MATHEMATICAL MODELING FOR THE MARTENSITE ADDICTS OF SOME DUAL-PHASE STEELS

Severin Traian Lucian[1,3], Dulucheanu Constantin[1,3] Dishliev Stefan[2]

[1]*Stefan cel Mare" University of Suceava, Department of Mechanics and Technologies, 13 Universitatii Street, 720229, Suceava, Romania, severin.traian@usm.ro*
[2]*University of Food Technologies, Plovdiv, Bulgaria*
[3]*Integrated Center for Research, Development and Innovation in Advanced Materials, Nanotechnologies, and Distributed Systems for Fabrication and Control (MANSiD), Stefan cel Mare University, Suceava, Romania*

Abstract: *In the past few years researches has been done to obtain dual-phase steels with a low content of manganese (less than 1%) [1, 2] and for that reason such alloys were chosen for analysis; two types of commercial steels were used ("Steel A" and "Steel B"), materials produced and used primarily for welding electrodes.*

This material has been studied in the literature only in terms of properties defining characteristics of materials without presenting any data of determine the martensite value depending on the composition concerning the influence of heat treatments and cooling medium.

The chemical compositions were determined with a FOUNDRY-MASTER Xpert Spectrophotometer. The ferrite-martensite structures, typical of the dual-phase steels, has been obtained by intercritical quenching that consisted of heating at temperatures ranging between 760 and 820 ℃ and cooling in water with a temperature of 20 ℃ (Ultrasound Bath LBS 2). For determining the influence of ultrasound on the structure of dual-phase steels, the cooling was made in three variants: water (without mechanical agitation), water in an ultrasonic field with f = 40 kHz and water in an ultrasonic field with f = 59 kHz. After carrying out intercritical quenching, the samples have been subjected to metallographic analysis (with LEXT OLS4100 Olympus Laser Microscope) through which the volume fraction of martensite, the morphology and distribution of this phase, have been determined.

Keywords: *dual-phase structures, heat treatment, ultrasound, cooling medium*

1. Introduction

The dual-phase steels are metallic materials with which have the structure formed of a soft and ductile ferrite matrix in which are homogeneously dispersed martensite (10 ÷ 35 %) and residual austenite (1 - 2 %). The dual-phase steels products worldwide have, in general, a percentage of carbon less than 0.12 %, a content of manganese between 1.0 % and 3.5 %, and elements such as V, Cr, Mo and, Nb, are to be found in chemical composition in proportions situated below 1%; in the last few years there have been studies on steels in which the content of manganese is less than 1 % (0.5 - 1 % Mn). [1, 2, 3, 4, 5, 6].

Worldwide studies worldwide show that the amount of martensite in the structure is influenced by both the volume fraction of austenite obtained during the heat treatment and the stability of austenite during transformation through the martensitic mechanism; the scientific literature advises that heating should be carried out at a temperature which allows obtaining a percentage of 40 ÷ 60% austenite. The cooling rate from temperatures in the intercritical range ($\alpha+\gamma$) determines the type of transformation products due to the cooling process. [1, 2, 3, 7, 8].

During quenching, the contact between the workpiece and the cooling medium is particularly important, knowing that due to the large temperature differences the vapors form a film between the piece and the cooling medium (the calefaction phenomenon) that changes the cooling capacity of the medium.

Remarkable results were obtained by applying ultrasonic oscillations to the medium in which the quenching takes place which under the action of pressure and cavitation phenomenon, destroys and prevents the formation of vapor and gas films, thereby ensuring a more prolonged contact between the workpiece and the cooling medium; in this way the cooling rate is increased, which leads to a cooling more vigorous, the quenching with ultrasounds being more efficient than the ordinary [9, 10, 11].

2. Experimental details

2.1. Materials

For these studies we used two commercial steels, which are produced and used in industry, mainly for welding electrodes. Chemical compositions of these alloys (noted DP-A și DP-B) they were determined with a spectrometer FOUNDRY-MASTER Xpert (Oxford Instruments Analytical GmbH, Germania), presented in Table 1.

Table 1 *Chemical compositions of the steels DP-A and DP-B*

Steel	Chemical compositions, (%)						
DP-A	C	Mn	Si	P	S	Cr	Mo
	0.087	0.511	0.091	0.0036	0.0039	0.029	0.005
	Ni	Al	Cu	V	W	Pb	Fe
	0.049	0.003	0.082	0.003	0.003	-	rest
DP-B	C	Mn	Si	P	S	Cr	Mo
	0.101	0.529	0.091	0.032	0.0037	0.036	0.005
	Ni	Al	Cu	V	W	Pb	Fe
	0.015	0.003	0.015	0.003	0.003	0.011	rest

The initial structure of the two steels are composed of ferrite and perlite on grain boundaries consisting of 85.30% ferrite and 14.70% perlite in DP-A case, respectively 83.90 % ferrite and 16.10 % perlite DP-B case.

2.2. Heat treatment

In order to obtain ferrite-martensite microstructure characteristic to dual-phase steels, samples of the alloys DP-A and DP-B were subjected to intercritical quenching at which the quenching temperatures (TQ) had the following values: 760, 780, 800 and 820 °C. The heating was conducted in an electric laboratory furnace Naberterm LT 40/11/P330 at constant values of the quenching temperature (TQ = constant), for 30 minutes, and the cooling was performed in an Ultrasound Bath LBS 2 that has the following technical characteristics: capacity - 22,5 dm^3, peak power - 650 W, absorbed power - 500 W; heating - from 20 to 80 °C, frequency: 0, 40 and 59 kHz.

To study the influence of ultrasounds on the microstructure of the two steels (DP-A and DP-B), the quenching was conducted in three mediums: 1) water with the temperature (T_{water}) of 20 ˚C, without mechanical agitation (denoted W), 2) water with the temperature (T_{water}) of 20 °C, activated with ultrasound, at the frequency of 40 kHz (denoted US40) and 3) water with the temperature (T_{water}) of 20 °C, activated with ultrasound, at the frequency of 59 kHz (denoted US59).

Tabel 2. *The amount of martensite in the dual-phase steel microstructures DP-A and DP-B (average values)*

Steel	The amount of martensite, V_M (%)											
	T_Q = 760 ˚C			T_Q = 780 ˚C			T_Q = 800 ˚C			T_Q = 820 ˚C		
	A	US40	US59	A	US40	US59	A	US40	US59	A	US40	US59
DP-A	20.19	21.34	23.74	23.83	25.04	28.15	29.41	30.88	32.96	36.98	38.67	40.71
DP-B	22.10	23.59	25.24	25.51	26.62	28.98	30.40	32.16	33.82	38.13	40.02	42.21

2.3. Results and discussions

Mathematical prediction modelling. for the experimental design process was adopted a 2^3 orthogonal central composite design with 5 levels (-α, -1, 0, 1, α) for each independent variables (x_1-C%, x_2-Mn%, x_3-P%, x_4-S%, x_5-Cr%, x_6-Ni, x_7-Cu%, x_8-Pb%, x_9-Fe%, x_{10} - temperature T (ºC), x_{11}-heat treatment medium).

In this paper was used Khuri and Cornell orthogonal design that contain only one observation at each of the n_f factorial points,

two observations at each q axial points, and n_c observations at the center [12]. To encode the natural values of the independent variables was used Eq. 1.

$$x_i = \frac{Y_i - Y_i^0}{\Delta Y_i}, \forall i = \overline{1,n}, \text{ n=11} \quad (1)$$

where x_i is the coded value (dimensionless value), Y_i is the natural value of the i^{th} test variable, Y_i^0 is the natural value in the center of the range of the i^{th} test variable and ΔY_i is the interval of variation for i^{th} test variable and n represent the number of the process variables [13, 14, 15].

The coded values of level $\pm\alpha$ were calculated using the Eq. 2 [11]:

$$\alpha = \left(\frac{\sqrt{n_f \cdot n} - n_f}{2} \right)^{1/2} \quad (2)$$

Correspondence between actual and coded values of design variables are presented in Table 3.

Table 3. *Experimental ranges and levels of independent variables*

Independent variable	Code	Range		
		-1	0	+1
C	x_1	0,087	0,094	0,101
Mn	x_2	0,511	0,52	0,529
P	x_3	0,0036	0,0178	0,032
S	x_4	0,0037	0,0038	0,0039
Cr	*x5*	0,029	0,0325	0,036
Ni	*x6*	0,015	0,032	0,049
Cu,	*x7*	0,015	0,0485	0,082
Pb	*x8*	0	0,0055	0,011
Fe	*x9*	99,12	99,135	99,15
Temperature, *T* (ºC)	*x10*	760	790	820
Heat treatment medium	*x11*	0	1	2

For this modelling process a design of 24 experiments was formulated (2 axial points on the axis of each design variable at a distance of α from the design center) and one replicated at the center [11]. The coded and the natural values of the test variables and the experimental values of surface hardness are presented in Table 4.

Table 4: *Orthogonal central composite design of 23 type*

No.	Alloy	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	*M*(%)
1	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	-1	-1	20,19
2	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	-1	0	21,34
3	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	-1	1	23,74
4	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	-0,333	-1	23,83
5	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	-0,333	0	25,04
6	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	-0,333	1	28,15
7	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	0,333	-1	29,41
8	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	0,333	0	30,88
9	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	0,333	1	32,96
10	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	1	-1	36,98
11	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	1	0	38,67
12	DP-A	-1	-1	-1	1	-1	1	1	-1	-1	1	1	40,71
13	DP-B	1	1	1	-1	1	-1	-1	1	1	-1	-1	20,10
14	DP-B	1	1	1	-1	1	-1	-1	1	1	-1	0	23,59
15	DP-B	1	1	1	-1	1	-1	-1	1	1	-1	1	25,24
16	DP-B	1	1	1	-1	1	-1	-1	1	1	-0,333	-1	25,51
17	DP-B	1	1	1	-1	1	-1	-1	1	1	-0,333	0	26,62
18	DP-B	1	1	1	-1	1	-1	-1	1	1	-0,333	1	28,98
19	DP-B	1	1	1	-1	1	-1	-1	1	1	0,333	-1	30,40
20	DP-B	1	1	1	-1	1	-1	-1	1	1	0,333	0	32,16
21	DP-B	1	1	1	-1	1	-1	-1	1	1	0,333	1	33,82
22	DP-B	1	1	1	-1	1	-1	-1	1	1	1	-1	38,13
23	DP-B	1	1	1	-1	1	-1	-1	1	1	1	0	40,02
24	DP-B	1	1	1	-1	1	-1	-1	1	1	1	1	42,21

To explain the behaviour of the studied system was used a second order polynomial equation (Eq. 7) for correlation between the independent variables (x_1, x_2 and x_3) and response function *W* [13].

$$W = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{\substack{i=1 \\ j=1}}^{n} \beta_{ij} x_i x_j \, , i \neq j \quad (7)$$

where W is the measured response for each experiment (in this case – the surface hardness), β_0 is the intercept term, β_i , β_{ii} and β_{ij} are, respectively, the measures of the linear, quadratic and interaction effects of the process variables x_i , x_{ii} and x_i x_j [14].

The regression coefficients of the empirical model (regression equation) were calculated by using Eq. 8.

$$\beta = (X^T \times X)^{-1} \times X^T \times W \quad (8)$$

where β is the column vector of the regression coefficients, X the design matrix of the coded levels of independent variables and M is a column vector of response determined experimentally according to the arrangement points into central composite design.

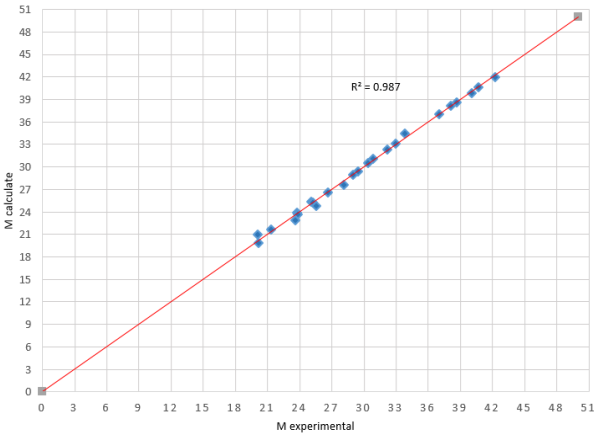

Figure 1: *The martensitic values of experimental data versus predicted data given by regression model*

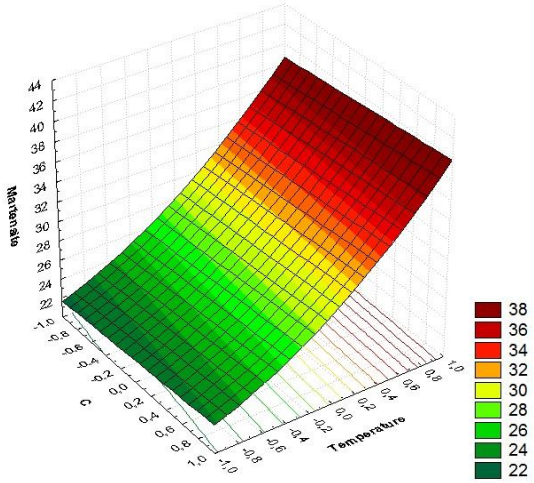

Figure 2. *Response surface plot for the effect of the C% (x_1) and the temperature, T (x_{10}).*

The quadratic model obtained by solving Eq. 8 was tested by means of the Student's "*t*" test. The effects was that x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_2^2, x_3^2, x_4^2, x_5^2, x_6^2, x_7^2, x_8^2, x_9^2, and interaction between them are non-significant and were excluded from the final regression equation (Eq. 9).

$$M = +28.58 + 0.62x_1 + 8.48x_{10} + 1.95x_{11} + 2.17x^2 + +23x_{11}^2 + 0{,}0015x_1x_{11} + 0.060x_1x_{11} - 0.13x_{10}x_{11} \quad (9)$$

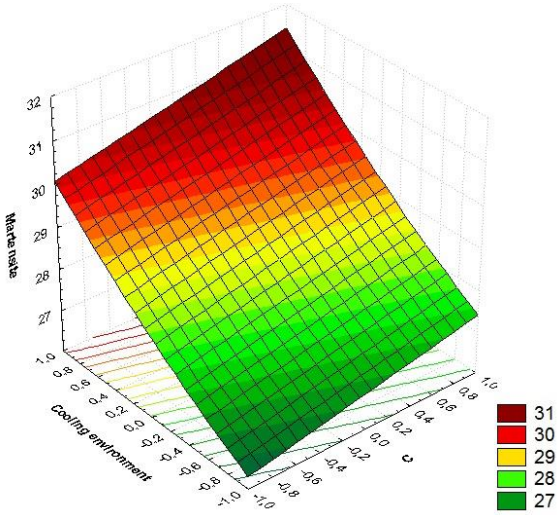

Figure 4. *Response surface plot for the effect of the C% (x_1) and the heat treatment medium (x_{11}).*

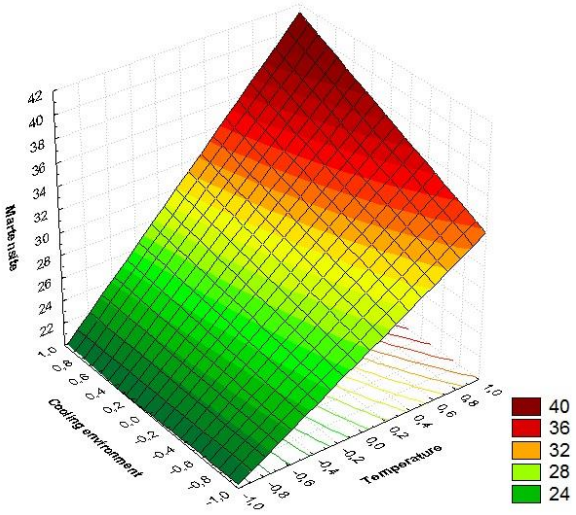

Figure 3. *Response surface plot for the temperature, T (x_{10}) and the heat treatment medium (x_{11})*

The response surface from Figure 2-4 show that increasing of both x10 (the temperatures) and x11 (the heat treatment medium) would increase the amount of martensite (M).

In order to check the adequacy of empirical model (Eq. 9) the statistical F-test (Fisher's

test) was performed. The F-test was done for a confidence level $\gamma = 0.05$. The calculated value of the Fisher's test ($F_C = 0.188$) was compared with the tabulated one ($FT(f_1,f_2) = 2.29$). Since $F_C < F_T$, the mathematical model is adequate with a probability of 95 %.

The suitability between the model and experimental data was confirmed by the goodness-of-fit between calculated (predicted) values and experimental values in Fig. 1.

Conclusions

The mathematical model proposed for the two steels (DP-A and DP-B), with all quenching temperatures, the use of ultrasounds at cooling and the raise of the frequency from 40 at 59 kHz lead of increasing the volume fraction of martensite (V_M) in microstructures.

Raising the quenching temperature (T_Q) has led, also, to an increase in the volume fraction of martensite (V_M) in microstructures, because raising the T_Q temperature in the intercritical range ($\alpha + \gamma$) has determined an increase in the volume fraction of austenite, phase which then by quenching (in W, US40 and US59) has turned into martensite.

The additional energy intake from the quenching in water activated with ultrasound at the frequency of 59 kHz, determined the realization of values, for the volume fraction of martensite very close to those obtained by quenching in water (without mechanical agitation), but at that the heating was made at a higher temperature.

The three parameters that modify the modelling process as independent variables (x_1 C%), x_{10} temperature T (ºC) and x_{11} the heat treatment medium) show an influence on the amount of martensite.

The 2^3 orthogonal central composite design of experiment and the Response Surface Methodology can be used successfully in modelling of predict this process.

Acknowledgment

This work was partially supported from the project “Integrated Center for Research, Development and Innovation in Advanced Materials, Nanotechnologies, and Distributed Systems for Fabrication and Control”, Contract No. 671/09.04.2015, Sectoral Operational Program for Increase of the Economic Competitiveness co-funded from the European Regional Development Fund.

References

[1] Rashid MS (1981) Dual-Phase Steels, Ann Rev Mater Sci 11:245-266

[2] Tsipouridis P (2006) Mechanical Properties of Dual-Phase Steels. PhD Dissertatin, Technische Universität München

[3] Jamwal RS (2011) Microstructural Origins of Variability in the Tensile Ductility of Dual Phase Steels. https://smartech.gatech.edu/bitstream/handle/1853/39477/jamwal_ranbir_s_201105_mast.pdf. Accessed 3 June 2014

[4] Akay SK, Yazici M, Avinc A (2009) The Effect of Heat Treatment on Physical Properties a Low Carbon Steel. http://www.acad.ro/sectii2002/proceedings/doc2009-1/05-Akay.pdf. Accessed 22 April 2016

[5] Pouranvari M (2010) Tensile Strength and Ductility of Ferrite-Martensite Dual Phase Steels, Metallurgical and Materials Engineering 16 (3):187-194

[6] Dulucheanu C, Bancescu N., Baesu M (2015) The Corrosion Behavior in 3,5% NaCl Solution of Dual-Phase Steel with 0.094% C and 0,53% Mn. In: International Multidisciplinary Scientific GeoConference - SGEM, Nano, Bio and Green - Technologies for a Sustainable Future, Vol II (SGEM 2015). STEF92 Technology Ltd., Sofia, pp 327-334

[7] Davies RG, Magee CL (1979) Physical Metallurgy of Automotive High Strength Steels. In: Kot RA, Morris JW (eds) Structure and Properties of Dual-Phase Steels. The Metallurgical Society of AIME, New York, pp 1-19

[8] Speich GR (1981) Physical Metallurgy of Dual-Phase Steels. In: Kot RA, Bramfitt BL (eds) Fundamentals of Dual-Phase

Steels. The Metallurgical Society of AIME, New York, pp 3-46
[9] Dulucheanu C, Băncescu N, Severin T (2013) Technological Characteristics of a Dual-Phase Steel with 0,09% C and 1,90% Mn Obtained by Intercritical Quenching, Advanced Materials Research 814:60-67
[10] Băncescu N, Gramaticu M, Dulucheanu C (1995) Instalații de tratament termic în câmp ultrasonor, Tehnomus 1:15-19
[11] Bancescu N, Dulucheanu C., Severin T (2013) The Quenching in Ultrasonic Field of a Bearing Steels. Advantages and Perspectives. Part 1: The Influence Quenching Technology on Hardness and Structure of a RUL 1 Steel, Metalurgia International, Special Issue 5:43-48
[12] N. Bradley, The Response Surface Methodology, Master of Science Thesis, University of South Bend, Indiana (2007), available at http://www.cs.iusb.edu/thesis/NBradley_thesis.pdf, accessed: 2.02.2014.
[13] M. Poroch-Seritan, S. Gutt, G.Gutt, I. Cretescu, C. Cojocaru, T. Severin, Design of experiments for statistical modeling and multi-response optimization of nickel electroplating process, Chem. Eng. Res. Des. 89 (2011) 136-147.
[14] C.D.Balan, C. Cojocaru, P. Bulai, D. Bilba, M. Macoveanu, Optimization of process variables for the cadmium removal onto sphagnum moss peat, Environ Eng Manag J. 8 (2009) 225-231.
[15] T-L Severin, A. Potorac, Mathematical modelling concerning the influence of chemical composition upon hardness of cadmium telluride crystal, XV International Scientific Conference Renewable Energy & Innovative Technologies, "RE&IT - 2016" Conference Proceedings Volume 1, 10-11 June, 2016, Smolyan, Bulgaria.