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MATHEMATICAL MODELLING OF THE MAIN CARBURIZING THERMOCHEMICAL TREATMENT PARAMETERS INFLUENCE ON THE SURFACE HARDNESS PARTS MADE IN AMS 6265 (SAE 9310) STEEL

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ABSTRACT

This work is a part of broader experimental research study on the influence of the main process parameters (thermal, temporal and chemical of carburizing thermochemical treatment on the level of the main microstructural features, chemical and physical-mechanical properties values, resulted to the carbon hardening process of the AMS 6265 (SAE 9310) steel parts used in the aeronautical industry. This paper treats only those aspects concerning the influence of these three key parameters temperature, T_K, maintaining time, t_K, and carbon potential, C_{potK} on the surface hardness parts, HRC_{SUP}. The originality of this work lie in the approach of the experimental study using the active experiment scheduled method with the second order of noncompositional programming.

KEYWORDS**:** carburizing; surface hardness; the active experiment scheduled method; programming matrix

1. Introduction

The complexity of the phenomena involved in the thermochemical treatments excludes to study these processes with the classical experimental methods, which are characterized by major difficulties in implementation and in most cases, do not lead to reliable results. The solving problems in the experimental researching processes, which are based on diffusion phenomena using experimental method, required to apply the scheduled experimental methods which permit to realize the empirical mathematical models which can be obtained either by passive or by active experiment methods [1].

The most information that are presented in the literature, concerning the AMS 6265 steel, used in aeronautical industry, characterize it more in terms of its performance of mechanical characteristics that can be obtained by using it to implement the execution of parts hardened by thermochemical treatment using the carbon as cement , without making reference on the concrete ways in which these performances can be obtained, often spectacular.

The majority of the works in the field of thermochemical treatments research present the information concerning the relatively modest performance of carbon hardened AISI 8620 steel, with low alloying elements [2, 3]. This is why the present work, detached from a broader study on the carburizing treatment of components made from this steel, aim to fill some of these goals information about the specific aspects of the carburizing process of the AMS 6265 steel parts, respectively, how the main process parameters influence the actual Rockwell hardness surface parts.

For carburized AMS 6265 parts steel, used in aeronautical industry are imposed the high wear and toughness features because they are used to perform components for gears who must face in terms of accidental demands (overload).

2. Experimental conditions

2.1. The study of the thermal, temporal and chemical parameters influence on the surface hardness parts using the active experimental scheduled method and the second order noncompositional programming

Existing knowledge about the processes that are based on the diffusion phenomena generally required that, for explicit the interactions between process parameters (independents parameters) and their effects on the level variation of structural features and the respective values of physical and mechanical characteristics (dependent parameters), to resort to use the second order noncompositional programming [4] The reason for using this type of programs consists on one side in the fact that the processes underlying the formation of diffusion layers can not be mathematically defined using linear models [5, 6] and on the other side, there are sufficient knowledge concerning the range where can be found the interest values.

In order to solve this type of problem it is necessary to explicit the experimental data using the second-order nonlinear equations of the form:

$$Y = b_0 + \sum_{\substack{i=1 \\ 1\le i\le k}}^{k} b_i x_i + \sum_{\substack{i=1, j=1, i\neq j \\ 1\le i\prec j\le k}} b_{ij} x_i x_j + \sum_{i=1}^{k} b_{ii} x^2 + \cdots \quad (1)$$

where: Y is the dependent parameter investigated and x_i, x_j the independent parameters that influence the dependent parameter taken in the analysis.

Independent variables (x_i…) taken in the analysis were those related to carbon enrichment phase: isothermal temperature, $T_K(x_1)$, the maintaining time, $t_K(x_2)$ at carburizing temperature and carbon potential, $C_{potK}(x_3)$.

In context of second order of noncompositional programming was imposed to vary the three independent variables at three levels of value, -1, 0 and +1. The noncompositional second order programming plan is itself a selected segment of the factorial experiment 3k (k is the number of factors or independent variables). As the dependent variables of the process (Y_1….Y_n), were selected those features that allow a more complete characterisation of the effects of surface enrichment in carbon due to maintenance of the AMS 6265 steel parts in the enriched gaseous saturated hydrocarbon (methane) atmosphere. The programming noncompositional matrix of the second order, for k=3, the basic level of the independent parameters, their range of variation and the results of the surface hardness measurements parts are presented in the Table 1.

Table 1. *Noncompositional programming matrix of the second order (k=3)*

-	F.V.	Independent parameters			$[HRC]_{SUP}$.
		1*	2*	3*	[HRC]
Code	X_0	X_1	X_2	X_3	Y
Basic level, (Z_{i0})	-	925	6	0,9	-
Range variation, (ΔZ_i)	-	25	3	0,2	-
Higher level, ($Z_{i0}+\Delta Z_i$)	-	950	9	1,1	-
Lower level, ($Z_{i0}-\Delta Z_i$)	-	900	3	0,7	-
EXP.nr.1	+1	+1	+1	0	62
EXP.nr.2	+1	+1	-1	0	62
EXP.nr.3	+1	-1	+1	0	63
EXP.nr.4	+1	-1	-1	0	62
EXP.nr.5	+1	+1	0	+1	63
EXP.nr.6	+1	+1	0	-1	60
EXP.nr.7	+1	-1	0	+1	63.5
EXP.nr.8	+1	-1	0	-1	60
EXP.nr.9	+1	0	+1	+1	63.5
EXP.nr.10	+1	0	+1	-1	61.5
EXP.nr.11	+1	0	-1	+1	63
EXP.nr.12	+1	0	-1	-1	62.5
EXP.nr.13	+1	0	0	0	63
EXP.nr.14	+1	0	0	0	63
EXP.nr.15	+1	0	0	0	62

Notes:
- F.V. – a fictive variable
- *1 - the carburizing temperature, T_K [ºC], Z_1;
- *2 – the maintaining time at carburizing temperature, t_K, [hours], Z_2;
- *3 – the carbon potential for carburizing process, C_{potK}, [%C], Z_3.

This paper has taken in analysis (as dependent variable) one of the most important mechanical characteristic variable of carbon hardened case, the surface hardness part, expressed in Rockwell (HRC) units, which together with other characteristics, that the effective case depth, ($\delta_{ef.}$), expressed in [mm], the subsurface carbon content, ($C_{0.1mm}$), the retained austenite, ($\%RA_{0.1mm}$), the subsurface microhardness, ($HV_{0.1mm}$), all of these measured to the 0.1mm distance from the workpiece surface and the case depth affected by internal oxidation, characterize the quality of the carburizing process.

To establish the algorithm for determining the particular forms of nonlinear models for the dependent variable which was taken in discussions it is necessary to be covered the following steps of the processing experimental results obtained:

- Calculation of non linear model coefficients (b_0, b_i, b_{ij}…);
- The statistical verification of nonlinear model coefficients;
- Calculation of the reproducibility results dispersion;
- Verification the concordance of nonlinear model adopted

2.2. The actual development of experimental batches and modalities for determining and evaluating experimental results

The experiments were conducted in a batch furnace type using endogas atmosphere enriched with methane gas. The chemical composition of the samples used (AMS 6265 steel) is presented in Table 2.

In order to study the influence of the independent parameters (temperature, maintaining time and carbon potential) on the mechanical characteristic (surface hardness part) as dependent parameter, fifteen carburizing batches were carried out, of which the last three batches have been performed under the same conditions of temperature, time and carbon potential. For each experimental batch were recorded temperature, carbon potential and real changes in their values.

Table 2. *Chemical composition of AMS 6265 steel*

Alloy (steel)	**Elements content, %**						
AMS 6265	**C**	**Si**	**Mn**	**Cr**	**Mo**	**Ni**	**Cu**
min.	0.07	0.15	0.4	1.00	0.08	3.0	max. 0.35
max.	0.13	0.35	0.7	1.40	0.15	3.5	
actual	0.11	0.33	0.57	1.14	0.13	3.26	0.09

In Table 1 are presented the parameters (thermal, temporal and chemical) adopted in the developing the fifteen experiments.

All actual cycles show the same general aspects of which the most significant features are the following two (see Figure 1):

1) The batches loading were performed in the preheated furnace to the carburizing temperature process. During the batches loading the furnace temperature down to about 50÷60ºC below to the initial setting point temperature. After 12÷16 minutes, batch temperature reached the prescribed value, specific to the each experimental cycle. For this reason the effective thermal cycles are easily moved to the right (recovery time) with a period of time which account the time for batch loading, batch reheating to the process temperature and time for achieving in the furnace the atmosphere carbon potential prescribed.

2) The real chemical cycles show a certain delay in the same initial period (recovery time) until achieving in the furnace the atmosphere carbon potential prescribed, whose duration varies according to the prescribed value of carbon potential.

Taking into consideration that chemical and thermal cycles are systematic, uniform and proportional with the carbon potential and carburizing temperature in all experimental batches, the displacements have not altered the types and degrees of influence of independent variables (process parameters) on the dependent variables (features), respectively on the experimental results obtained. The specimens (ø 18.5 mm x 30 mm) on which were made the HRC surface parts measurements were taken from the carbon hardened samples final heat treated which were used for the metallographic evaluations.

In Table 1 are presented the values obtained for the surface HRC parts measurements.

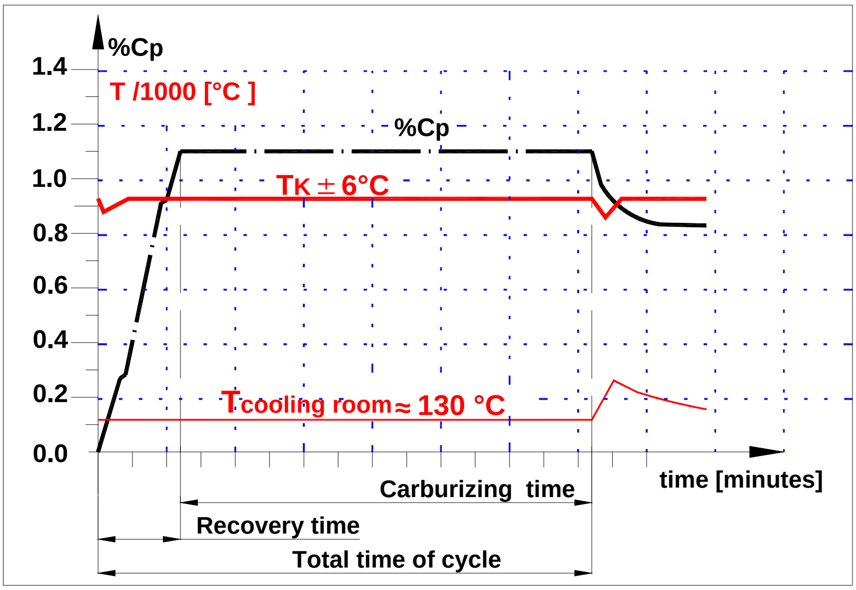


Fig.1. *Thermal and chemical cycles used in the experimental study, general characteristics.*

3. Experimental research results

The mathematical model was accomplished by determining the regression equations, able to allow the prediction performance which can be obtained by choosing the concrete conditions of the carburizing process on the AMS 6265 steel parts for the aeronautical industry.

After the stages calculating of the coefficients and statistical verifications specific to the programming method chosen, the following particular forms of the regression equations, specific to the steel taken in the analysis have resulted:

$$Y = 62.666 + 1.125X_3 - 0.708X_1X_2 \qquad (2)$$

$$[HRC]_{SUP} = 5.1875 + 0.0566T_K + 8.73t_K + 5.62C_{potK} - 0.00942T_K \cdot t_K \qquad (3)$$

The equations (2) and (3) represent the encoded respectively decoded forms of the mathematical model of the surface hardness parts, expressed in HRC units.

3.1. Numerical processing, analysis and interpretation of experimental research results

The comparative analysis of the two equations show that the terms with the greatest influence is the term of the first order degree (X_3, respectively C_{potK}) and the second degree term of the form X_1X_2 (T_Kt_K) has a significant influence in the both equations.

Based on this finding it can be concluded that the mathematical model deduced is predominantly linear, fact also confirmed by the aspects of response surfaces and by the positions of the certain isoproperties areas of the HRC surface hardness (see Figure 2 and Figure 3).

By analysis the encoded equation (2) shows that the coefficient for independent variable X_3 (first order degree term) is positive, which leads to the conclusion that the value of Y (HRC) increases with the increasing value of this independent process parameter.

The coefficient of the second - degree term in X_1X_2 ($-0.708X_1X_2$) is negative which leads to the conclusion that the value of Y (HRC) decreases with increasing values of X_1 and X_2 independent parameters.

Regarding the numerical value and sign of the influence coefficients which determine the degree and the direction of the influence of independent variables, these may be more strongly evident in the case of the decoded equation, in which the b_ix_i, $b_{ij}x_{ij}$, products, are terms whose by algebraically summing permit to obtain the dependent parameter value (see Table 3).

Table 3. *Detailed calculation of the surface HEC hardness in the concrete case (the base level of independent parameters): T_K = 925°C, t_K = 6 hours, C_{potK} = 0.9%C*

Characteristic	b_0	b_1T_K	b_2t_K	$b_3C_{pot\,K}$	$b_{12}\,T_K\,t_K$	$Y_{calculated}$
$[HRC]_{SUP}$	5.1875	52.416	52.4025	5.0625	-52.2856	**62.7829**

In the regression decoded equation on observe that:

- the first - degree term in C_{potK} ($5.62C_{potK}$) is positive (5.0625) which leads to the conclusion that the value of Y(HRC) increases with the increasing of C_{potK} value in all range of variation of independent parameters X_1, X_2, X_3 (-1, 0, +1) respectively:
- process temperature, T_K: 900ºC, 925 ºC and 950ºC;
- maintain time process t_K: 3 hours, 6 hours and 9 hours;
- carbon potentials C_{potK}: 0.7 %C, 0.9 %C and 1.1 %C.

- the first - degree terms in T_K ($0.0566T_K$) and in t_K ($8.73t_K$) are positive (52.416 respectively 52.4025) which leads that these parameters have a positive influence on the variation of Y(HRC) value.

- the second-degree term in $T_K \cdot t_K$, ($-0.00942T_K \cdot t_K$), has a negative value (-52.2856) which leads to the conclusion that the combination of these parameters have a negative influence on the variation of Y(HRC) value.

In order to determine practical how the variation of the three technological parameters affects the surface hardness value of carburized parts made from the studied steel, the decoded equation (2) was introduced into a numerical simulation program for determining the numerical values ranges of temperature and maintaining time for which these parameters have the most significant influences. In Table 4 are presented the hardness values results, after numerical processing, concerning the influence of the maintaining time on the variation value of the hardness surface, by modification the temperature value at the three levels adopted in the experimental program.

Table 4. *Influence of the maintaining time (t_K) on the surface hardness at T_K = 900ºC, 925 ºC and 950 ºC*

T_K = 900ºC (X_1 = -1)			
C_{potK} [%C]	Maintaining time [hours]		
	3	**6**	**9**
0.7	60.8175	61.5735	62.3295
0.9	61.9415	62.6975	63.4535
1.1	63.0655	63.8215	64.5775
T_K = 925ºC (X_1 = 0)			
C_{potK} [%C]	Maintaining time [hours]		
	3	**6**	**9**
0.7	61.526	61.5755	61.625
0.9	62.65	62.6995	62.749
1.1	63.774	63.8235	63.873
T_K = 950ºC(X_1 = +1)			
C_{potK} [%C]	Maintaining time [hours]		
	3	**6**	**9**
0.7	62.2345	61.5775	60.9205
0.9	63.3585	62.7015	62.0445
1.1	64.4825	63.8255	63.1685

In Table 5 are presented the hardness values results, after numerical processing, concerning the influence of the temperature on the variation values of the hardness surface, by modification the maintaining time value at the three levels adopted in the experimental program.

By analysis the results presented in Table 4 on observe that, at the same carbon potential and at constant temperature value T_K = ct.= 900ºC (the inferior level) the surface hardness value increases with the increasing of the maintaining time in all the range of variation of the time values (3h ≤ t_K ≤ 9h). At T_K = 925ºC (the base level) on observe that the increasing value of the maintaining time, in the same range of values of the time, (3h ≤ tK ≤ 9h), affects in very slight the surface hardness value (it remain practically constant). When the temperature value is T_K = ct. = 950ºC (the superior level), the increasing value of the maintaining time affects negative, respectively decreases the surface hardness value.

Table 5. *Influence of the temperature (T_K) on the surface hardness at t_K = 3 hours, 6 hours and 9 hours*

t_K = 3 hours (X_2 = -1)			
C_{potK} [%C]	Maintaining time [hours]		
	900	925	950
0.7	60.8175	61.526	62.2345
0.9	61.9415	62.65	63.3585
1.1	63.0655	63.774	64.4825
t_K = 6 hours (X_2 = 0)			
C_{potK} [%C]	Maintaining time [hours]		
	900	925	950
0.7	61.5735	61.5755	61.5775
0.9	62.6975	62.6995	62.7015
1.1	63.8215	63.8235	63.8255
t_K = 9 hours (X_2 = +1)			
C_{potK} [%C]	Maintaining time [hours]		
	900	925	950
0.7	62.3295	61.625	60.9205
0.9	63.4535	62.749	62.0445
1.1	64.5775	63.873	63.1685

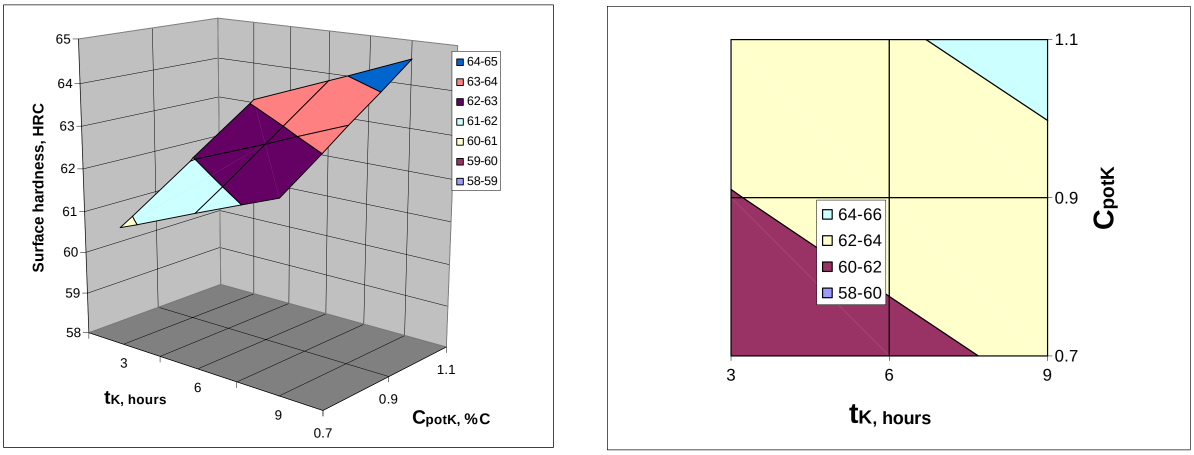
In Table 5 on observe that at the same carbon potential value and at constant time value, t_K = ct. = 3h (the inferior level), the superficial hardness increases with increasing the value of temperature in all range of variation of temperature values, (900ºC ≤ T_K ≤ 950ºC). At t_K = ct. = 6 h (the base level) on observe that the increasing temperature, in same range of the temperature values affects in slight the superficial hardness value (it remain practically constant), as with previously analyzed for T_K = 925ºC. When the maintaining time is t_K = ct. = 9 h (the superior level) the increasing value temperature process affects negative, respectively decreases the superficial hardness value.

The analysis presented above emerges that the statistical ensemble of carburizing process the carbon potential has a positive influence on the value of the surface hardness, without overcoming the certain values levels, but the combination between time and temperature can have a negative influence on this characteristic (they can cause the reduction in value of this feature).

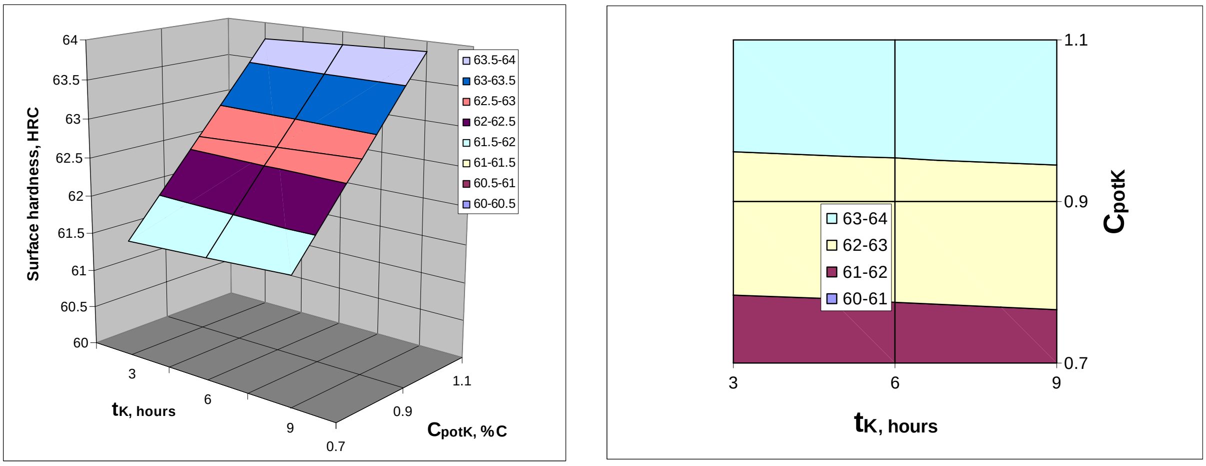
3.2. Graphical processing of experimental results

The graphical processing of the experimental research results (Figure 2 and Figure 3) creates a more suggestively picture of the manner in which the three main independent variables (process parameters) of the carburizing process: the temperature at which the process is carried out, T_K, the maintaining time t_K, at this temperature, and the carbon potential, C_{potK}, of the furnace atmosphere influence the value of the surface hardness value.

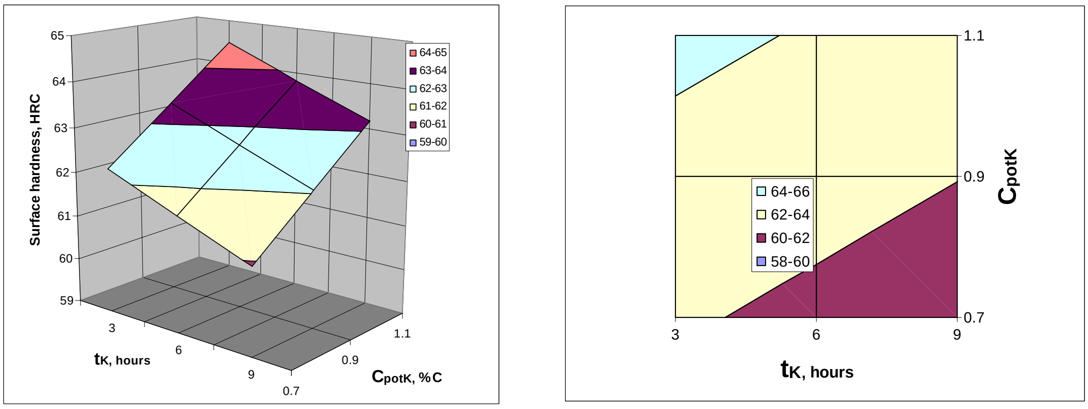
T_K = ct. = 900 ºC



T_K = ct. = 925 ºC



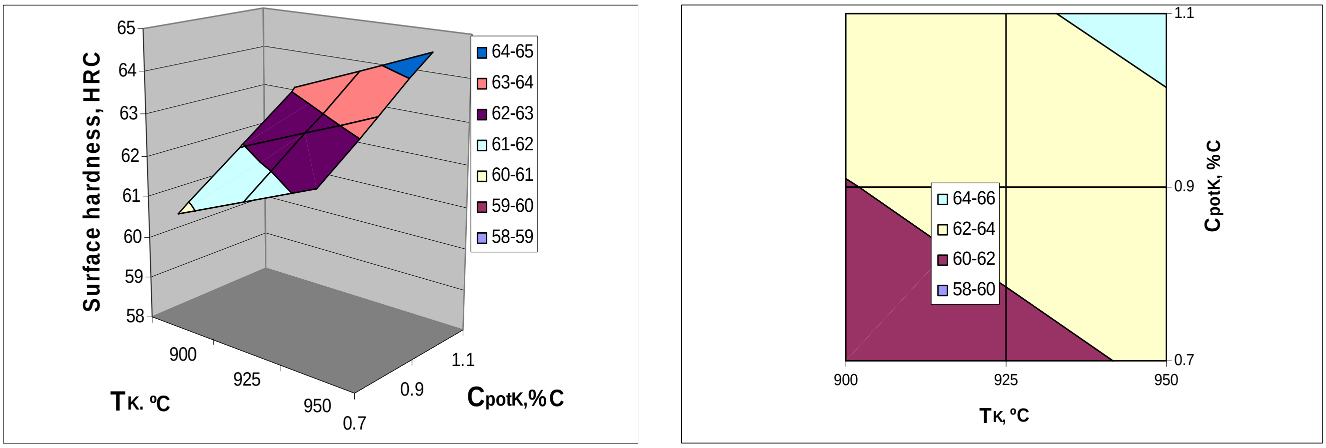
T_K = ct. = 950 ºC



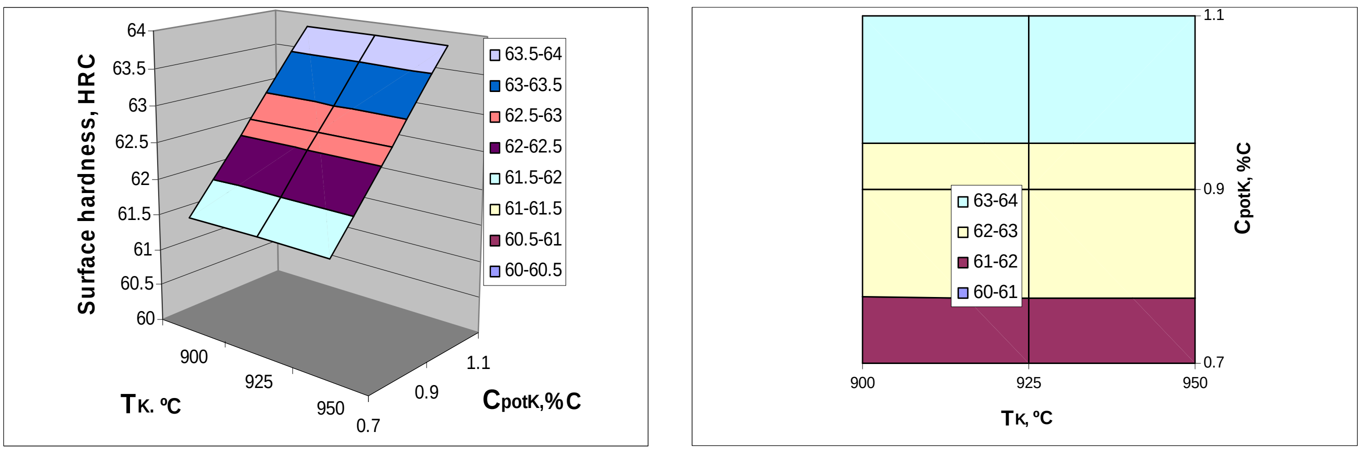
AMS 6265 (SAE 9310)

Fig.2. *The surfaces response of the mathematical model that describes the variation of surface hardness at T_K = 900 ºC, T_K = 925 ºC, T_K = 950 ºC (left) and the delimitation areas of isoproperties (right), depending on the temporal and chemical parameters of the carburizing process AMS 6265 (SAE 9310) steel parts.*

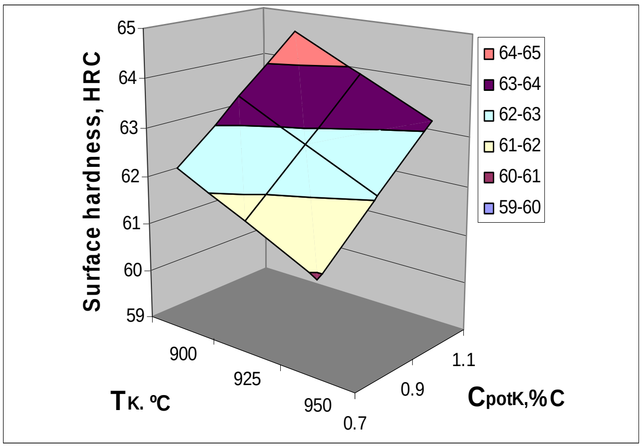
t_K = ct. = 3 hours

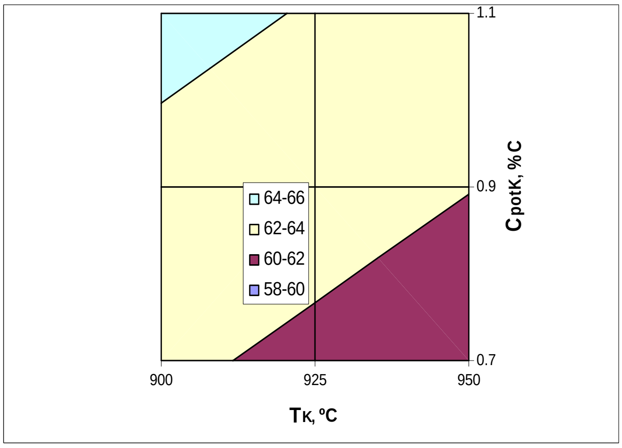


t_K = ct. = 6 hours



t_K = ct. = 9 hours





AMS 6265 (SAE 9310)

Fig.2. *The surfaces response of the mathematical model that describes the variation of surface hardness at t_K =3 hours, t_K = 6 hours, t_K = 9 hours (left) and the delimitation areas of isoproperties (right), depending on the thermal and chemical parameters of the carburizing process AMS 6265 (SAE 9310) steel parts.*

7. Conclusions

From the analysis of the results obtained after performing experimental study concerning the influence of the three main technological parameters, the thermal, the temporal and the chemical of the carburizing process (which is based on mass transport phenomena by diffusion) on the HRC surface hardness value of the AMS 6265 (SAE 9310) steel parts it can draws the following conclusions:

1. The HRC surface hardness value is positive influenced by the carbon potential of furnace atmosphere and negative by the time and the temperature values, when the values exceed certain levels, according to the mathematical model, calculated and expressed by the both equations (2 and 3). The reason of the positive carbon potential influence on the surface hardness parts consist in the fact that an elevate carbon content in austenite determine, after hardening, a high carbon content in the martensite with a high hardness.

The negative influence of increasing the temperature and the maintaining time of carburizing process above certain limits can be explained by the fact that by increasing the values of these two technological parameters can determine the excessive grows of the austenitic grain size and increases the internal oxidation phenomenon so that, after hardening, on obtain a large proportion of retained austenite and in the surface of parts the martensite is replaced by the high temperature product (troostite) characterized by low values of the hardness.

2. For increasing the parts hardness surface is indicate during the carburizing process, to operate with low temperatures and maintaining times (minimum possible) and with high value of carbon potential, but not more than the solubility limit of carbon in austenite (approximately 1.1% C_{potK}) taking in consideration that the AMS 6265 steel is alloyed in a high enough proportion with chromium;

3. The mathematical model calculated in this work was verified in industrial practice with good results witch allow to use it for to estimate the HRC hardness surface parts and for optimizing thermochemical carburizing treatment of AMS 6265 parts steel, in a large enough range of the key process parameters values:

- temperature: 900 ºC ≤ T_K ≤ 950 ºC;
- maintain time: 3 hours ≤ t_K ≤ 9 hours;
- carbon potentials: 0.7 %C ≤ C_{potK} ≤ 1.1 %C.

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