real coefficients enter into the expression u = f (x, y, z,…) is done, in the vast majority of the cases, through the method of the smallest squares.

Depending on the number of free variables (the technological parameters) that we consider, it was chosen the analysis of multiple regressions studying the influence of free variables x, y, z,… upon the dependent variable u. In this sense, it was aimed to establish calculus methodologies of values for the technological parameters in the manufacturing process of the semihard rolling mill rolls, obtained through the simplex classical cast of the iron with nodular graphite, for which the mechanical features of rolling mill rolls have the required values.

Having "n" experimental points, respectively $(x_1, y_1, u_1)_1$, $(x_1, y_1, u_1)_2$, …. $(x_1, y_1, u_1)_n$, we need to determine the real coefficients c_0, c_1 and c_2 in the equation of the plan. This is accomplished through the method of the smallest squares, which leads to finding them through the following system of three equations with three unknown variables (a_0, a_1, a_2):

$$\begin{cases} n\cdot c_0+\left(\sum_{i=1}^{n}(x)_i\right)\cdot c_1+\left(\sum_{i=1}^{n}(y)_i\right)\cdot c_2=\sum_{i=1}^{n}u_i \\ \left(\sum_{i=1}^{n}(x)_i\right)\cdot a_0+\left(\sum_{i=1}^{n}(x)_i^2\right)\cdot a_1+\left(\sum_{i=1}^{n}(x)_i\cdot(y)_i\right)\cdot a_2=\sum_{i=1}^{n}(x)_i\cdot u_i \\ \left(\sum_{i=1}^{n}(y)_i\right)\cdot a_0+\left(\sum_{i=1}^{n}(x)_i\cdot(y)_i\right)\cdot a_1+\left(\sum_{i=1}^{n}(y)_i^2\right)\cdot a_2=\sum_{i=1}^{n}(y)_i^2\cdot u_i \end{cases} \quad (1)$$

where the real coefficients (the sums from parentheses) are calculated tabularly. The solution of the system is done through the Cramer rule, using the determinants of the system.

Departing from the experimental results, in a first phase the stage are determined the mathematical models of dependencies for optimized parameters (the mechanical features the materials) with the technological parameters in the influences of the process, in the form of equation (2). In mathematical model it is reduced to complex mathematical processing of dependences in the features analyzed depending on two or three chemical elements, grouped depending on the influence upon them. Thus we can analyze dependences type (3).

$$\begin{aligned} HB_{(infneck)} &= f(\text{basic chemical elements}) \\ HB_{(supneck)} &= f(\text{basic chemical elements}) \\ HB_{(body)} &= f(\text{basic chemical elements}) \\ HB_{(infneck)} &= f(\text{alloying chemical elements}) \\ HB_{(supneck)} &= f(\text{alloying chemical elements}) \\ HB_{(body)} &= f(\text{alloying chemical elements}) \end{aligned} \quad (2)$$

$$\begin{aligned} HB_{(infneck)} &= f(C, Si, Mn); \\ HB_{(infneck)} &= f(Ni, Cr, Mo); \\ HB_{(supneck)} &= f(C, Si, Mn); \\ HB_{(supneck)} &= f(Ni, Cr, Mo); \\ HB_{(body)} &= f(C, Si, Mn); \\ HB_{(body)} &= f(Ni, Cr, Mo); \end{aligned} \quad (3)$$

Following the experiments we determine the mechanical features according to the technological parameters of influences in the process. Because we dispose of real data, afterwards it is required to present the model of optimization on industrial data, sampled from rolling mills rolls. As parameters for optimization we selected:

- *the Brinell hardness, measured on the body of rolls, $HB_{(body)}$;*
- *the Brinell hardness, measured on the necks of rolls, $HB_{(infnecks)}$ and $HB_{(supnecks)}$.*

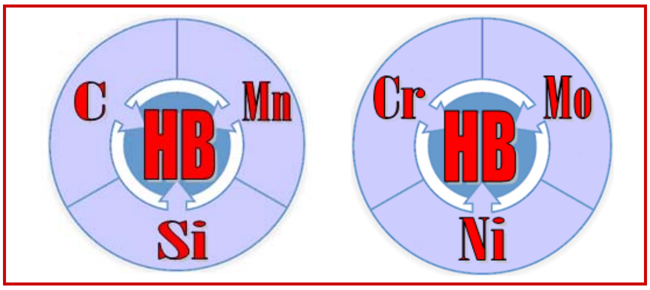

Figure 2. The influence of the basic and the alloyed elements upon the brinell hardness, in mathematical perspective

In order to reduce the experiments number and to simplify the optimization calculi, among the parameters of influence, we chose the chemical composition of the cast irons with nodular graphite. These hypotheses lead the optimization model through the prism of the multi-component correlations in formula (II).

The industrial data are modeled in the form of equation (4). We consider the variations limits of the variables (x, y, z), as well as the variation limits of the analyzed features. Also, in the limits of graphical representation (lim x_{inf}, lim x_{sup}, lim y_{inf}, lim y_{sup}, lim z_{inf}, lim z_{sup}), as well as the average values of the variables and of the analyzed features (x_{med}, y_{med}, z_{med}, u_{med}) are stated.

$$u(x, y, z) = C_1 x^2 + C_2 y^2 + C_3 z^2 + C_4 y z + C_5 x z + C_6 y x + C_7 x + C_8 y + C_9 z + C_{10} \quad (4)$$

At that rate, the equations of the regression hyper-surfaces are in equation (3), for which there is a correlation coefficient (rf) and a deviation from the regression surface (sf).

THE PRESENTATION OF GRAPHICAL ADDENDA

Figure 3 presents the screen which generates the regression surfaces of the variable ($HB_{(body)}$, $HB_{(infnecks)}$, $HB_{(supnecks)}$) for the cases $x = x_{med}$, $y = y_{med}$ and $z = z_{med}$, waves x, y, z represent combination of chemical elements depending on the mathematical model under study.

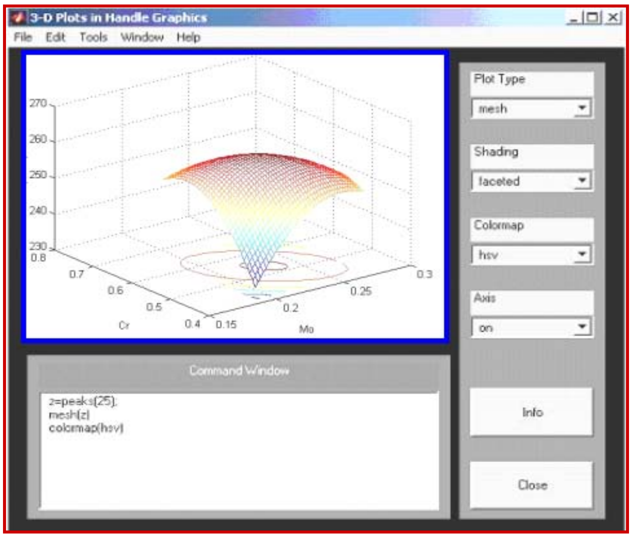

Figure 3. Regression surface of the variabile u ($HB_{(body)}$, $HB_{(infnecks)}$, $HB_{(supnecks)}$) for the cases $x = x_{med}$, $y = y_{med}$ and $z = z_{med}$

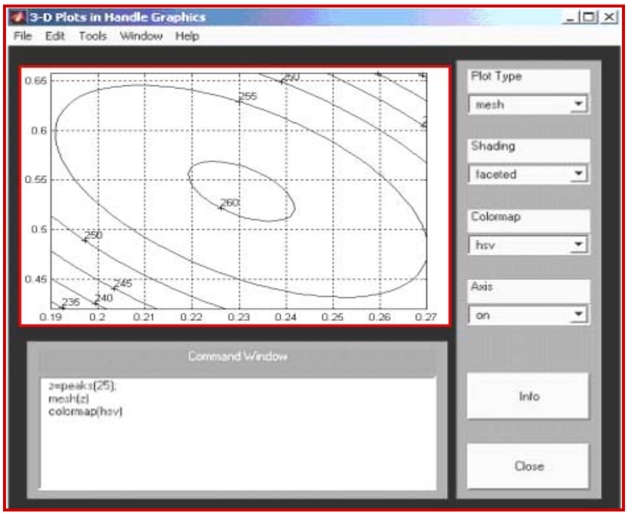

Figure 4. The level curves generation for the dependences u = f(x, y, z), formally u = f(x_{med}, y, z), u = f(x, y_{med}, z) and u = f(x, y, z_{med})

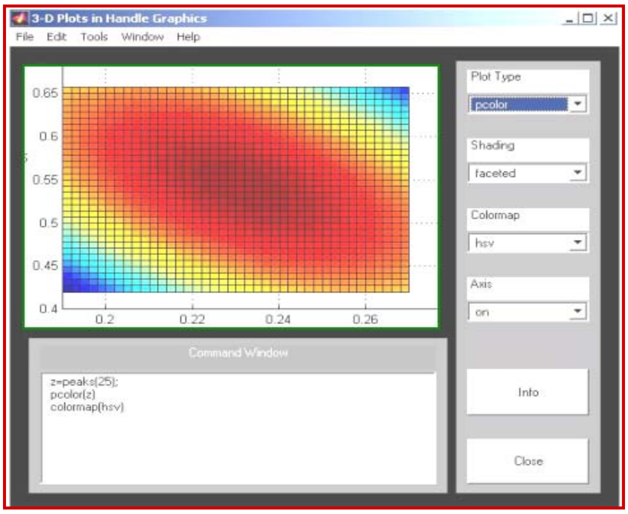

Figure 5. Screen for the variation domain generation of the dependences u = f(x, y, z), formally u = f(x_{med}, y, z), u = f(x, y_{med}, z) and u = f(x, y, z_{med})

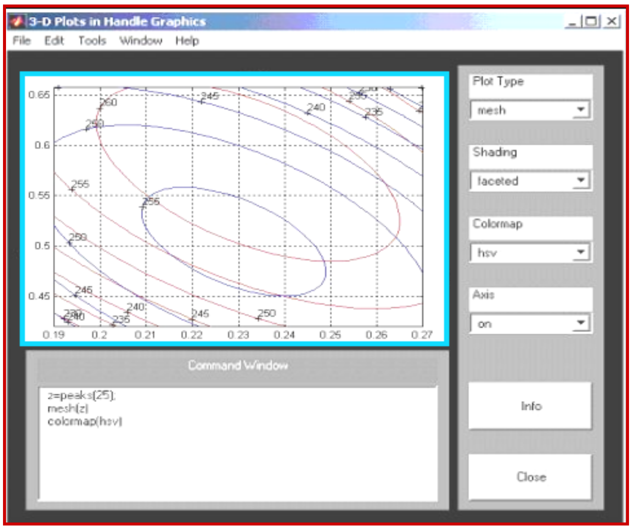

Figure 6. Screen for the adjusting diagrams generation built for the average values ale parameters (x_{med}, y_{med}, z_{med})

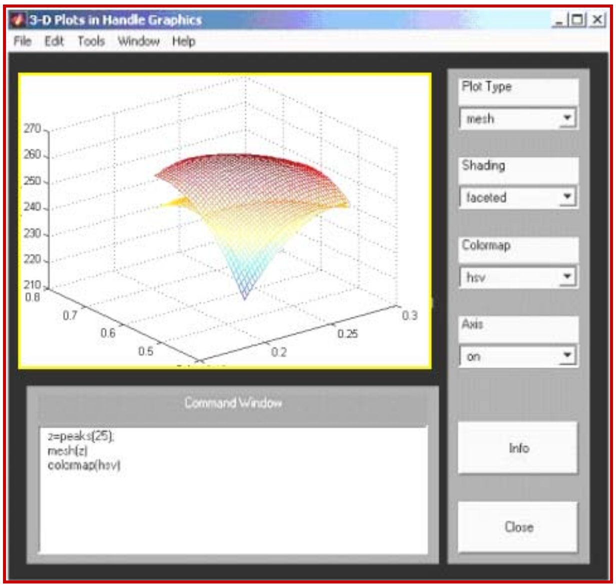

Figure 7. Screen for the regression surface volume variation generation for the average values $x = x_{med}$, $y = y_{med}$ and $z = z_{med}$

Figure 4 presents the program screen capture which generates the level curves of the dependence $u = f(x, y, z)$, formally $u = f(x_{med}, y, z)$, $u = f(x, y_{med}, z)$ and $u = f(x, y, z_{med})$ for the cases $x = x_{med}$, $y = y_{med}$ and $z = z_{med}$. This level curves represents the projection in the two-dimensional plan of the regression surfaces presented in the Figure 3.

Figure 5 presents the screen which generates the variation domain of the characteristics $u = f(x, y, z)$, formally $u = f(x_{med}, y, z)$, $u = f(x, y_{med}, z)$ and $u = f(x, y, z_{med})$ for the cases $x = x_{med}$, $y = y_{med}$ and $z = z_{med}$. This geometrical areas represents level curves variations in the two-dimensional plan.

These diagrams are built for the average values of the parameters (x_{med}, y_{med}, z_{med}), only that through the representation of the diagrams for parameters values contained in the variations limits we can obtain adjusting diagrams (Figure 6), with which we can completely controlled the process.

Figure 7 presents the screen, which generates the correlation surfaces, meaning the projection in the two-dimensional plan of the variation volumes of the regression surfaces. These are obtained through superposing of the $u = f(x_{med}, y_{med}, z_{med})$ and one of surfaces corresponding for the average values $x = x_{med}$, $y = y_{med}$ and $z = z_{med,}$ meaning $u = f(x_{med}, y, z)$, $u = f(x, y_{med}, z)$ and $u = f(x, y, z_{med})$.

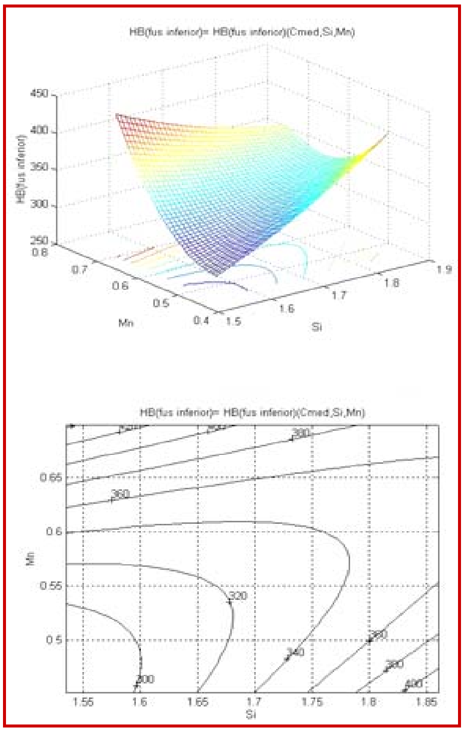

Figure 8.a The regression surface and the level curves generated by the program for the dependences between hardness and chemical composition [presented example for the variation of the parameter $HB_{(Fusinf)}$ in the cases $C = C_{med}$, in the $HB_{(Fusinf)} = f(C_{med}, Si, Mn)$ dependences]

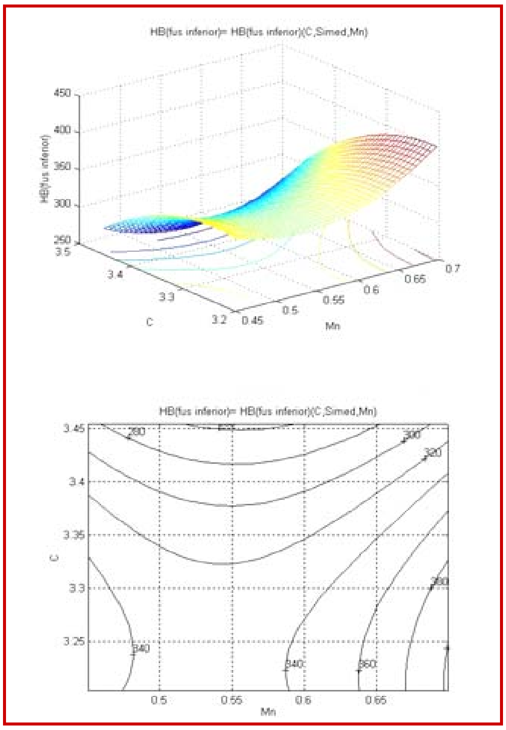

Figure 8.b. The regression surface and the level curves generated by the program for the dependences between hardness and chemical composition [presented example for the variation of the parameter $HB_{(Fusinf)}$ in the cases $Si = Si_{med}$ in the $HB_{(Fusinf)} = f(C, Si_{med}, Mn)$ dependences]

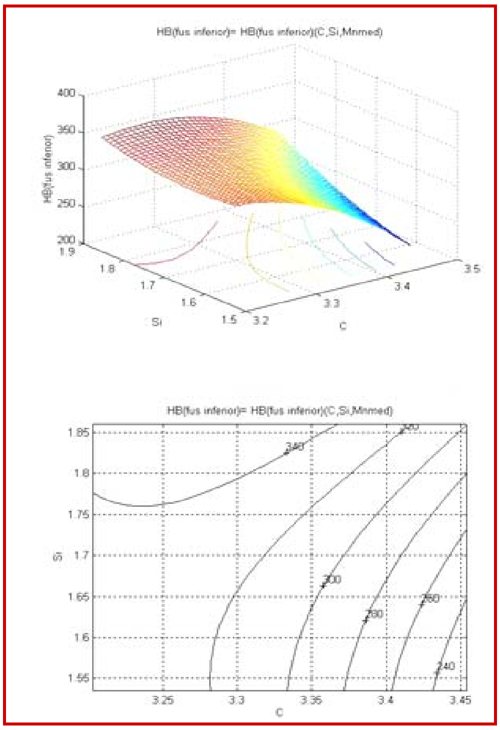

Figure 8.c. The regression surface and the level curves generated by the program for the dependences between hardness and chemical composition [presented example for the variation of the parameter $HB_{(Fusinf)}$ in the cases $Mn = Mn_{med}$, in the $HB_{(Fusinf)} = f(C, Si, Mn_{med})$ dependences]

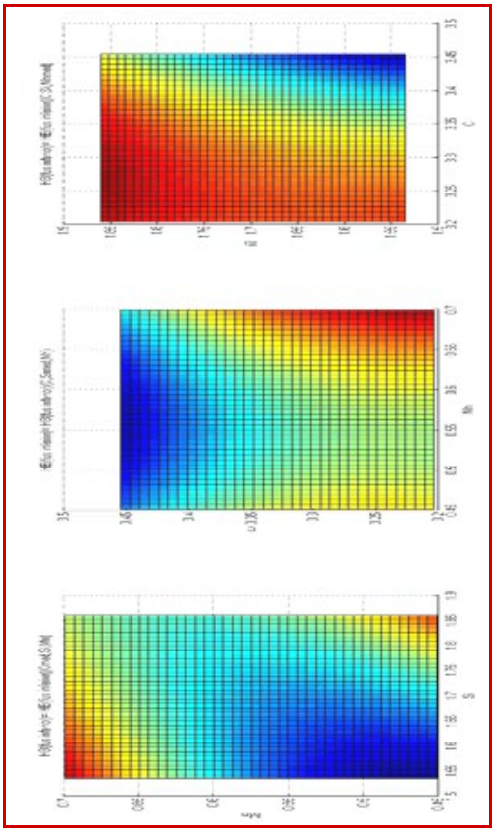

Figure 9. The variation domain in color panel presentation for the dependences between hardness and chemical composition [same cases]

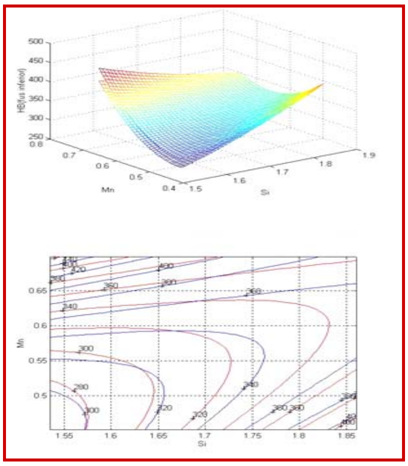

Figure 10. The regression surface volume variation domain and the adjusting diagrams for the dependences between hardness and chemical composition [case $C = C_{med}$]

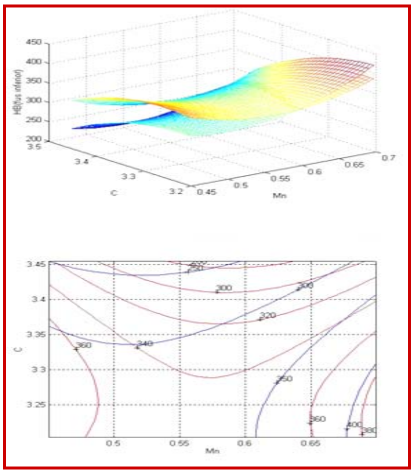

Figure 10. The regression surface volume variation domain and the adjusting diagrams for the dependences between hardness and chemical composition [case $Si = Si_{med}$]

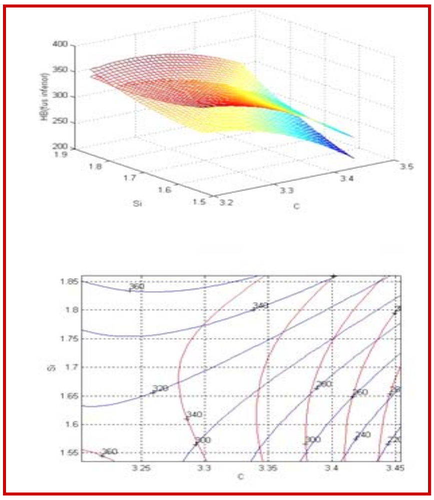

Figure 10. The regression surface volume variation domain and the adjusting diagrams for the dependences between hardness and chemical composition [case $Mn = Mn_{med}$]

CONCLUSIONS

The performed study had in view to obtain correlations between the hardness of the cast iron rolls (on the necks and on the working surface) and its chemical composition, defined by basic and the representative alloying elements. Analyzing the graphical dependences from the performed researches, based on literature review data and from own experimental work it results the fallowing conclusions:

- *the values processed were made using Matlab calculation program. Using this calculation program we determine some mathematical correlation, correlation coefficient and the deviation from the regression surface. This surface in the four-dimensional space (described by the equation) admits a saddle point to which the corresponding value of hardness is an optimal value of alloying elements.*
- *the existence of a saddle point inside the technological domain has a particular importance as it ensures stability to the process in the vicinity of this point, stability which can be either preferable of avoidable.*
- *the behavior of this hyper-surface in the vicinity of the stationary point (when this point belongs to the technological domain) or in the vicinity of the point where the three independent variables have their respective average value, or in a point where the dependent function reaches its extreme value in the technological domain (but not being a saddle point) can be rendered only as a table, namely, assigning values to the independent variables on spheres which are concentric to the point under study.*
- *as this surface cannot be represented in the three-dimensional space, we resorted to replacing successively one independent variable by its mean value. These surfaces (described by the equation), belonging to the three-dimensional space can be reproduced and therefore interpreted by technological engineers.*
- *knowing these level curves allows the correlation of the values of the two independent variables so that we can obtain a viscosity within the required limits.*

The realization of a mathematical model starting from industrial data, gathered at the rolls hardness measurement, and at the national standards reglementations, which recommends the hardness, for different chemical compositions, also determines the degree of originality of the research. The determination of the equations of regression hiperplanes, which describe the mathematical dependency between the chemical composition and the hardness, the determination of the multicomponent relations and the realization of the graphic interfaces for the representations variation areas of the cast-irons chemical composition, completes this area of preoccupations within a processing mathematical of molding and optimization.

The realization of an optimal chemical composition can constitute a technical efficient mode to assure the exploitation properties, the material from which the rolling mills rolls are manufactured having an important role in this sense. From this point of view is applied the mathematical molding, witch is achieved starting from the differentiation on rolls component parts, taking into consideration the industrial data obtained from the hardness measuration on rolls, as well as the national standards reglementations, which recommends the hardness, for different chemical compositions.

The optimum solution is determined through some mathematical restrictions to the input values that the mathematical molding is started. As a work method is chosen the way of the constraint of average successive values to some of the elements of chemical composition, leaving free the variation of a number of variables submitted to optimization. Is searched to constraint average values, inclusively to dependent variables, desired to achieve through the chemical optimum composition. It will be determined the equations of regression hiperplanes, which describe the mathematical dependency between the chemical composition and the hardness, and is searched a solution which can determine the optimum chemical composition for hardness desirable values.

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cylinders through mathematical molding of the manufacturing process and the experimental study of durability in exploitation" [KISS, I.(manager), ALEXA, V. (collaborator), between the years 2005-2008],

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