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TECHNOLOGICAL CORRELATIONS BETWEEN THE HARDNESS AND MAIN ALLOYED ELEMENTS IN THE AREA OF CAST IRON HALF-HARD ROLLS

Imre Kiss, Stefan Maksay

Subject review

The technical conditions, which are imposed on the cast iron rolls in the exploitation period, are very different and often contradictory. The obtaining of various physical and mechanical properties at the different points of the same foundry product meets difficult technological problems in the industrial conditions. One of the parameters, which determine the structure of the irons destined for rolls casting, is the chemical composition. If we do not respect this composition, which guarantees the exploitation properties of 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 suggests a mathematical interpretation of the influence of the main alloying elements on the mechanical characteristics (the hardness on the crust of the rolls) of this nodular irons, resulting in 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 some 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 two independent variables so that HB can be obtained within the requested limits.

Keywords: *half-hard rolls, cast nodular iron, alloying elements, hardness, mathematical correlations, moulding, optimization, graphical addenda*

Tehnološke korelacije između tvrdoće i glavnih legirnih elemenata kod valjaka od polutvrdog lijevanog željeza

Pregledni članak

Tehnički uvjeti koji djeluju na valjke od lijevanog željeza tijekom upotrebe su jako različiti i često kontradiktorni. Tijekom dobivanja različitih fizičkih i mehaničkih svojstava u različitim fazama istog proizvoda susrećemo se s teškim tehnološkim problemima u industrijskim uvjetima. Kemijski sastav je jedan od parametara koji određuje strukturu željeza predodređenih za lijevanje valjaka. Ako ne poštujemo ovaj sastav, koji garantira dobra svojstva svakog valjka u valjaonici, to će dovesti do pojave škarta. Legirni elementi imaju u principu isti utjecaj na strukturu i svojstva. Ovaj rad predlaže matematički model utjecaja glavnih legirnih elemenata na mehanička svojstva (tvrdoća površine valjka) ovih nodularnih lijevova, što rezultira srednjim vrijednostima i srednjim kvadratnim odstupanjem varijabli HB, i glavnih legirnih elemenata (Cr, Ni, Mo), jednadžbe hiper-površine u četverodimenzionalnom prostoru. Za statističku i matematičku analizu korišteni su neki industrijski slučajevi. Tehnolozi mogu prikazati i interpretirati dobivene površine koje pripadaju trodimenzionalnom prostoru. Poznavanje tih krivulja nivoa omogućuje korelaciju vrijednosti dvije neovisne varijable tako da se HB može dobiti unutar traženih granica.

Ključne riječi: *polutvrdi valjci, nodularno lijevano željezo, legirni elementi, tvrdoća, matematičke korelacije, oblikovanje, optimizacija, grafički dodaci*

1 Introduction
Uvod

The nodular graphite cast iron is considered to be one of the most versatile roll materials nowadays. A small proportion of magnesium added to the melt as nickel-magnesium or alternative alloy, or as pure magnesium produces it. In the nodular graphite's iron roll, the free carbon takes the shape of spheroids or nodules, thereby eliminating the notch effect of flake graphite and improving the mechanical properties of the cast iron.

Large scale alloyed nodular graphite cast iron, pearlitic nodular graphite cast iron and a circular nodular graphite cast iron can be manufactured. 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 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 these types of rolls exhibit 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 casting form, and under the influence of the cooling speed, the main criterion, 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 determine the structure of the irons destined for rolls casting, is the chemical composition. If we do not respect this composition, which guaranteed the exploitation properties of each roll in the stand of rolling mill, it could lead to rejection of this. All FNS type rolls are alloyed especially with chrome, nickel and molybdenum, in different percentages. The irons destined for these cast rolls belong to the class of low-alloyed irons, with reduced content of these elements.

Table 1. Recommended hardness of the half-hard cast iron rolls
Tablica 1. Preporučena tvrdoća valjaka od polutvrdog lijevanog željeza

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 composition of the half-hard cast iron rolls
Tablica 2. Preporučen kemijski sastav valjaka od polutvrdog lijevanog željeza

Type	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	Alloyed elements and 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

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 magnesium from the nodulising agent, upon the structure and the form of the graphite.

2 Technological interpretation
Tehnološka interpretacija

Therefore, we suggest a mathematical interpretation of the influence of the main alloying elements on the mechanical characteristics (the hardness on the crust of the rolls) of these nodular irons, the resulting 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 some industrial cases. The chemical composition, the hardness and the error are presented in Table 3 .

Table 3. Comparison of the experimental and theoretical data
Tablica 3. Usporedba rezultata eksperimenata i teoretskih podataka

Mathematical variables, [%]			The hardness on the body, [HB]		Error
Ni	Cr	Mo	experimental measured	theoretical determined	
1,99	0,62	0,22	342	333,71	8,30
2,21	0,64	0,26	341	319,33	21,66
2,16	0,57	0,25	326	326,31	- 0,29
2,16	0,53	0,24	328	324,08	3,91
1,59	0,38	0,22	292	289,46	2,53
2,24	0,51	0,28	306	300,86	5,13
1,82	0,36	0,26	291	288,48	2,51
1,97	0,52	0,27	282	309,53	- 27,52
2,22	0,66	0,21	322	331,03	- 9,03
1,49	0,63	0,22	312	312,35	- 0,35
1,63	0,51	0,27	284	294,99	- 10,98
1,55	0,39	0,25	299	295,61	3,39
1,52	0,47	0,21	286	307,05	- 21,05
1,63	0,45	0,23	296	311,37	- 15,37
1,65	0,43	0,18	280	265,79	14,21
2,11	0,68	0,27	289	300,02	- 11,02
2,19	0,67	0,24	321	330,17	- 9,16
1,62	0,44	0,21	297	301,49	- 4,48
1,63	0,49	0,25	352	311,79	40,21
1,66	0,42	0,27	296	293,05	2,95
2,08	0,72	0,23	328	327,38	0,62
1,94	0,64	0,24	339	327,52	11,48
1,92	0,4	0,22	282	289,66	- 7,66

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 is HB = 219 - 276. Therefore, the graphical representation limits, for this moulding case, are presented in Table 4. The mean values for three variables (Ni, Cr, Mo) and the hardness (HB), necessary for the calculation of the optimal form of moulding are presented in Table 5.

Table 4. The graphical representation limits
Tablica 4. Grafički prikaz granica

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

Table 5. The mean values
Tablica 5. Srednje vrijednosti

Ni_{med}	Cr_{med}	Mo_{med}	HB_{med}
1,86	0,52	0,23	251,52

Next, there are shown the results of the multidimensional processing of experimental data. For that purpose, we searched for a method of molding the dependent variables depending on the independent variables x, y and z (see equation 1). The optimal form of molding, studied on a sample of the cases is given by the equations (2). The correlation coefficients and the aberrations from the regression surface are presented in Table 6.

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

$$HB_{(body)} = -69{,}2668 \cdot Ni^2 - 843{,}9321 \cdot Cr^2 - 13082{,}6971 \cdot Mo^2 + 258{,}4342\ Ni \cdot Cr - 3258{,}4415 \cdot Cr \cdot Mo + 757{,}2487 \cdot Mo \cdot Ni - 45{,}2572 \cdot Ni + 1278{,}2053 \cdot Cr + 6349{,}4428 \cdot Mo - 739{,}6223 \quad (2)$$

Table 6. The correlation coefficients and the aberrations
Tablica 6. Koeficijenti korelacije i odstupanja

$rf_{HB(body)}$ = f(Ni, Cr, Mo)	$sf_{HB(body)}$ = f(Ni, Cr, Mo)
0,77	13,96

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 have 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.

$$HB_{(body)}Ni_{med} = -843{,}9321 \cdot Cr^2 - 13082{,}6971 \cdot Mo^2 - 3258{,}4415 \cdot Cr \cdot Mo + 1761{,}1402 \cdot Cr + 7764{,}5101 \cdot Mo - 1066{,}0756 \quad (3)$$

$$HB_{(body)}Cr_{med} = -13082{,}6971 \cdot Mo^2 - 69{,}2668 \cdot Ni^2 + 757{,}2487 \cdot Mo \cdot Ni + 4630{,}9691 \cdot Mo + 91{,}0387 \cdot Ni - 300{,}2406 \quad (4)$$

$$HB_{(body)}Mo_{med} = -69{,}2668 \cdot Ni^2 - 843{,}9321 \cdot Cr^2 + 258{,}4342 \cdot Ni \cdot Cr + 135{,}8241 \cdot Ni + 499{,}0128 \cdot Cr + 30{,}6111 \quad (5)$$

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

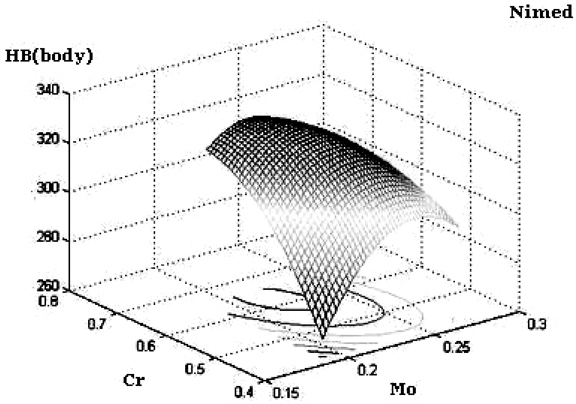

Fig. 1. The regression surface $HB_{(body)}$ *for* $Ni = Ni_{med}$
Slika 1. Površina regresije $HB_{(body)}$ *za* $Ni = Ni_{med}$

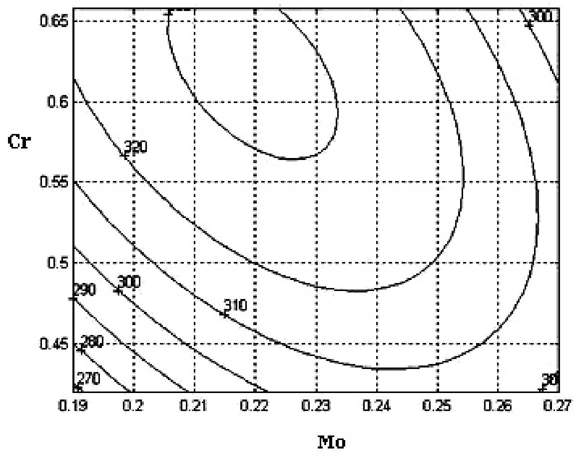

Fig. 2. Level curves $HB_{(body)} = f(Ni_{med}, Cr, Mo)$
Slika 2. Krivulje razine $HB_{(body)} = f(Ni_{med}, Cr, Mo)$

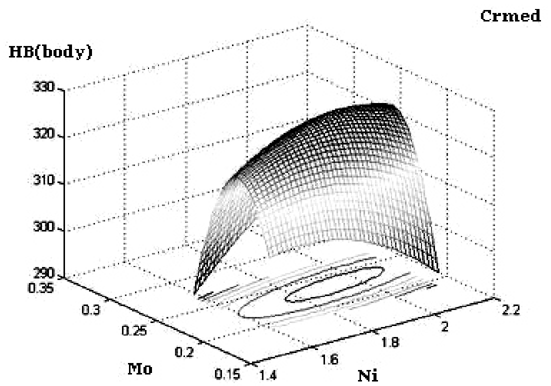

Fig. 3. The regression surface $HB_{(body)}$ *for* $Cr = Cr_{med}$
Slika 3. Površina regresije $HB_{(body)}$ *za* $Cr = Cr_{med}$

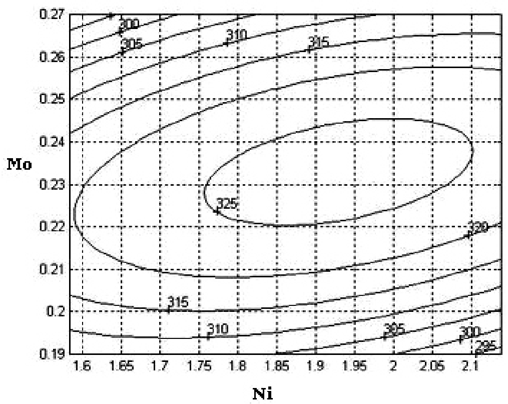

Fig. 4. Level curves $HB_{(body)} = f(Ni, Cr_{med}, Mo)$
Slika 4. Krivulje razine $HB_{(body)} = f(Ni, Cr_{med}, Mo)$

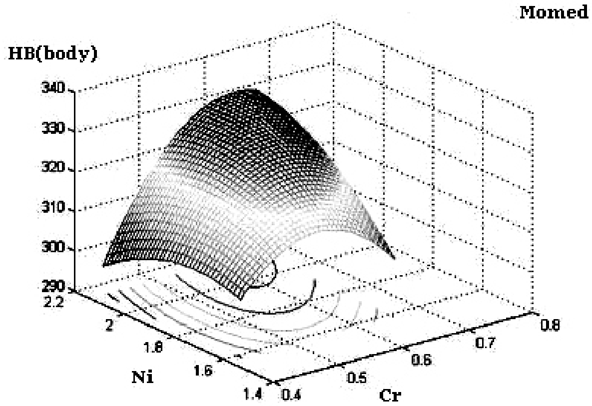

Fig. 5. The regression surface $HB_{(body)}$ *for* $Mo = Mo_{med}$
Slika 5. Površina regresije $HB_{(body)}$ *za* $Mo = Mo_{med}$

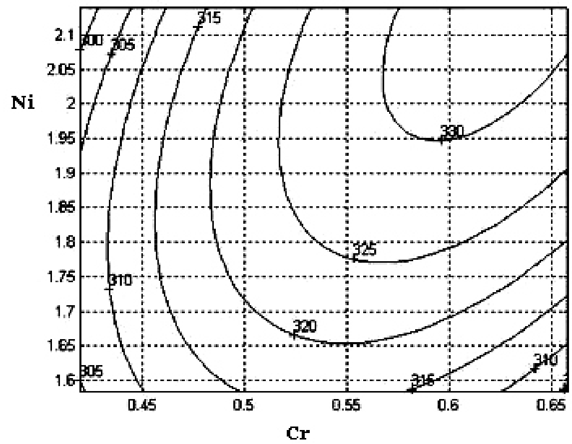

Fig. 6. Level curves $HB_{(body)} = f(Ni, Cr, Mo_{med})$
Slika 6. Krivulje razine $HB_{(body)} = f(Ni, Cr, Mo_{med})$

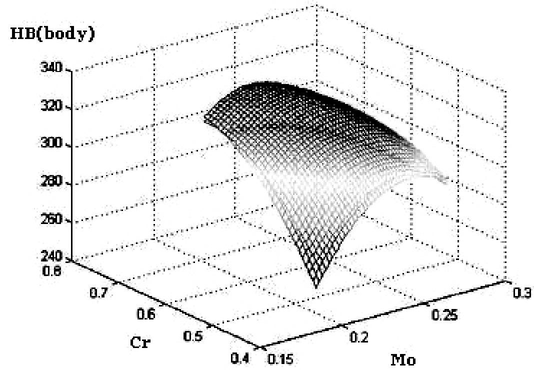

Fig. 7. The volume variation of the regression surface $HB_{(body)}$ *for* $Ni = Ni_{med}$
Slika 7. Varijacija volumena površine regresije $HB_{(body)}$ *za* $Ni = Ni_{med}$

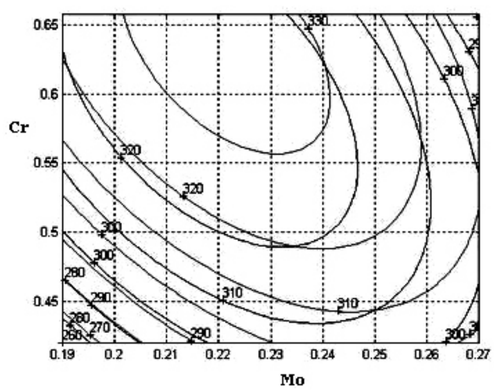

Fig. 8. Level curves for the volume variation of the regression surface $HB_{(body)}$ *for* $Ni = Ni_{med}$
Slika 8. Krivulje razine za varijaciju volumena površine regresije $HB_{(body)}$ *za* $Ni = Ni_{med}$

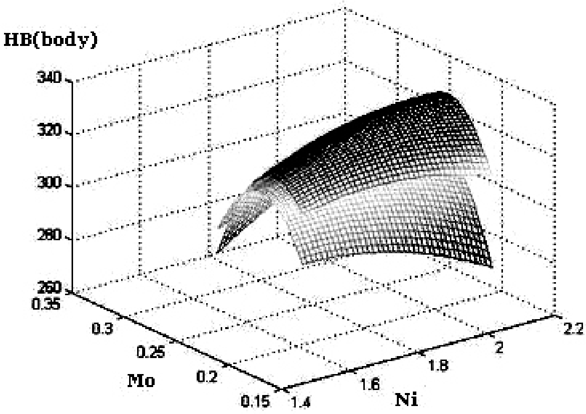

Fig. 9. The volume variation of the regression surface $HB_{(body)}$ *for* $Cr = Cr_{med}$
Slika 9. Varijacija volumena površine regresije $HB_{(body)}$ *za* $Cr = Cr_{med}$

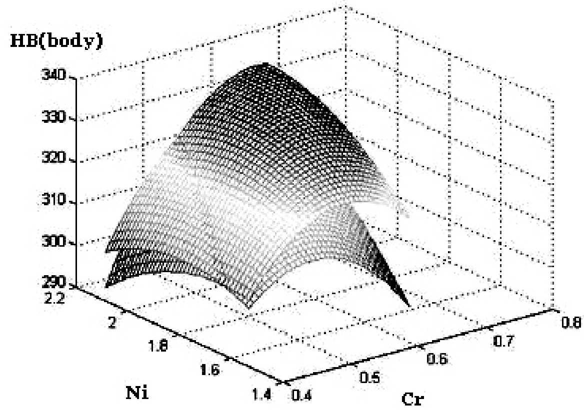

Fig. 11. The volume variation of the regression surface $HB_{(body)}$ *for* $Mo = Mo_{med}$
Slika 11. Varijacija volumena površine regresije $HB_{(body)}$ *za* $Mo = Mo_{med}$

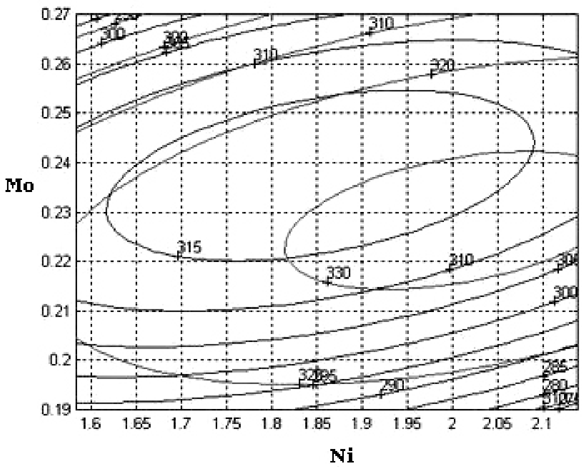

Fig. 10. Level curves for the volume variation of the regression surface $HB_{(body)}$ *for* $Cr = Cr_{med}$
Slika 10. Krivulje razine za varijaciju volumena površine regresije $HB_{(body)}$ *za* $Cr = Cr_{med}$

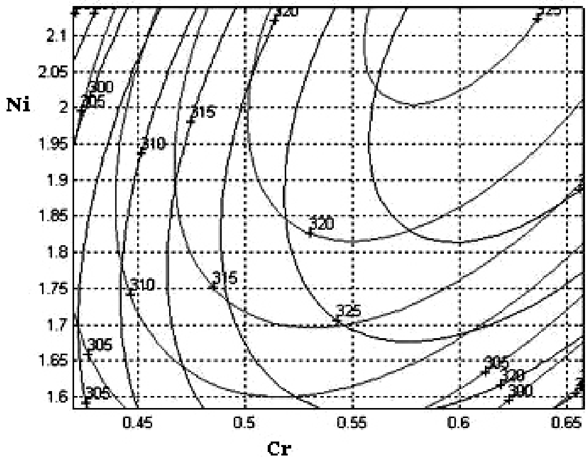

Fig. 12. Level curves for the volume variation of the regression surface $HB_{(body)}$ *for* $Mo= Mo_{med}$
Slika 12. Krivulje razine za varijaciju volumena površine regresije $HB_{(body)}$ *za* $Mo= Mo_{med}$

These surfaces, belonging to the three-dimensional space can be reproduced and therefore interpreted by technological engineers. Also, knowing the level curves allows the correlation of the values of the two independent variables so that we can obtain the hardness within the required limits. These level curves can help the engineers to determine the optimal values of the alloying elements contents, which assure the mechanical properties (hardness) of the cast iron half-hard rolls.

3 Conclusions
Zaključci

The object of the performed research was to obtain correlations between the hardness of the cast iron rolls on the working surface (body) and its chemical composition, defined by the representative alloying elements. The values processing were acquired using Matlab calculation program. Using this calculation program, we have determined some mathematical correlation, correlation coefficient and the deviation from the regression surface. This surface in the four-dimensional space (described by the equation 1 and 2) admits a saddle point to which the corresponding value of hardness is an optimal alloying element. Based on the results, the following conclusions can be presented:

- The existence of a saddle point inside the technological domain has a particular importance as it ensures stability of 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 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 concentrical 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 3…5), belonging to the three-dimensional space can be reproduced and therefore interpreted by technological engineers (Figures 1, 3, 5). Knowing these level curves (Figures 2, 4, 6) 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 presented the volume variation of the regression surface $HB_{(body)}$ for one of the middle value of Ni, Cr, Mo. In Figures 8, 10, 12 the level curves

for the volume variation of the regression surface $HB_{(body)}$ (for the Ni_{med}, Cr_{med} and Mo_{med}) are presented;

- The usage of the Matlab area, can also be extended to the study of influences of other chemical components, or other constructive parts of the rolls (for example the necks of the rolls).

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Author's Address
Adrese autora

Dr. Imre KISS, Met. Eng.
University "Politehnica" Timisoara,
Faculty Engineering Hunedoara,
Revolutiei, 5
Hunedoara, 331128, Romania
e-mail: ikiss@fih.upt.ro

Dr. Stefan MAKSAY, Math.
University "Politehnica" Timisoara,
Faculty Engineering Hunedoara,
Revolutiei, 5
Hunedoara, 331128, Romania
e-mail: stefan.maksay@fih.upt.ro