SOME INTERPRETATIVE RESEARCH IN THE AREA OF CAST IRON ROLLS QUALITY ASSURANCE

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Abstract
This paper suggest a mathematical interpretation of the influence of the basic chemical composition over the mechanical characteristics (the hardness on the rolling surface and on the necks of the rolls) of this nodular irons, resulting the equations of the hyper surface in the four and three dimensional space, the average values and mean average square deviation of the dependencies. For the statistical and mathematical analysis, there were used some industrial cases. The values processing was made using Matlab program, which can generate multi-component correlations, enounced by mathematical formulas. The resulting surfaces, belonging to the three-dimensional space, can be represented and, therefore, interpreted by technologists. Also, the level curves can be interpreted by engineers. Knowing the level curves allows the correlation of the values of the twos independent variables so that the hardness can be obtained inside the requested limits. It is presented, in graphical form, the influence of the basic chemical composition upon the hardness, which is measured on the necks and the core of the rolls, respectively on the working surface (body) of these very important rolling mill components. 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 chemical elements (C, Si, Mn).

Keywords: iron, rolls, hardness, modeling, level curves, correlations

1 Introduction

The technical conditions, which are imposed to the cast iron rolls in the exploitation period, are very different and often contradictory.[1-2,14,16] 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. 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. [3,14,17] 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. [1-2,5-7,14,16] One of the parameters, which determine the structure of the irons destined for rolls casting, is the chemical composition. [1-2,8-13,18-23] If we do not respect this composition, which guarantees the exploitation properties of the each roll in the stand of rolling mill, it will lead to rejection. [1-2]

This study is required because of numerous defects, which cause rejection, since the phase of elaboration (melting and treatment in the ladle) of irons intended for the cast rolls. [1-2,5-

6,14,16] According to the practical conditions in foundries, it results that one of the most important reject categories is due to the inadequate hardness of the rolls. [1-2] All these types of rolls have high strength, excellent thermal properties and resistance to accidents and there is very little hardness drops in the surface work layer. This study analyses iron rolls cast in the simplex procedure, in combined forms (iron chill, for the crust and modeling sand, for the necks 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. [1-2,9-10,13,18-23]

2 Technical Interpretation in Matlab Area

Therefore, we suggest a mathematical interpretation of the influence of the basic elements (C, Si, Mn) on the mechanical characteristics (the hardness on the crust of the rolls) of this nodular irons, resulting average values and mean square deviation of the variables HB, and chemical elements, the equations of the hyper surface in the four dimensional space. [1-2,4,7]
For the statistical and mathematical analysis, there were used 23 industrial cases. [1-2,9-10] The variables variation limits, and the middle values for the three variables (C, Si, Mn) are presented in **Table 1**. The variables variation limits, in the hardness variation limits $HB_{(necks)}$ = 219-276 and $HB_{(body)}$ = 282-352, are presented in **Table 2**. Also, the graphical representation limits, for this modeling case, and the middle values for the three variables (C, Si, Mn) and the hardness (HB), necessary for the calculation of the optimal form of modeling are:

$C_{med} = 3.29$; $Si_{med} = 1.81$; $Mn_{med} = 0.63$; and
$HB_{(necks-inf)med} = 328$; $HB_{(necks-sup)med} = 336$; $HB_{(body)med} = 382$;

Table 1 The variables (C, Si, Mn) variation limits and the middle values for the three variables

C [%]			Si [%]			Mn [%]		
minim	maxim	middle	minim	maxim	middle	minim	maxim	middle
3.14	3.52	3.2985	1.48	2.19	1.8100	0.42	0.78	0.6385

Table 2 The hardness variation limits and the middle values ($HB_{(body)}$, $HB_{(necks-inf)}$, $HB_{(necks-sup)}$)

$HB_{(body)}$			$HB_{(necks-inf)}$			$HB_{(necks-sup)}$		
minim	maxim	middle	minim	maxim	middle	minim	maxim	middle
282	486	382	219	478	328	224	479	336

Next, there are shown the results of the multidimensional processing of experimental data. For that purpose, we searched for a method of modeling the dependent variables u depending on the independent variables x, y, z (see **equation 1**). The optimal modeling's form is given by **equations 2-4**. Using this area some mathematical correlation, correlation coefficient and the deviation from the regression surface are determinate (presented in **Table 3**).

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

$$HB_{(necks-inf)} = -1517.8859\,C^2 + 371.0275\,Si^2 + 2542.0539\,Mn^2 + 752.5868\,C \cdot Si - 2570.8629\,Si \cdot Mn - 487.8739\,Mn \cdot C + 8776.4821\,C - 2156.8091\,Si + 3277.8632\,Mn - 13020.6111 \quad (2)$$

$$HB_{(necks-sup)} = -1344.3081\,C^2 + 1321.4452\,Si^2 - 106.5153\,Mn^2 + 1238.0976\,C \cdot Si - 1650.6309\,Si \cdot Mn - 2489.3387\,Mn \cdot C + 7933.1227\,C - 7724.1531\,Si + 11152.6156\,Mn - 8875.5144 \quad (3)$$

$$HB_{(body)} = 638.1423\ C^2 - 241.4879\ Si^2 + 1975.1556\ Mn^2 - 687.6853\ C{\cdot}Si + 310.443\ Si{\cdot}Mn + 142.3547\ Mn{\cdot}C - 2995.1496\ C + 3009.1012\ Si - 3135.5616\ Mn + 3363.0033 \qquad (4)$$

In the technological field, the behavior of these hyper surfaces in the vicinity of the saddle point, or of the point where three independent variables acquire their average value, can be studied only tabular, which means that the independent variables are attributed values on spheres concentric to the studied point.

Table 3 The correlation coefficients and the aberrations from the regression surface

$HB_{(necks\text{-}inf)} = f(C, Si, Mn)$	$HB_{(necks\text{-}sup)} = f(C, Si, Mn)$	$HB_{(body)} = f(C, Si, Mn)$
The correlation coefficients, rf		
$rf_{HB(necks\text{-}inf)= f(C, Si, Mn)}$	$rf_{HB(necks\text{-}sup) = f(C, Si, Mn)}$	$rf_{HB(body) = f(C, Si, Mn)}$
0.82	0.76	0.46
The aberrations from the regression surface, sf		
$sf_{HB(necks\text{-}inf)= f(C, Si, Mn)}$	$sf_{HB(necks\text{-}sup) = f(C, Si, Mn)}$	$sf_{HB(body) = f(C, Si, Mn)}$
30.06	27.22	32.56

The surfaces in the four-dimensional space (described by **equations 2, 3** and **4**) admits a saddle point to which the corresponding value of hardness is an optimal chemical composition. The behavior of this hypersurface 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 concentric to the point under study.

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 (see **equations packs 5-7**, **8-10** and **11-12**).

$$HB_{(necks\text{-}inf)}C_{med} = 371.0275\ Si^2 + 2542.0539\ Mn^2 - 2570.8629\ Si{\cdot}Mn + 316.2565\ Si + 1674.6672\ Mn - 571.0181 \qquad (5)$$

$$HB_{(necks\text{-}inf)}Si_{med} = 2542.0539\ Mn^2 - 1517.8859\ C^2 - 487.8739\ Mn{\cdot}C - 1141.7854\ Mn + 70.2768\ C - 15631.9089 \qquad (6)$$

$$HB_{(necks\text{-}inf)}Mn_{med} = -1517.8859\ C^2 + 371.0275\ Si^2 + 752.5868\ C{\cdot}Si + 8499.2423\ C - 3617.7299\ Si - 10337.0485 \qquad (7)$$

$$HB_{(necks\text{-}sup)}C_{med} = 1321.4452\ Si^2 - 106.5153\ Mn^2 - 1650.6309\ Si{\cdot}Mn - 3655.6567\ Si + 2972.4323\ Mn + 2677.0847 \qquad (8)$$

$$HB_{(necks\text{-}sup)}Si_{med} = -106.5153\ Mn^2 - 1344.3081\ C^2 - 2489.3387\ Mn{\cdot}C + 8314.9658\ Mn + 10061.5741\ C - 18248.9293 \qquad (9)$$

$$HB_{(necks\text{-}sup)}Mn_{med} = -1344.3081\ C^2 + 1321.4452\ Si^2 + 1238.0976\ C{\cdot}Si + 6518.5289\ C - 8662.1421\ Si - 2572.3153 \qquad (10)$$

$$HB_{(body)}C_{med} = -241.4879\ Si^2 + 1975.1556\ Mn^2 + 310.4431\ Si\cdot Mn + 749.3075\ Si - 2667.7716\ Mn + 411.5766 \quad (11)$$

$$HB_{(body)}Si_{med} = 1975.1556\ Mn^2 + 638.1423\ C^2 + 142.3547\ Mn\cdot C - 2601.8695\ Mn - 4177.3703\ C + 7822.3452 \quad (12)$$

$$HB_{(body)}Mn_{med} = 1975.1556\ Mn^2 + 638.1423\ C^2 + 142.3547\ Mn\cdot C - 2601.8695\ Mn - 4177.3703\ C + 7822.3452 \quad (13)$$

3 Presentation the Graphical Addenda

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

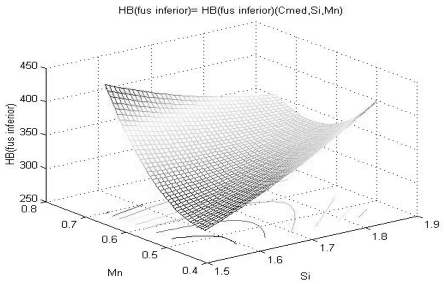

Fig.1 Regression surface $HB_{(necks-inf)}$ for $C = C_{med}$

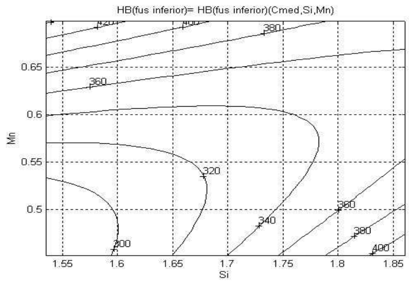

Fig.2 Level curves $HB_{(necks-inf)} = f(C_{med}, Si, Mn)$

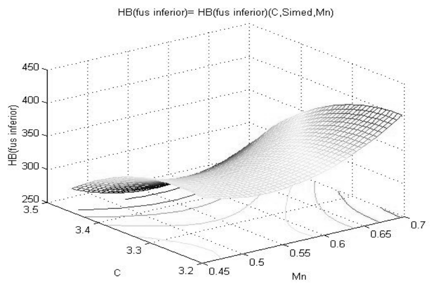

Fig.3 Regression surface $HB_{(necks-inf)}$ for $Si = Si_{med}$

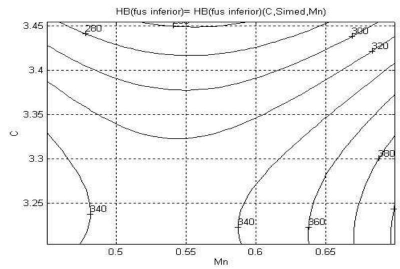

Fig.4 Level curves $HB_{(necks-inf)} = f(C, Si_{med}, Mn)$

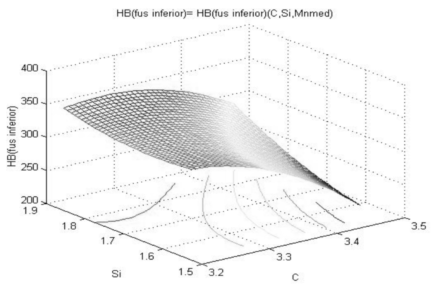

Fig.5 Regression surface $HB_{(necks-inf)}$ for $Mn = Mn_{med}$

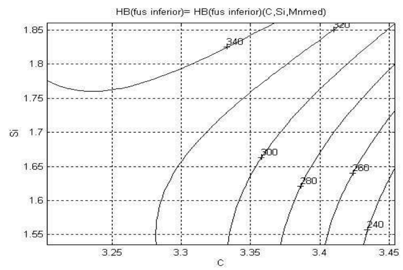

Fig.6 Level curves $HB_{(necks-inf)} = f(C, Si, Mn_{med})$

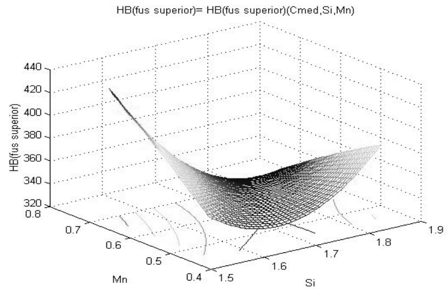

Fig.7 Regression surface $HB_{(necks\text{-}sup)}$ for $C = C_{med}$

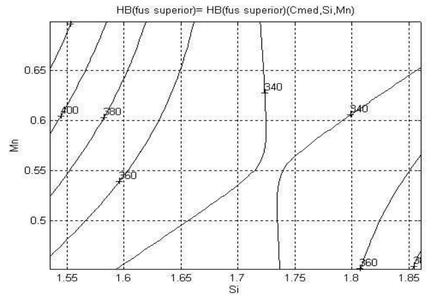

Fig.8 Level curves $HB_{(necks\text{-}sup)} = f(C_{med}, Si, Mn)$

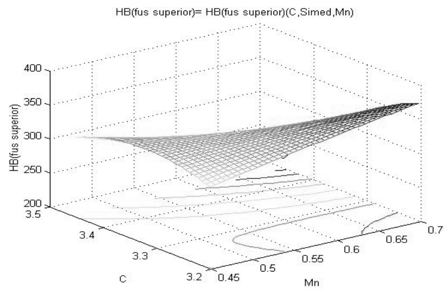

Fig.9 Regression surface $HB_{(necks\text{-}sup)}$ for $Si = Si_{med}$

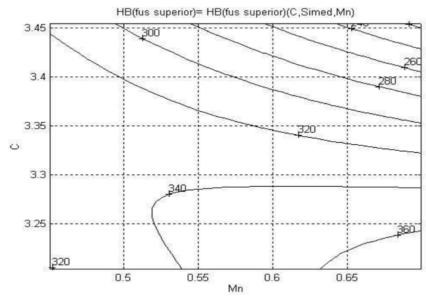

Fig.10 Level curves $HB_{(necks\text{-}sup)} = f(C, Si_{med}, Mn)$

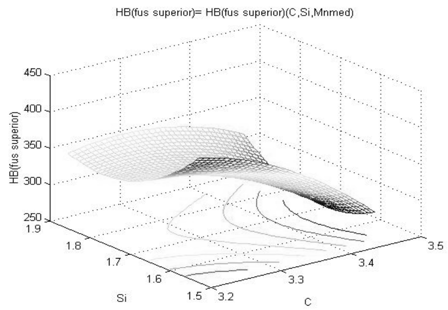

Fig.11 Regression surface $HB_{(necks\text{-}sup)}$ for $Mn = Mn_{med}$

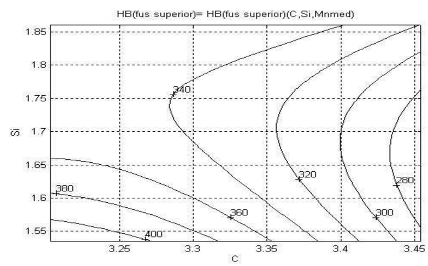

Fig.12 Level curves $HB_{(necks\text{-}sup)} = f(C, Si, Mn_{med})$

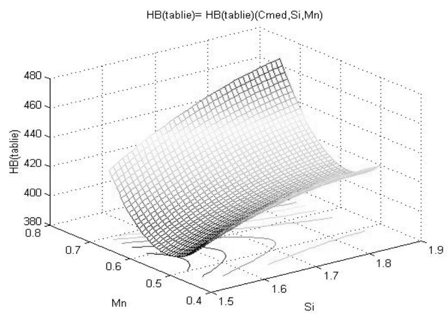

Fig.13 Regression surface $fHB_{(body)}$ for $C = C_{med}$

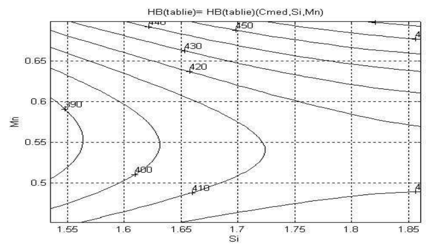

Fig.14 Level curves $HB_{(body)} = f(C_{med}, Si, Mn)$

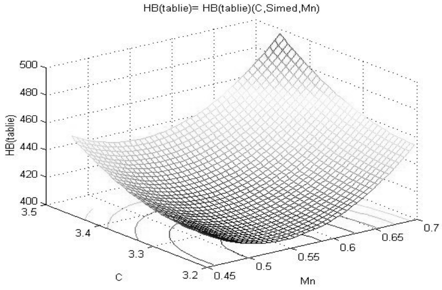

Fig.15 Regression surface $HB_{(body)}$ for Si = Si_{med}

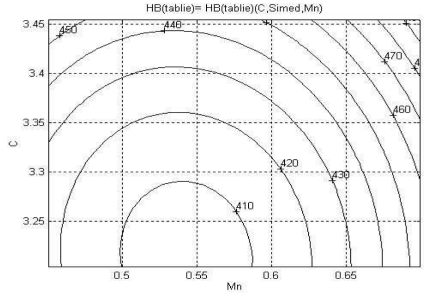

Fig.16 Level curves $HB_{(body)}$ = f(C, Si_{med}, Mn)

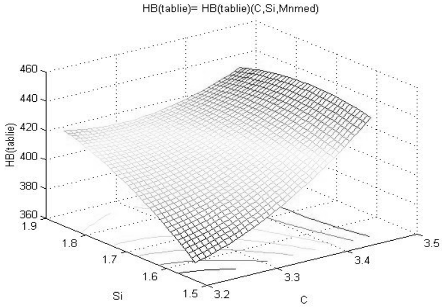

Fig.17 Regression surface $HB_{(body)}$ for Mn = Mn_{med}

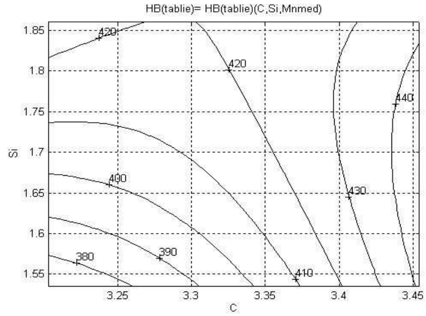

Fig.18 Level curves $HB_{(body)}$ = f(C, Si, Mn_{med})

4 Conclusions

The performed research had in view to obtain correlations between the hardness of the cast iron rolls (both on the superior and inferior necks, respectively on the body) and the representative basic chemical elements (C, Si, Mn). Therefore, the following conclusions can be presented:

- The chemical composition of the alloy used to cast rolls is one of the main factors that contribute to the obtaining of the usage properties. After an eventual processing in liquid state, a modifying in directional conditions of solidification and cooling, and, in some cases, after thermo treatment, this determines the macrostructure and microstructure.
- The lot of analyzed rolls is representative for the half-hard category. The half-hard rolling mill rolls, obtained through the simplex classical cast. Because we dispose of real data, afterwards it is required to present the model of optimization on industrial data, sampled from rolling mills rolls.
- The values processing was made using Matlab program. As parameters for optimization we selected the Brinell hardness. 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, enounced by mathematical formulas. The purpose is the optimization of the chemical composition as an influential factor on the rolls hardness, thus, implicitly, on their exploiting qualities.
- The realization of an optimal chemical composition can constitute a technical efficient mode to assure the exploitation properties, the rolling mills rolls material having an important role in this sense. From this point of view is applied the mathematical modeling,

starting from the differentiation on rolls component parts, taking into consideration the industrial data obtained in rolls-foundry, as well as the national standards specifications, which recommends the hardness, for different chemical compositions. From this point of view the research 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 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.
- As the hypersurfaces 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 group of **equation 5-7, 8-10**, and **11-12**), belonging to the three-dimensional space can be reproduced and therefore interpreted by engineers (**Figures 1, 3** and **5**, respectively **Figures 7, 9** and **11**, and **Figures 13, 15** and **17**).
- Knowing these level curves, describes for the rolling rolls body and necks (**Figures 2, 4** and **6**, respectively **Figures 8, 10** and **12**, and **Figures 14, 16** and **18**) allows the correlation of the values of the two independent variables so that we can obtain the hardness within the required limits.
- The Matlab calculation program can generate some graphical addenda, which presents the volume variation of the regression surfaces $HB_{(necks\text{-}sup)}$, $HB_{(necks\text{-}inf)}$ and $HB_{(body)}$ for one of the middle value of the selected variables (C, Si, Mn). Also, can generate some graphical addenda, which presents the level curves for the volume variation of the regression surfaces $HB_{(necks\text{-}sup)}$, $HB_{(necks\text{-}inf)}$ and $HB_{(body)}$, for the middle value of the chemical composition elements, respectively C_{med}, Si_{med} and Mn_{med}.

The use of the Matlab area can also be extended to the study of other elements influences (respectively S, P, Mg). An important research area can be the alloying elements (Ni, Cr, Mo) influences upon the necks and the body of the rolling mills rolls.

The work is of practical immediate utility, inscribing itself in the context of technical capitalization of the manufacturing technologies and of exploitation of cast-iron rolling mill rolls, for which exists an attentive preoccupation both from foundry sectors, as well as from lamination sectors, having as determinate aim the quality assurance and increase the durability in exploitation.

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References

[1] I. Kiss: The quality of rolling mill cylinders cast from cast-iron with nodular graphite, first ed., Mirton Publishing House, Timisoara, 2005

[2] I. Kiss: Cast-iron rolls – Approaches of the quality in the multidisciplinary research, first ed., Mirton Publishing House, Timisoara, 2005

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

[4] St. Maksay: Special Mathematics, Vols. I & II, first ed., Politehnica Publishing House, Timisoara, 2001
[5] I., Kiss, T. Heputţ, Scientific Bulletin of University Politehnica of Timişoara, Transactions on Mechanics, Vol. 2, 2002, p. 169-174
[6] I. Kiss, T. Heputţ, Scientific Bulletin of University Politehnica of Timisoara, Transactions on Mechanics, Vol. 2, 2002, p. 175-181
[7] I. Kiss, Revista de Metalurgia, 44(4), Centro National Investigationes Metalurgicas – CENIM, Madrid, 2008, p. 335-342
[8] I. Kiss, St. Maksay: Technical Gazette, Vol. 3, Slavonski Brod, 2008, p. 33-37
[9] I. Kiss, St. Maksay: Metalurgia International, Vol. 2, Bucuresti, 2008, p. 22-28
[10] I. Kiss, St. Maksay: Metalurgia International, Vol. 10, Bucuresti, 2007, p. 11-18
[11] I. Kiss, V. Cioata: Manufacturing Engineering, Vol. 2, Presov, 2008, p. 79-82
[12] I. Kiss, St. Maksay, S. Ratiu: Metalurgia International, Vol. 2, Bucuresti, 2005, p. 14-21
[13] I. Kiss, St. Maksay: Acta Polytehnica Hungarica – Journal Of Applied Science, Vol. 5 (14), no. 4, budapest, 2008, p. 19-29
[14] K.H. Schröder: A basic understanding of the mechanics of rolling mill rolls, Eisenwerk Sulzau-Werfen, ESW-Handbook, 2003
[15] K.H. Ziehenberger, M. Windhager: Recent Developments in HSM Rougher Rolls – Risks and Chances, In.: Iron & Steel Technology, p. 38-41, PA/USA, 2006
[16] K.H. Schröder: Questions, answers, more questions - twenty-five years of experience in discussing rolls and rolling technology, In.: 42nd Mechanical Working and Steel Processing Conference, Iron & Steel Society, Vol. 38, Baltimore, 2000
[17] K.H. Ziehenberger, M. Windhager, state of the art work rolls for hot rolling flat products, In.: CONAC 2007 – 3rd Steel Industry Conference and Exposition, Centro Convex, Monterrey, N.L., México, 2007
[18] I. Kiss, St. Maksay: Annals of Faculty Engineering Hunedoara, Vol. 1, 2007, p. 135-142
[19] I. Kiss, St. Maksay: Annals of Faculty Engineering Hunedoara, Vol. 2, 2006, p. 77-82
[20] I. Kiss, I. Riposan, St. Maksay: Annals of Faculty Engineering Hunedoara, Vol. 2, 2005, p. 193-200
[21] I. Kiss, St. Maksay: Annals of Faculty Engineering Hunedoara, Vol. 3, 2004, p. 134-143
[22] I. Kiss, S. Raţiu: Annals of Faculty Engineering Hunedoara, Vol. 2, 2004, p. 137-144
[23] I. Kiss, V. Cioată, V. Alexa: Annals of Faculty Engineering Hunedoara, Vol. 2, 2004, p. 145-150