MATHEMATICAL MODELING OF THE INFLUENCE OF MAIN CARBURIZING THERMOCHEMICAL TREATMENT PARAMETERS ON THE SURFACE HARDNESS OF PARTS MADE OF MSRR 6009 STEEL

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The paper describes application of mathematical modeling to study the influence of the main technological parameters of the thermochemical carburizing of the MSSR 6009 steel, such as: the carburizing temperature, T_{K}; the maintaining time at carburizing temperature – t_{K}; and the carbon potential for carburizing process – $C_{\mathrm{pot.K}}$, on the surface characteristics and the hardness of parts made of the MSSR 6009 steel, used in aerospace industry.

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INTRODUCTION

The complexity of the phenomena involved in the processes of thermochemical treatment excludes the study of these processes with the classical experimental research methods, which are characterized by major difficulties in implementation and, in most cases, do not lead to reliable results.

Solution of problems in the experimental research of processes, based on diffusion phenomena using experimental methods, requires the application of the scheduled experimental methods, thus permitting to realize the empirical mathematical models, which can be obtained either by passive or by active experimental methods [1].

The majority of information presented in literature, concerning MSRR 6009 steel, used in aerospace industry, characterizes that steel mostly in terms of indicators of its mechanical characteristics when it is used for fabrication of parts hardened by the thermochemical treatment with carbon cement. The literature available to the authors does not describe concrete ways by which these indicators can be obtained, which is surprising. The majority of the works in the field of the thermochemical treatment research present the information concerning the relatively modest performance of the carbon hardened AISI 8620 steel, with low alloying elements [2]. This is why the present paper aims at filling some of the information gaps concerning specific aspects of the carburizing process of parts from the MSRR 6009 steel, as well as establishing how the main process parameters influence the Rockwell Hardness surface parts. For carburized parts from MSRR 6009 steel, used in aerospace industry, high wear and toughness characteristics are obligatory because those parts are used to fabricate components for gears that must be strong enough to face overloads in case of an accident.

1. THE STUDY OF THE INFLUENCE OF THERMAL, TEMPORAL AND CHEMICAL PARAMETERS ON THE SURFACE HARDNESS OF PARTS USING THE ACTIVE EXPERIMENTAL SCHEDULED METHOD AND THE SECOND-ORDER NONCOMPOSITIONAL PROGRAMMING

The existing information about the processes based on diffusion phenomena generally requires to use the second-order noncompositional programming for the explanation of interactions between process parameters (independent parameters) and their effects on the level of variation of structural features and the respective values of physical and mechanical characteristics (dependent parameters) [3].

The reason for using this type of programs consists, on the one part, in the fact that the processes underlying the formation of diffusion layers cannot be mathematically defined using linear models [4, 5] and, on the other part, there is sufficient knowledge concerning the range where the values of interest can be found. In order to solve the problem it is necessary to explain the experimental data using a second-order nonlinear equations of the form:

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

where Y is the dependent parameter investigated, and x_i, x_j are independent parameters that influence the dependent parameter under investigation in the present paper.

Independent variables (x_i ...) studied were those related to the carbon enrichment phase: isothermal temperature T_K (x_1), the maintaining time t_K (x_2) at carburizing temperature and the carbon potential $C_{pot\ k}$, (x_3). In the context of the second-order, nocompositional programming was imposed to vary the three independent variables at three levels of value, -1, 0, and 1. A second-order noncompositional programming plan is itself a selected segment of the factorial experiment 3k (k is the number of factors or independent variables). Those features that allow for a more complete characterization of the effects of surface enrichment in carbon due to the maintenance of the MSRR 6009 steel parts in the enriched gaseous hydrocarbon (methane) atmosphere were selected as dependent variables of the process ($Y_1 .... Y_n$),.

The second-order noncom positional programming matrix, for k = 3, the basic level, its range of variation and the results of measurements of the parts surface hardness are presented in 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	61
EXP.nr.2	+1	+1	-1	0	61.5
EXP.nr.3	+1	-1	+1	0	61
EXP.nr.4	+1	-1	-1	0	63
EXP.nr.5	+1	+1	0	+1	60
EXP.nr.6	+1	+1	0	-1	60
EXP.nr.7	+1	-1	0	+1	63
EXP.nr.8	+1	-1	0	-1	60
EXP.nr.9	+1	0	+1	+1	62.5
EXP.nr.10	+1	0	+1	-1	60
EXP.nr.11	+1	0	-1	+1	63
EXP.nr.12	+1	0	-1	-1	62
EXP.nr.13	+1	0	0	0	61
EXP.nr.14	+1	0	0	0	60
EXP.nr.15	+1	0	0	0	61.5

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

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

The samples on which measurements were made to assess the surface hardness were taken from the final heat treated parts (subcritical annealing, hardening, subzero cooling and tempering), which were used for metallographic evaluation.

To establish the algorithm for determining particular forms of nonlinear models for the dependent variable under discussion, for the processing of the experimental results obtained, it is necessary to follow the steps below:

- – Calculation of nonlinear model coefficients (b_0, b_i, b_{ij} ...);
- – Statistical verification of nonlinear model coefficients;
- – Calculation of the reproducibility of results dispersion.
- – Verification of the concordance of nonlinear models adopted.

2. EXPERIMENTAL

2.1 THE ACTUAL DEVELOPMENT OF EXPERIMENTAL BATCHES AND MODALITIES FOR DETERMINING AND EVALUATING THE EXPERIMENTAL RESULTS

The experiments were conducted in a batch furnace in endogas atmosphere enriched with methane. The chemical composition of the samples used (MSRR 6009 steel) is presented in table 2.

Table 2. Chemical composition of MSRR 6009 steel

Alloy (steel)	Elements content, %					
MSRR 6009	C	Si	Mn	Cr	Mo	Ni
min.	0.14	0.1	0.2	1.0	0.2	3.8
max.	0.18	0.4	0.5	1.4	0.3	4.3
actual	0.16	0.2	0.5	1.20	0.25	4.10

In order to study the influence of independent parameters (temperature, maintaining time and carbon potential) on the microstructure and on the physical and mechanical characteristics (surface hardness), as dependent parameters, fifteen carburizing batches were carried out, of which the last three were performed under the same conditions of temperature, time and carbon potential.

For each batch of experiments, the temperature, the carbon potential and the actual variation of them were recorded. Table 1 presents the parameters (thermal, temporal and chemical) adopted in running fifteen experiments.

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

1) The batches loading were carried out in the preheated furnace to the carburizing temperature process. During the batches loading, the furnace temperature was set down at 50–60°C, below the initial point setting temperature. After about 12–16 minutes, the batch temperature reached the temperature programmed for carrying out the carburizing cycle, and the recording of the maintaining time for the process was done only after the carbon potential of atmosphere in the furnace has reached the prescribed value, specific to each experimental cycle. For this reason, the effective thermal cycles are easily moved to the right (recovery time), with a period of time which accounts for the time of the batch loading, batch reheating to the process temperature and the time for achieving the atmosphere of the prescribed carbon potential in the furnace.

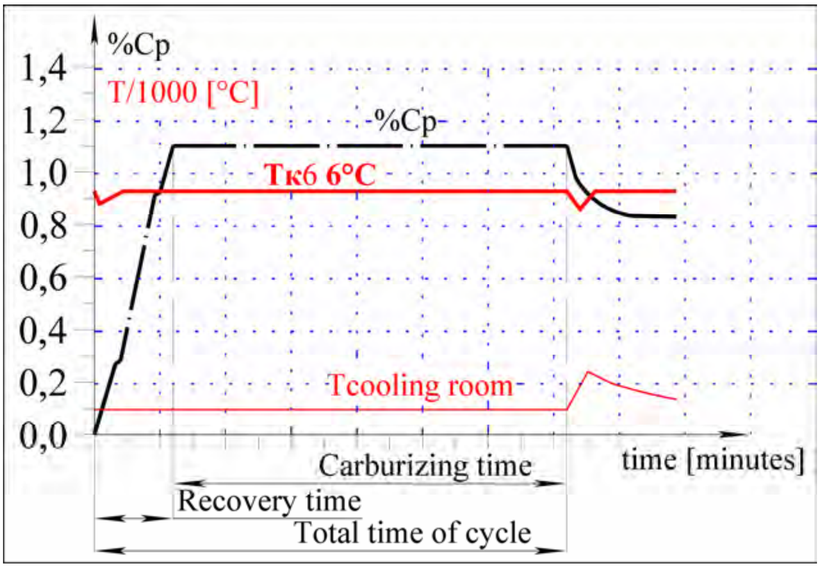

Fig. 1. General characteristics of thermal and chemical cycles used in experimental study

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

Taking into consideration that chemical and thermal cyclings displacements are systematic, uniform and proportional to the carbon potential and carburizing temperature in all experimental batches, the displacements have not altered the types and degrees of the influence of independent variables (process parameters) on the dependent variables (features) and on the experimental results obtained.

2.2 THE HRC SURFACE PARTS EVALUATION

The specimens (ø 18.5 mm x 30 mm) to the measure the HRC surface hardness of parts were taken from the carbon hardened samples finally heat-treated, which were used for metallographic evaluations.

Table 1 presents the values obtained for the surface HRC parts.

3. EXPERIMENTAL REASEARCH RESULTS

The mathematical model was accomplished by determining the regression equations, able to allow for the prediction performance that can be obtained by choosing the concrete conditions of the carburizing process on the parts made of MSRR 6009 steel for the aerospace industry.

After the stages of 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 under investigation, have resulted:

$$Y = 60.833 - 0.625X_2 + 1.125X_3 - 1.375X_1X_3, \quad (2)$$

$$[HRC]_{SUP} = -171.917 + 0.2475T_K - 0.208t_K + 260C_{pot} - 0.275T_K C_{pot}. \quad (3)$$

Equations (2) and (3) represent the encoded and decoded forms of a mathematical model of the hardness surface of parts, expresed in HRC units, respectively.

4. ANALYSIS AND INTERPRETATION OF EXPERIMENTAL RESEARCH RESULTS

The comparative analysis of the two equations shows that the terms with the greatest influence are the terms of the first-order degree (X_1, X_2, X_3, and T_K, T_K, C_{pot} , respectively $_K$), and that the second-degree term of the form X_1X_3 ($T_K \cdot C_{pot\ K}$) has significant influence in both equations.

Based on this finding, it can be concluded that the mathematical model deduced is predominantly linear, the fact also confirmed by the aspects of response surfaces and by the positions of certain isoproperties areas of the HRC surface hardness (see fig. 2. – *A*, *B*, *C*, *D*, *E* and *F*).

The analysis of the encoded equation (2) shows that the coefficient for the independent variable X_3 (first order term) is positive, which leads to the conclusion that the value of *Y* (HRC) increases with the increase of the value of this independent variable. The coefficients for X_2, and X_1X_3 are negative, which leads to the conclusion that the value of *Y* (HRC) decreases with the increase of the values of X_1 and X_2 independents parameters.

Regarding the numerical value and the 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 decoded equation, in which the $b_i x_i$, $b_{ij}\, x_{ij}$ products are terms whose algebraic summing permits to obtain the dependent parameter value (see table 3).

Table 3. Detailed calculation of the surface HRC hardness in the concrete case (base level of independent parameters: T_K = 925ºC; t_K = 6 hours; $C_{pot\ K}$ = 0.9%C)

Characteristic	b_0	b_1T_K	b_2t_K	$b_3C_{pot\ K}$	$b_{13}T_KC_{pot\ K}$	$Y_{calculated}$
$[HRC]_{SUP}$	– 171.917	228.937	-1.24875	234	-228.9380	60.83

In the regression decoded equation we observe that:

– the first-order term in $C_{pot.K}$ ($260C_{pot}$) is positive (234, which leads to the conclusion that the value of the *Y* (HRC) increases with the increase of $C_{pot.K}$ value;

– the first-order term in t_K ($-0.208t_K$) has negative value (-1.24875), which leads to the conclusion that the value of the *Y* (HRC) decreases with the increase of t_K;

– the increasing tendency of the surface hardness caused by the first-order term $0.2475T_K$, whose absolute value is 228.937, is annihilated by the second-order term in $T_K C_{\mathrm{pot\,K}}$ $(-0.275T_K C_{pot})$ whose the absolute value is (|-228. 9380|).

The analysis presented above demonstrates that the statistical ensemble of the carburizing process the carbon potential has a positive influence on the value of the surface hardness but the time and temperature have a negative influence on this characteristic.

5. GRAPHICAL PROCESSING OF EXPERIMENTAL RESULTS

The graphical processing of the experimental research results (fig. 2) creates a more suggestive picture of the manner in which the three independent variables of the carburizing process: the temperature at which that process is carried out, $T_{\mathrm{K};}$; the maintaining time at this temperature, t_{K}; and the carbon potential, C_{potK}, of the furnace atmosphere influence the value of the value of the HRC surface hardness.

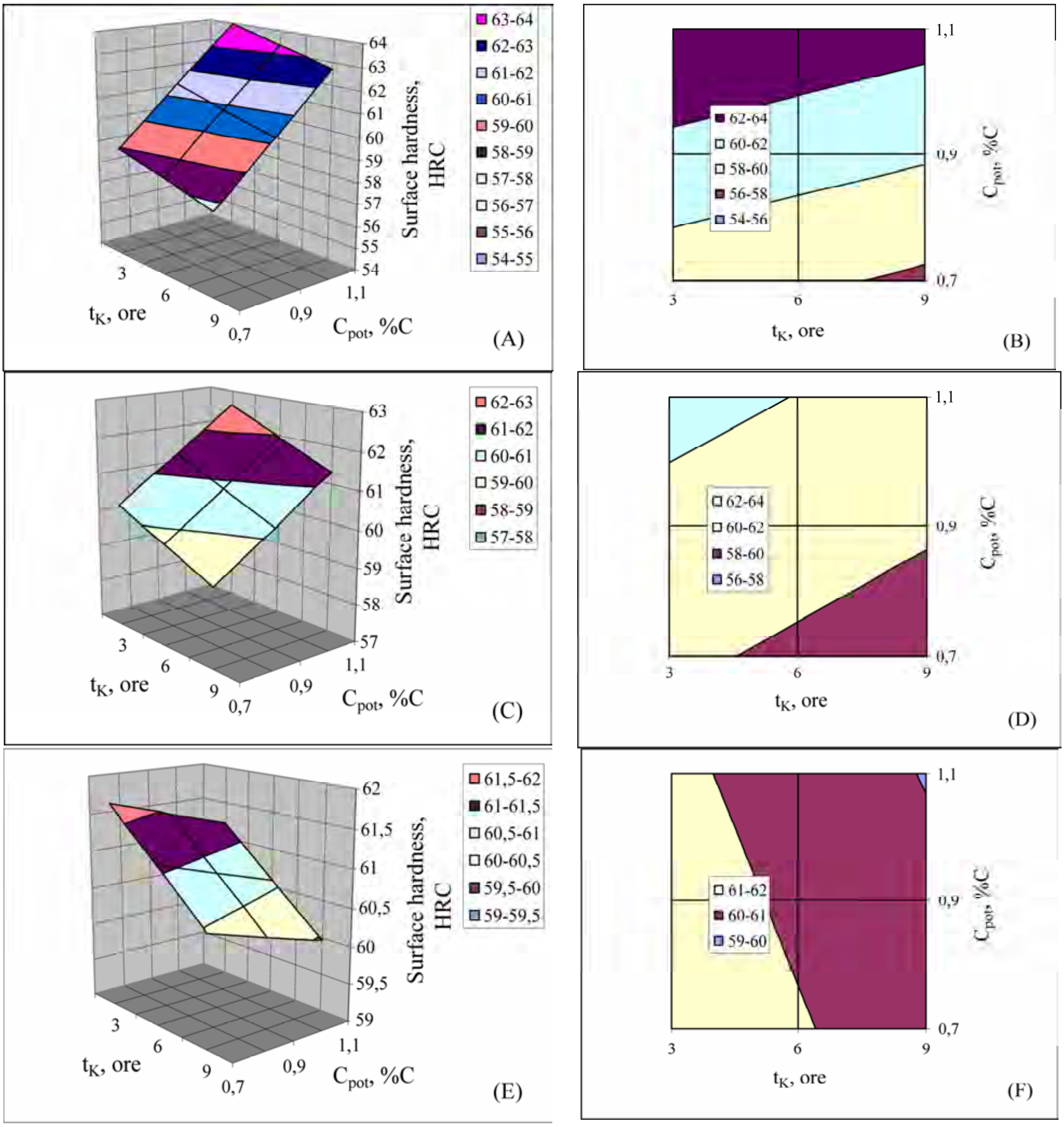

Fig. 2. Surfaces response of the mathematical model that describes the variation of HRC surface hardness at the temperatures: (A) T_K = 900°C, (C) T_K = 925°C and (E) T_K = 950°C; and the delimitation areas of isoproperties (B) (D) (F), depending on the temporal and chemical parameters of the process in carburizing MSRR 6009 steel parts

The charts presented below were drawn using one proper regression equations (coded or encoded) of the mathematical model established. Also the values (-1, 0, 1) were assigned to one of the process parameters (temperature in this case), corresponding to the three levels of variation specified in the second-order noncompositional (for $k = 3$) programming matrix of the experiment.

6. CONCLUSIONS

From the analysis of the experimental study results concerning the influence of the three main technological parameters: thermal, temporal and chemical, of the carburizing process (which is based on the mass transport phenomena by diffusion) on the HRC surface hardness of the MSRR 6009 steel parts the following conclusions can be drawn:

1. The value of the HRC surface hardness is positive as influenced by the carbon potential of the furnace atmosphere and is negative by the time and the temperature values, according to the mathematical model, calculated and expressed by both equations (2 and 3). The negative influence of the increase of temperature and of the maintaining time of the carburizing process can be explained by the fact that the increase of the values of these two technological parameters leads to the increase of the austenitic grain size and the internal oxidation phenomenon. After hardening, a large proportion of the retained austenite is obtained, and at the surface, martensite is replaced by the high-temperature product troostite characterized by the low values of hardness.

2. To increase the surface parts hardness during the carburizing process, it is indicate to operate at low temperature and maintaining time (the minimum possible) and with a high value of the carbon potential (but not above 1.1% C_{potK});

3. The mathematical model calculated in the present paper can be applied to the MSRR 6009 carburizing steel parts in order to estimate the HRC surface hardness in a wide range of temperatures (900ºC $\leq T_K \leq$ 950ºC), maintaining the time (3 hours $\leq t_K \leq$ 9 hours), carbon potentials (0.7%C $\leq T_K \leq$ 1.1 %C), and it can be applied to optimize the carburization process of the MSRR 6009 steel parts.

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Реферат

В данной статье, с использованием методов математического моделирования, представлены результаты исследования влияния основных технологических параметров химико-термического науглероживания стали марки MSSR 6009, таких как: температура процесса – $T_к$; длительность изотермической выдержки – t_k; а также углеродный потенциал – $C_{\text{pot.. K}}$, на характеристики структуры и поверхностную твердость деталей из стали MSSR 6009, применяемой в авиационной промышленности.