Graphical Addenda in the Technological Area of the Nodular Iron Cast Rolls Production

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Abstract: 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 same foundry product meets difficult technological problems in the industrial condition. One of the parameters, which determine the structure of the irons destined for rolls casting, is the chemical composition. If we not respect this composition, which guaranties the exploitation properties of the each roll in the stand of rolling mill, it will lead to rejection. Alloying elements have in principle the same influence on structure and properties. This paper suggest a mathematical interpretation of the influence of the main alloy elements over the mechanical characteristics (the hardness on the crust and on the necks of the rolls) of this nodular irons, resulting the average values and average square aberration of the variables HB, and the main alloying elements (Cr, Ni, Mo), the equations of the hyper surface in the four dimensional space. For the statistical and mathematical analysis, there were used 23 industrial cases. The resulted surfaces, belonging to the three-dimensional space, can be represented and, therefore, interpreted by technologists. Knowing these level curves allows the correlation of the values of the twos independent variables so that the hardness can be obtained in between the requested limits. The paper presents the results of some researches regarding the chemical composition of the nodular irons destined for casting half-hard rolls. It is presented, in graphical form, used the Matlab area, the influence of the main alloying elements upon the hardness, and measured on the necks and the core of the rolls, respectively on the working surface (body) of these very important rolling mill components 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 cylinders are manufactured having an important role in this sense. From this point of view is applied the mathematical molding, which is achieved starting from the differentiation on rolls component parts, taking into consideration the industrial data obtained from the hardness mensuration on rolls, which recommends the hardness, for different chemical compositions.

Keywords: iron rolls, alloying elements, hardness, modelling, graphical addenda

1   Introduction

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. The rolls must present high hardness at the crust of rolls and lower hardness in the core and on the necks, adequate with the mechanical resistance and in the high work temperatures. If in the crust the hardness is assured by the quantities of cementite from the structure of the irons, the core of the rolls must contain graphite to assure these properties. 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 the exploitation properties of the each roll in the stand of rolling mill, leads to rejection of this.

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 rise the quality of rolls. In this case, the contents of these elements stand between large limits. Also, the contents of these alloying elements can be reduced due to the strong effect of the magnesium from the nodulising agent, upon the graphite's structure and form.

This study analyses iron rolls cast in the simplex procedure, in combined forms (iron chill, for the crust and moulding sand, for the necks of the rolls). The research included rolls from the half-hard class, with hardness, between 33…59 Shore units (219…347 Brinell units) for the 0 and 1 hardness class, measured on the crust, respectively 59…75 Shore units (347…550 Brinell units), for the class 2 of hardness.

This study is required because of the numerous defects, which cause rejection, since the phase of elaboration of these irons, destined to cast rolls. According to the previous presentation, it results that one of the most important reject categories is due to the inadequate hardness of the rolls. The research includes half-hard cast rolls, from nodular graphite irons (type FNS), hardness class 1 and 2, with the half-hard crust of 40…150 mm depth. All these types of rolls have high strength, excellent thermal properties and resistance.

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 cylinders, obtained through the simplex classical cast of the iron with nodular graphite, for which the mechanical features of rolling mill cylinders have the required values.

Table 1

Recommended hardness of half-hard cast iron rolls

Roll Types	Class of Hardness	Recommended hardness for these rolls			
		on the surface of rolls		on core and necks of rolls	
		[Shore]	[Brinell]	[Shore]	[Brinell]
FNS	0	33…42	218…286	30…40	195…271
FNS	1	43…59	294…347	30…40	195…271
FS	2	59…68	420…491	35…45	218…309
FNS	2	69…75	499…550	35…45	218…309

Table 2

Recommended chemical compositionof the half-hard cast iron rolls

Type	The basic chemical composition [%]				
	C	Si	Mn	P	S
FS	2.9...3.6	0.3...1.2	max 0.6	max 0.15	max 0.1
FNS	3.0...3.5	1.2...2.5	0.1...0.7	max 0.15	max 0.02
Type	The alloying elements and the nodulising agent [%]				
	Ni	Cr	Mo	Mg	
FS	max 0.6	max 0.5	0.3...0.5	-	
FNS	1.5...2.5	max 0.8	0.3...0.5	0.02...0.04	

2   Interpretation and Simulation

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 rise the quality of rolls.

In this case, the contents of these elements stand between large limits. Also, the contents of these alloying elements can be reduced due to the strong effect of the magnesium from the nodulising agent, upon the graphite's structure and form.

The two-dimensional representations can not present only that than of tendencies of influences, through his diminution or the enlargement of the feature characteristics, and the polynomial functions just appreciate, on ensemble, the influence of the chemical elements upon hardness in different in points of rolls, indicating just the limits of variation. For this reason is enforced an analysis of the cumulated influences of elements upon the hardness in different in parts of rolls, which study will be the study of the further researches.

Therefore, we suggest a mathematical interpretation of the influence of the main alloy elements over the mechanical characteristics (the hardness on the crust of the rolls) of this nodular irons, resulting the average values and average square aberration of the variables HB, and the main alloying elements (Cr, Ni, Mo), the equations of the hyper surface in the four dimensional space. For the statistical and mathematical analysis, there were used 23 industrial cases.

Table 3

The experimental mesured data, the theoretical determined data and the error

No.	Alloying elements [%]			The hardness on the body			The hardness on the necks		
	Ni	Cr	Mo	*	**	error	*	**	error
1.	1.99	0.62	0.22	342	333.71	8.30	270	262.39	7.60
2.	2.21	0.64	0.26	341	319.33	21.66	269	263.75	5.25
3.	2.16	0.57	0.25	326	326.31	- 0.29	266	265.57	4.32
4.	2.16	0.53	0.24	328	324.08	3.91	256	262.61	- 6.60
5.	1.59	0.38	0.22	292	289.46	2.53	249	244.5	4.49
6.	2.24	0.51	0.28	306	300.86	5.13	269	258.32	10.68
7.	1.82	0.36	0.26	291	288.48	2.51	246	245.84	0.16
8.	1.97	0.52	0.27	282	309.53	- 27.52	242	257.95	- 15.95
9.	2.22	0.66	0.21	322	331.03	- 9.03	266	265.49	0.50
10.	1.49	0.63	0.22	312	312.35	- 0.35	219	223.71	- 4.70
11.	1.63	0.51	0.27	284	294.99	- 10.98	238	239.9	- 1.90
12.	1.55	0.39	0.25	299	295.61	3.39	251	246.71	4.29
13.	1.52	0.47	0.21	286	307.05	- 21.05	241	246.96	- 5.95
14.	1.63	0.45	0.23	296	311.37	- 15.37	244	252.09	-8.08
15.	1.65	0.43	0.18	280	265.79	14.21	239	235.33	3.67
16.	2.11	0.68	0.27	289	300.02	- 11.02	247	249.77	- 2.76
17.	2.19	0.67	0.24	321	330.17	- 9.16	253	265.16	- 12.16
18.	1.62	0.44	0.21	297	301.49	- 4.48	242	248.65	- 6.65
19.	1.63	0.49	0.25	352	311.79	40.21	276	249.19	26.81
20.	1.66	0.42	0.27	296	293.05	2.95	238	247.5	- 9.49
21.	2.08	0.72	0.23	328	327.38	0.62	258	255.56	2.44
22.	1.94	0.64	0.24	339	327.52	11.48	264	255.99	8.00
23.	1.92	0.4	0.22	282	289.66	- 7.66	242	242.08	- 0.07

* experimental measured data

** theoretical determined data

The variables variation limits are: Ni = 1.49…2.24; Cr = 0.36…0.72; Mo = 0.18…0.28, and the hardness variation limits are $HB_{(necks)}$ = 219…276 and $HB_{(body)}$ = 282…352. Therefore, the graphical representation limits, for this modelling case, are presented in *Table 4*.

Table 4

lim Ni_{inf}	lim Ni_{sup}	lim Cr_{inf}	lim Cr_{sup}	lim Mo_{inf}	lim Mo_{sup}
1.61	2.11	0.40	0.67	0.19	0.27

The middle values for the three variables (Ni, Cr, Mo) and the hardness (HB), necessary for the calculation of the optimal form of modelling are:

$$Ni_{med} = 1.86; Cr_{med} = 0.52; Mo_{med} = 0.23;$$

and

$$HB_{(necks)med} = 251.52; HB_{(body)med} = 308.32;$$

Next, there are shown the results of the multidimensional processing of experimental data. For that purpose, we searched for a method of modelling the dependent variables u depending on the independent variables x, y, z:

$$u = c_1 \cdot x^2 + c_2 \cdot y^2 + c_3 \cdot z^2 + c_4 \cdot x \cdot y + c_5 \cdot y \cdot z + c_6 \cdot z \cdot x + c_7 \cdot x + c_8 \cdot y + c_9 \cdot z + c_{10} \quad (1)$$

The optimal modelling's form is given by the equations:

$$HB_{(body)} = - 69.2668\ Ni^2 - 843.9321\ Cr^2 - 13082.6971\ Mo^2 + 258.4342\ Ni \cdot Cr$$
$$- 3258.4415\ Cr \cdot Mo + 757.2487\ Mo \cdot Ni - 45.2572\ Ni + 1278.2053\ Cr$$
$$+ 6349.4428\ Mo - 739.6223 \quad (2)$$

$$HB_{(necks)} = - 77.1259\ Ni^2 - 678.1307\ Cr^2 - 4915.8057\ Mo^2 + 384.4321\ Ni \cdot Cr$$
$$- 1990.8226\ Cr \cdot Mo + 646.2006\ Mo \cdot Ni - 39.5771\ Ni + 471.3705\ Cr$$
$$+ 2131.6892\ Mo - 101.7176 \quad (3)$$

where the correlation coefficients are:

$$rf_{\ HB(body)\ =\ f(Ni,\ Cr,\ Mo)} = 0.77;\ and\ rf_{\ HB(necks)\ =\ f(Ni,\ Cr,\ Mo)} = 0.76$$

and the aberrations from the regression surface are:

$$sf_{\ HB(body)\ =\ f(Ni,\ Cr,\ Mo)} = 13.96;\ and\ sf_{\ HB(necks)\ =\ f(Ni,\ Cr,\ Mo)} = 8.73$$

3 Presentation the Obtained Results

In the technological field, the behaviour of these hyper surfaces in the vicinity of the saddle point, or of the point where three independent variables take their average value, can be studied only tabular, which means that the independent variables are attributed values on spheres concentric to the studied point. Because these surfaces cannot be represented in the three-dimensional space, the independent variables were successively replaced with their average values. This is how the following equations were obtained.

$$HB_{(body)}Ni_{med} = - 843.9321\ Cr^2 - 13082.6971\ Mo^2 - 3258.4415\ Cr \cdot Mo$$

$$+ 1761.1402\ Cr + 7764.5101\ Mo - 1066.0756 \tag{4}$$

$$HB_{(body)}Cr_{med} = - 13082.6971\ Mo^2 - 69.2668\ Ni^2 + 757.2487\ Mo \cdot Ni$$

$$+ 4630.9691\ Mo + 91.0387\ Ni - 300.2406 \tag{5}$$

$$HB_{(body)}Mo_{med} = - 69.2668\ Ni^2 - 843.9321\ Cr^2 + 258.4342\ Ni \cdot Cr$$

$$+ 135.8241\ Ni + 499.0128\ Cr + 30.6111 \tag{6}$$

$$HB_{(necks)}Ni_{med} = - 678.1307\ Cr^2 - 4915.8057\ Mo^2 - 1990.8226\ Cr \cdot Mo$$

$$+ 1189.7571\ Cr + 3339.2414\ Mo - 445.0005 \tag{7}$$

$$HB_{(necks)}Cr_{med} = - 4915.8057\ Mo^2 - 77.1259\ Ni^2 + 646.2006\ Mo \cdot Ni$$

$$+ 1081.7467\ Mo + 163.1691\ Ni - 41.7373 \tag{8}$$

$$HB_{(necks)}Mo_{med} = - 77.1259\ Ni^2 - 678.1307\ Cr^2 + 384.4321\ Ni \cdot Cr$$

$$+ 114.9492\ Ni - 4.6957\ Cr + 126.9318 \tag{9}$$

4 Presentation the Graphical Addenda

These surfaces, belonging to the three-dimensional space, can be represented and, therefore, interpreted by technologists. Knowing these level curves allows the correlation of the values of the twos independent variables so that the hardness can be obtained in between the requested limits.

These diagrams are built for the average values of the parameters (Cr_{med}, Ni_{med}, Mo_{med}), only that through the representation of the diagrams for parameters values contained in the variations limits we can obtain adjusting diagrams, with which we can completely controlled the process.
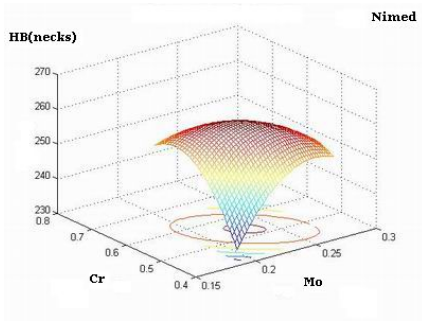
Figure 1
The regression surface
HB $_{(necks)}$ for Ni = Ni$_{med}$
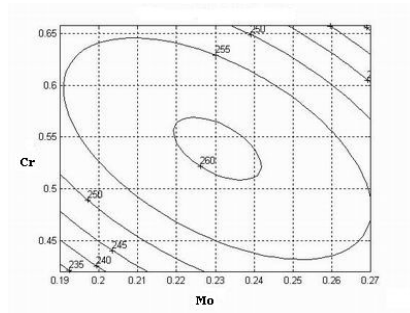
Figure 2
Level curves
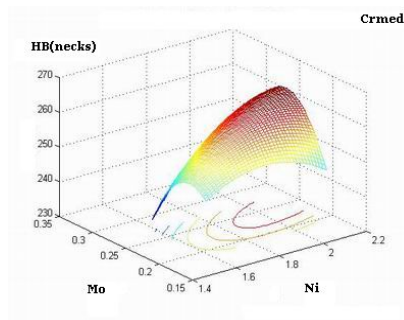HB $_{(necks)}$ = f(Ni$_{med}$, Cr, Mo)

Figure 3
The regression surface
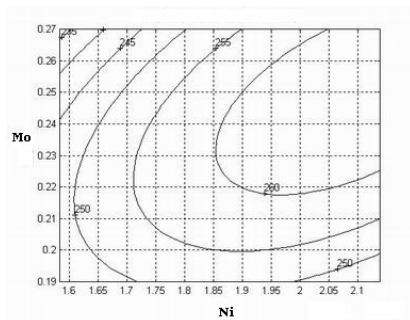HB $_{(necks)}$ for Cr = Cr$_{med}$

Figure 4
Level curves
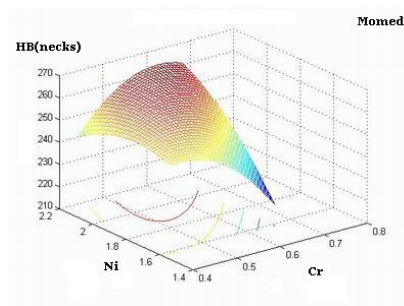HB $_{(necks)}$ = f(Ni, Cr$_{med}$, Mo)

Figure 5
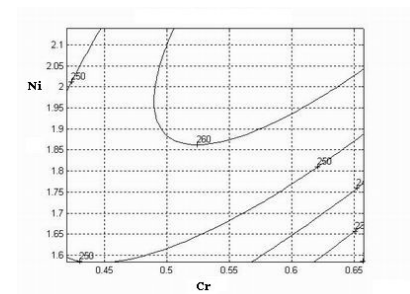The regression surface
HB $_{(necks)}$ for Mo = Mo$_{med}$

Figure 6
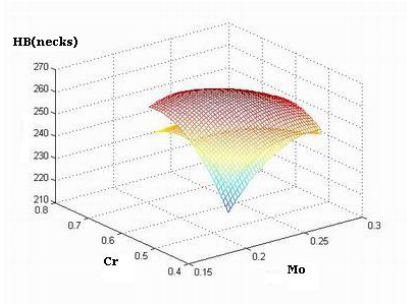Level curves
HB $_{(necks)}$ = f(Ni, Cr, Mo$_{med}$)

Figure 7
The volume variation of the regression surface
HB $_{(necks)}$ for Ni = Ni$_{med}$
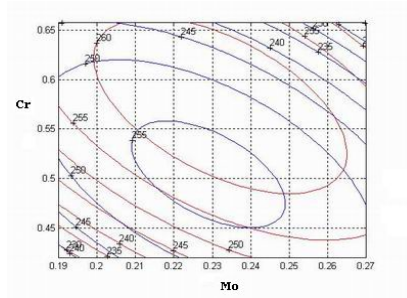
Figure 8
Level curves for volume variation of the
regression surface HB $_{(necks)}$ for Ni= Ni$_{med}$
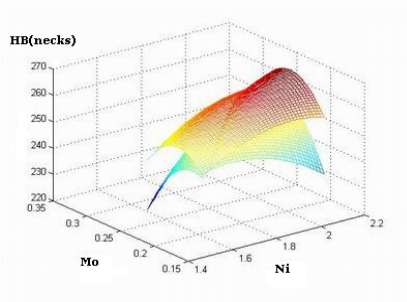
Figure 9
The volume variation of the regression surface
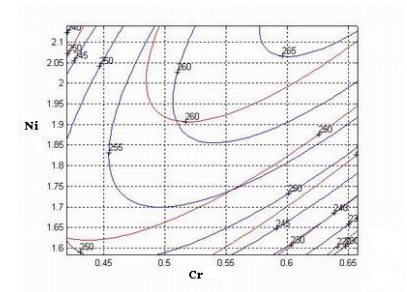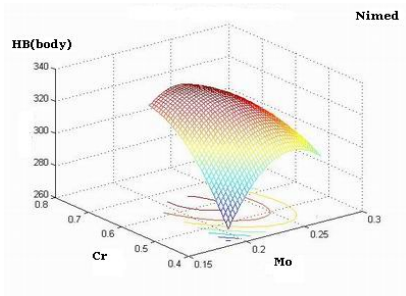HB $_{(necks)}$ for Cr = Cr$_{med}$
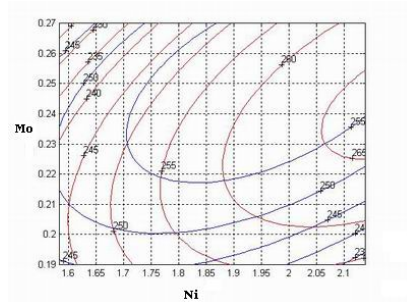
Figure 10
Level surves for volume variation of the
regression surface HB $_{(necks)}$ for Cr = Cr$_{med}$
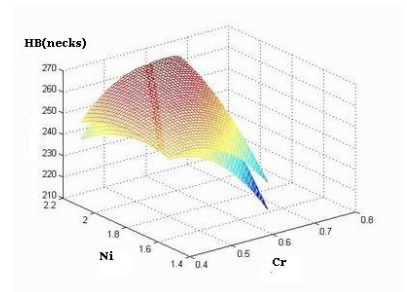
Figure 11
The volume variation of the regression surface
HB $_{(necks)}$ for Mo = Mo$_{med}$

Figure 12
Level curves for volume variation of the
regression surface HB $_{(necks)}$ for Mo= Mo$_{med}$

Figure 13
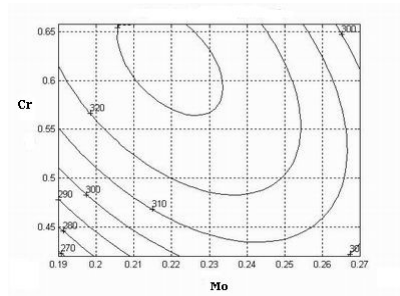The regression surface
HB $_{(body)}$ for Ni = Ni$_{med}$

Figure 14
Level curves
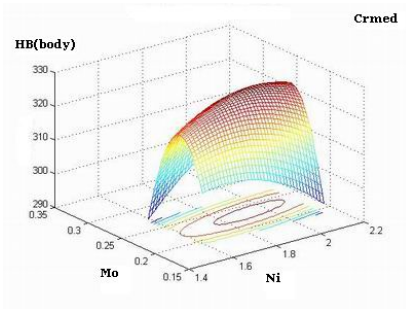HB $_{(body)}$ = f(Ni$_{med}$, Cr, Mo)

Figure 15
The regression surface
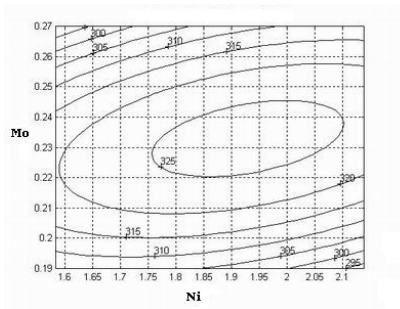HB $_{(body)}$ for Cr = Cr$_{med}$

Figure 16
Level curves
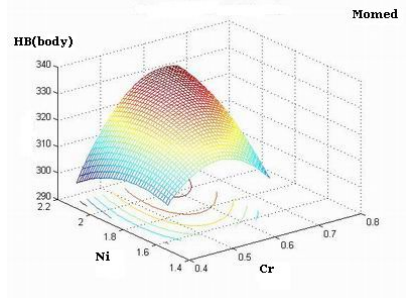HB $_{(body)}$ = f(Ni, Cr$_{med}$, Mo)

Figure 17
The regression surface
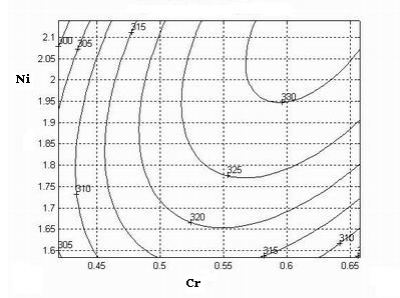HB $_{(body)}$ for Mo = Mo$_{med}$

Figure 18
Level curves
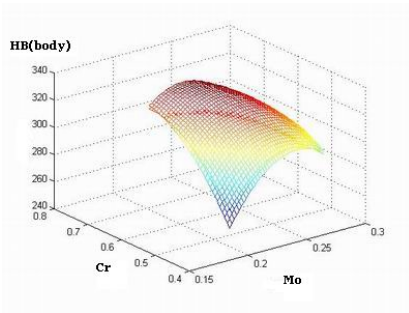HB $_{(body)}$ = f(Ni, Cr, Mo$_{med}$)

Figure 19

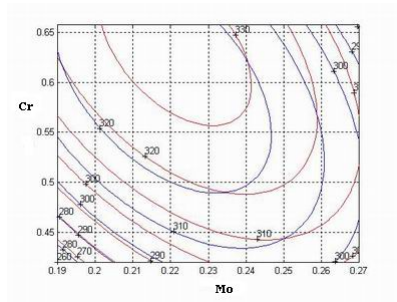The volume variation of the regression surface HB $_{(body)}$ for Ni = Ni$_{med}$

Figure 20

Level curves for volume variation of the regression surface HB $_{(body)}$ for Ni= Ni$_{med}$

Figure 21
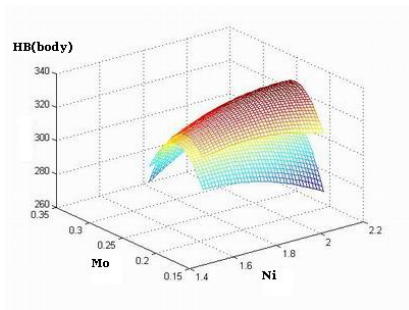
The volume variation of the regression surface HB $_{(body)}$ for Cr = Cr$_{med}$
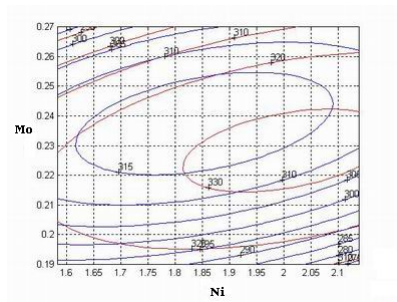

Figure 22

Level surves for volume variation of the regression surface HB $_{(body)}$ for Cr = Cr$_{med}$
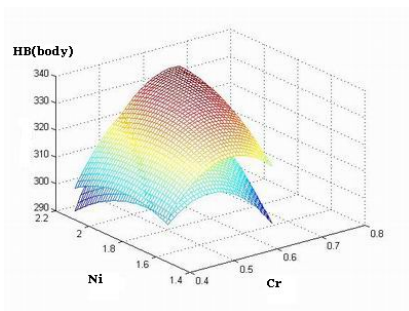

Figure 23

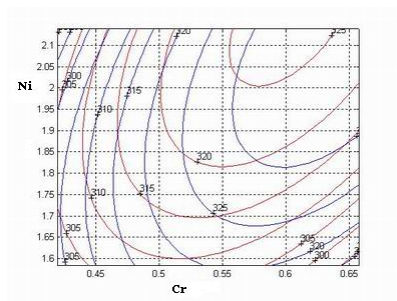The volume variation of the regression surface HB $_{(body)}$ for Mo = Mo$_{med}$

Figure 24

Level curves for volume variation of the regression surface HB $_{(body)}$ for Mo= Mo$_{med}$

Conclusions

The performed research had in view to obtain correlations between the hardness of the cast iron rolls (on the necks and on the body) and the representative alloying elements (Ni, Cr, Mo). The values processing were made using Matlab calculation program. Using this area we determinate some mathematical correlation, correlation coefficient and the deviation from the regression surface. This surface in the four-dimensional space (described by the general equation 1, and particular equations 2 and 3) admits a saddle point to which the corresponding value of hardness is an optimal alloying elements. Therefore, some conclusions could be presented:

⊹ 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 behaviour 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 mean 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 concentrically to the point under study.

⊹ as these surfaces 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 4…9), belonging to the three-dimensional space can be reproduced and therefore interpreted by technological engineers (Figures 1, 3, 5, respectively Figures 13, 15, 17). Knowing these level curves (Figures 2, 4, 6, respectively Figures 14, 16, 18) allows the correlation of the values of the two independent variables so that we can obtain the hardness within the required limits.

⊹ the Figures 7, 9, 11, respectively Figures 19, 21, 23 presented the volume variation of the regression surfaces $HB_{(necks)}$ and $HB_{(body)}$ for one of the middle value of the variables Ni, Cr, Mo.

⊹ in the Figures 8, 10, 12, respectively Figures 20, 22, 24, the level curves for the volume variation of the regression surfaces $HB_{(necks)}$ and $HB_{(body)}$, for the Ni_{med}, Cr_{med} and Mo_{med}, are presented in the graphical addenda.

⊹ the usage of the Matlab area, can also be extended to the study of influences other chemical components (C, Si, Mn, S, P, Mg), and this influences upon the necks and the body of the rolling mills;

Engineering is concerned with the design of a solution to a practical problem. A scientist may ask *why* a problem arises, and proceed to research the answer to the question or actually solve the problem in his first try, perhaps creating a

mathematical model of his observations. By contrast, engineers want to know *how* to solve a problem, and *how* to implement that solution. In other words, scientists attempt to *explain* phenomena, whereas engineers use any available knowledge, including that produced by science, to *construct* solutions to problems.

Often when engineers analyze a system to be controlled or optimized, they use a mathematical model. In analysis, engineers can build a descriptive model of the system as a hypothesis of how the system could work, or try to estimate how an unforeseeable event could affect the processes. As with all modern scientific and technological endeavors, computers and software play an increasingly important role. Numerical methods and simulations can help predict design performance more accurately than previous approximations. A mathematical model usually describes the processes by a set of variables and a set of equations that establish relationships between the variables. In this sense, the following research had in view to obtain correlations between the hardness of cast iron rolls and its chemical composition, defined by the representative alloying elements.

References

[1]   Maksay, St,: Special Mathematics, Vols. I & II, Politehnica Publishing House, Timisoara, 2001

[2]   Taloi, F., Bratu, C., Florian, E., Berceanu, E.: The Optimization of the Metallurgical Process, Didactical and Pedagogical Publishing House, Bucuresti, 1983

[3]   Bonollo, F., Gramegna, N., Odorizzi, S.: Modellizzazioni dei processi di fonderia, in: Fonderia, 11/12, 1997, pp. 50-54

[4]   Carless, P.: Present and Future Hot Strip Mill Finishing Train Work Rolls, Ironmaking and Steelmaking, Vol. 27, No. 1, 2000

[5]   Frolish, M. F., Beynon, J. H.: Design Criteria for Rolling Contact Fatigue Resistance in Back-up Rolls, at: International Symposium "Rolls 2003" - International Convention Centre, Birmingham, United Kingdom, 2003

[6]   Kerr, E. J., Webber, R.: Roll Performance - Present Overview and Look to the Future, at: International Symposium "Rolls 2003" - International Convention Centre, Birmingham, United Kingdom, 2003

[7]   Kiss, I., Heput, T.: Mechanical Properties of the Cast Iron Rolls, assured by the chemical composition, in: Scientific Bulletin of the University Politehnica of Timisoara, Transactions on Mechanics, Tome 47, Fascicule 2, pp. 175-181, 2002

[8]   Gorvany, V., Mamuzic, I., Radsinsky, V.: Influence of Cooling on the Resistance of Chrom-Nickel Iron Rolls, in: Metalurgija, 42, 2003, pp. 245-247

[9]   Sofroni, L., Riposan, I., Cernat, C., Chira, I., Gradinaru, C: The Complex Alloying of Cast Iron used for Hard Crust Millrolls Casting in View to

Minimise the Nickel Content, la: 42nd International Foundry Congress, Lisabona, Portugalia – 1975, Giesserei – Praxis, 21, 1976, pp. 50-58

[10] Kiss, I., Maksay, St.: Model de optimizare a compozitiei chimice a fontelor cu grafit nodular (Cr, Ni, Mo) destinate turnarii cilindrilor de laminar, Analele Facultatii de Inginerie din Hunedoara, Tome IV, Fascicule 4, 2002, pp. 159-168

[11] Budaghiant, N. A., Karsski, V. E.: Cast Iron Rolls, Editura Tehnica, Bucuresti, 1984

[12] Kiss, I.: The Quality of Rolling Mills Cylinders Cast by Iron with Nodular Graphite, Mirton, Timisoara, 2005

[13] Kiss, I.: Researches Concerning the Improvement Quality of Rolling Mill Cylinders Cast from Cast-Iron with Nodular Graphite, Doctoral Thesis, Bucuresti, 2005

[14] Kiss, I., Hepuţ, T.: The Hardness of the Cast Iron Rolls, Assured by the Alloy Elements and the Modification Treatment of the Graphite Nodularity, in: Scientific Bulletin of Politehnica University of Timişoara, Transactions on Mechanics, Tome 47, Fascicule 2, pp. 169-174, 2002

[15] Kiss, I.: Researches Regarding the Quality Assurance of the Rolling Mills Cast-Iron Cylinders through Mathematical Molding of the Manufacturing Process and the Experimental Study of Durability in Exploitation, National contract No. 5889/2005, Bucuresti

[16] Lipinski, D. M., Schaefer, W., Flender, E.: Numerical Modelling of the Solidification of Castings, Atti del Convegno "Modelling of Casting, Welding and Advanced Solidification Processes VI", 1993, pp. 389-398

[17] McCann, J.: Overview of Work Rolls for Cold Rolling, Ironmaking and Steelmaking, Vol. 27, No. 1, 2000

[18] Pellizzari, M., Molinari, A., Biggi, A.: Optimization of the Hot Roll Performances through Microstructural Tailoring, at Conference of University Trento, Brescia, Italy, 2002

[19] Stevens-Oost, B.: Roll Quality and Roll Cost Development: Where do We Come from and Where are We Going?, at International Symposium "Rolls 2003" - International Convention Centre, Birmingham, United Kingdom, 2003

[20] STAS 9432 – 85: Rolling Mills. Half-Hard Cast Iron Rolls Specification