Influence of the Cooling Regime on the Characteristics of Plasticity in the Case of Steel for Metal Structures

CARMEN PENELOPI PAPADATU[1], IOAN GABRIEL SANDU[2,3]*, MARIAN BORDEI[1], MARCIN NABIALEK[4], ANDREI VICTOR SANDU[2,3,5]*

[1] Dunarea de Jos University of Galati, Faculty of Engineering, 111 Domneasca Str., 800008, Galati, Romania

[2] Gheorghe Asachi Technical University of Iasi, Faculty of Materials Science and Engineering, 61A D. Mangeron Str., 700050, Iasi, Romania

[3] Romanian Inventors Forum, 3 Sf. Petru Movila St., Bl. L11, Sc. A., III/3, 700089, Iasi, Romania

[4] Czestochowa University of Technology, Institute of Physics, 19 Armii Krajowej Av, 42-217 Czestochowa, Poland

[5] Center of Excellence Geopolymer & Green Technology (CeGeoGTech), School of Material Engineering, University Malaysia Perlis (UniMAP), P.O. Box 77, d/a Pejabat Pos Besar, 01000 Kangar, Perlis Malaysia

An important influence factor is the cooling speed value after the heat treatment. It is important to be chooses the optimal cooling regime because the steel can be laminate at high temperature. Another reason for the monitoring of the cooling speed and the conditions of the cooling regime is the possibility that the steel was heated at high temperature after lamination process, for plastic deformation, to realize metallic sculptures or other components used in industry. For this study we considered three groups of samples of the steel, each group had eight samples. Three different mediums for directing of the cooling process were considered. The characteristics of the plasticity and some mechanical properties of the steel have been modified. Finally, after an experimental program, a statistical model tried to demonstrate that a causal connection between two variables such as: the cooling speed (VR) and tensile elongation (A5) of the samples from steel exists. This work proposes to achieve a statistical model and it studies the possibility to improve the characteristics of the plasticity implicitly other properties of steel used for metal structures.

Keywords: steel, cooling regime, plasticity characteristics, properties, correlation, statistical model

Long steel products go through long thermo-mechanical processing in order to be realized [1] and they are the raw products which suffer further processing/manufacturing operations. A good quality of the raw products can be of utmost importance for the final product, and, from this point of view, continuous improvement of the production process is necessary.

Therefore, this study determine the best cooling regime after heat treatment or after hot lamination, to obtain better plasticity characteristics in the case of a steel used for metal structures [2]. A statistical model can predict the connection between the plasticity characteristics and properties of the steel, in dependence by the cooling speed (VR). To study the effects of the cooling regimes for hot laminated steel samples, it is necessary to analyze the hot plasticity of deformed structures. These structures can be considered as the result of two processes which simultaneously take place: the plastic deformation process-which produces changes of the properties (steel reinforced through plastic deformation) and the re-crystallization process-which determine the softening of the steel. If the deformation temperature increases gradually, the speed of re-crystallization process increases and the material is soft. In case of hot plastic deformation, the speed of stiffening determined by plastic deformation is greater than the speed of softening due by re-crystallization process. The re-crystallization process continues because the final temperature of the deformation is greater. In this case, the structure and the properties of the hot laminated steel are depending by the temperature, the cooling regimes and the speed of cooling.

The main structural changes that can be obtained from hot rolling (deformation) of the steel with a low carbon content are: the compacting of the material and the cover of the gaps (murmurs) from casting; the crumbling of the crystalline grain, the forming of the structure in strings which can strongly influence the transformation of the austenite to cooling process. Thermal stresses occurring in heating process is due to the elastic properties of the material.

For steels with approx.0.11% C, the microstructures parameters which determine the mechanical properties of this class of steel are the size and the shape of pearlitic and ferritic grains which constitute the microstructure [2].

According to literature [3, 4], the steel with a low carbon content has pronounced elastic properties. Over 550°C, in generally, the elastic properties decrease and the plasticity properties of the steel are improved. Therefore, thermal stresses are larger and more dangerous when the heating of the steel is until to 550°C. Because the steel with low carbon has high plastic properties below 550°C, the thermal stresses will not leads to the formation of cracks. When it reaches the level of the yield strength of steel, the plastic deformation occurs. Damage of materials means the progressive or sudden deterioration of their mechanical strength due to loading, thermal or chemical effects [5, 14]. Because ductile steels can sustain large plastic deformations without fracture it is important to know how the properties of the steel can be improved. For this case, it is necessary to find a causal relation between a technological parameter (the speed of cooling) and mechanical properties of the steel. To discover this causal relation between variables, the method of least squares was applied, taking into account a unifactorial regression case.

Experimental part

There were considered three groups of samples of the steel, each group had eight prysmatic samples with the thickness

* email: gisandu@yahoo.com; sav@tuiasi.ro

Table 1
CHEMICAL COMPOSITION OF THE STEEL

Chemical Element	C (%)	Mn (%)	Si (%)	P (%)	S (%)	Al (%)
Amount	0.14	1.51	0.31	0.010	0.010	0.041

Table 2
INFLUENCE OF THE COOLING CONDITIONS ON THE PLASTICITY CHARACTERISTICS AND MECHANICAL PROPERTIES OF THE STEEL [6]

Cooling conditions	Initial temperature [°C]	Ψ [%] (Z)	HB	Speed of cooling (VR) [°C/min]	KV(20°C)	A5 [%]	Rm [N/mm²]	Code of sample
(2)	1000	78. 6	165	5.03	93	35. 3	549	2.1
(2)	950	78.2	165	6.2	94	31.2	547	2.2
(2)	900	73.7	164.5	6.82	88	32	551	2.3
(2)	850	77	181.5	7.35	89	32.5	562	2.4
(1)	1000	77.8	172	3.69	96	35.3	558	2.5
(1)	950	79.3	162	3.88	86	34	548	2.6
(1)	900	77.8	160	4.15	90	36.8	534	2.7
(1)	850	78.5	162.5	4.61	91	35.8	562	2.8
(3)	1000	76.8	183	19.6	98	33.8	542	2.10
(3)	950	76.6	178	20.21	96	34.8	549	2.11
(3)	900	72.6	175	20.95	98	33.8	555	2.12
(3)	850	77.8	184	21.84	90	33.2	551	2.13

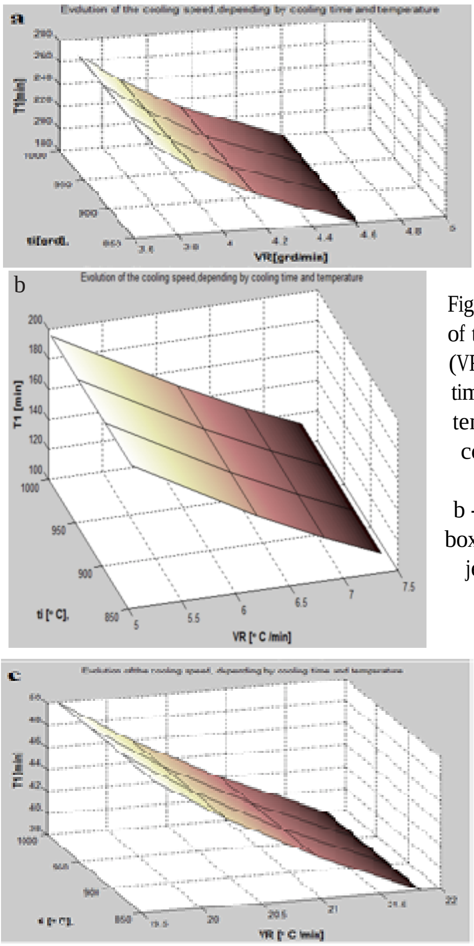

Fig. 1. The evolution of the cooling speed (VR), versus cooling time (T1) and initial temperature: a - for cooling in normal conditions (2); b - cooling in metal box (2); c - cooling in jet of cold air (3)

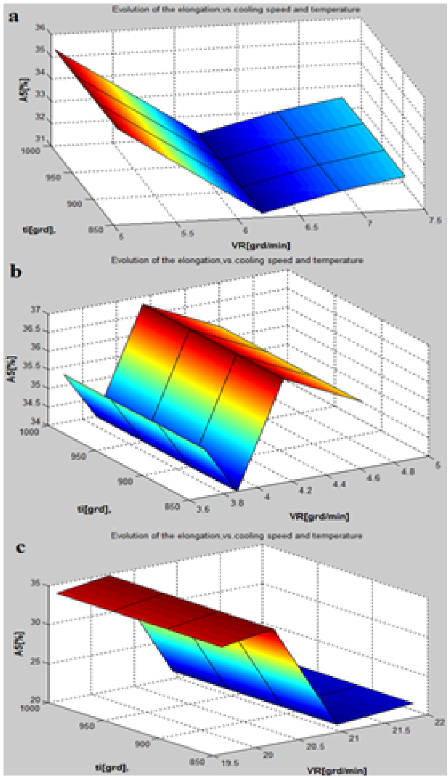

Fig. 2. The evolution of the elongation at break (A5) versus cooling speed (VR) and initial temperature corresponds to the cooling conditions: a - (2); b - (2) and c - (3)

of the tread by 20 mm. Chemical composition of the material was presented in table 1.

There were applied three cooling regimes: (1) cooling in a metallic box; (2) cooling regime in normal conditions; (3) cooling in air flow (in jet of air). The initial temperatures were 850°C (for the first batch of samples), 900°C (for the second batch of samples), 950°C (for the third batch of samples) and 1000°C (for the last batch of samples). If the cooling mediums are different, the speeds of the cooling are different. In case of cooling in jet of cold air, the speed of the cooling will be the highest.

In table 2 were presented the influence of the cooling conditions on the plasticity characteristics [6].

We have made the representations of the evolution of the cooling speed versus initial temperature and cooling time, using Matlab Program. In these cases there are three situations presented in the figure 1. Simultaneously, the variation of the cooling speed, characteristics of plasticity and mechanical properties of the steel have been changed. For example, the elongation at break (A5) corresponding to the traction tests has higher values when the cooling speed is lower, according to figure 2. The thinning (necking) has a spectacular variation according to the cooling speed and initial temperature in figure 3.

The hardness of the steel increases when the speed of the cooling process and the initial temperature have higher values (fig. 4).

Microstructural aspects are presented in figure 5 for all the cooling conditions from 1000°C.

Statistical model

Adjusted values of the resulting features

If it is considered the initial temperature Ti = 850°C, the cooling speed values for these three different conditions corresponding to the cooling regime were presented in table 3.

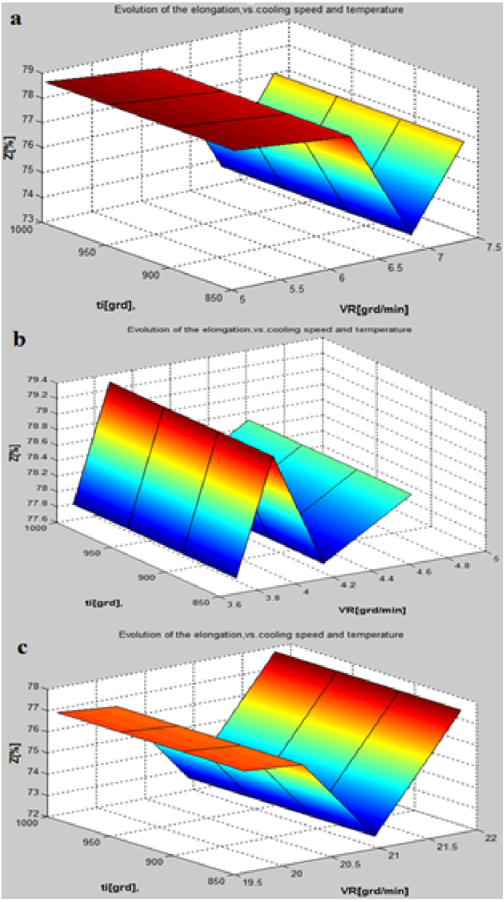

Fig. 3. The evolution of the thinning (Z) versus cooling speed (VR) and initial temperature, corresponds to: a - normal conditions (2); b - cooling in metal box (1); c - cooling in jet of cold air (3)

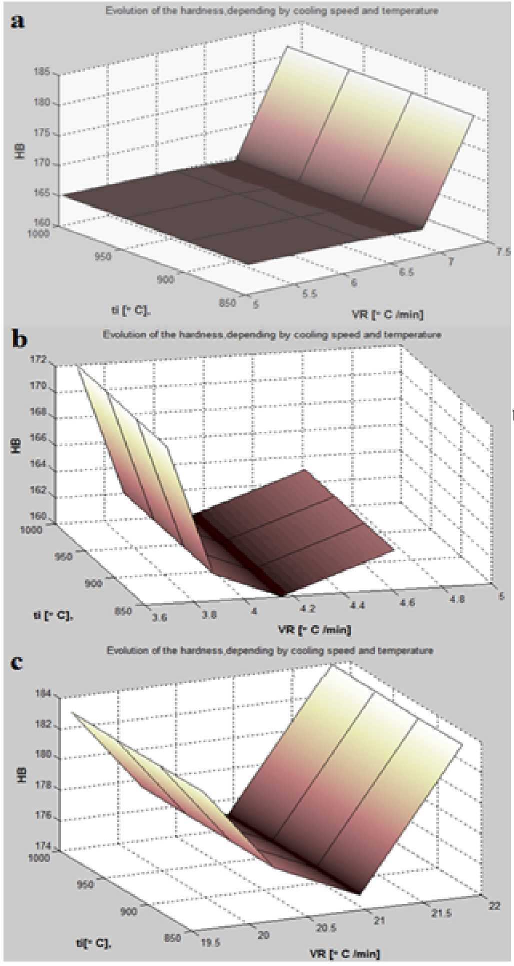

Fig. 4. The evolution of the hardness (HB) versus cooling speed (VR) and initial temperature, for: a - normal conditions (1); b - cooling in metal box (2); c - cooling in jet of air (3)

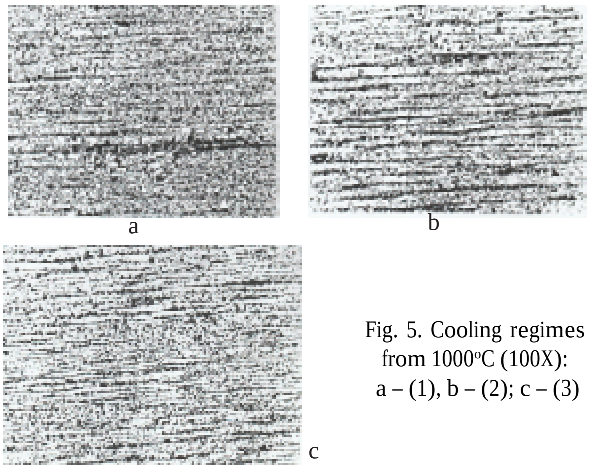

Fig. 5. Cooling regimes from 1000°C (100X): a – (1), b – (2); c – (3)

In figure 6 was represented the evolution of the plasticity characteristic (A5) of the steel, cooled from 850° C vs. the type of the cooling regime.

For any regression model is important to determine the model parameters. This operation can be performed using the least squares approximation method. It starts from the regression equation of a simple linear model [7, 14]:

$$y = a + b x + u \quad t = 1, \qquad (1)$$

For this equation, t and u are theoretical values for variable y obtained only function by the values of essential factor x and dependent by the values for the parameters a and b respectively, â and b.

To prove the causation between the cooling speed (VR.) and the characteristic of plasticity of the material (A5) in the case of the initial temperature Ti = 850°C, we resort to statistical methods for checking the next assumption: we assume that there is a causal relationship between the independent variable VR and a dependent variable A5.

Between these variables there is a direct connection. To realize an analysis model of regression and the correlation implies some steps [7, 8, 14].

First Step represents a correct identification of the variables x and y. In this case, VR (the cooling speed) will be considered the factorial variable x (the cause) and A5 will be the dependent variable y (the efficient variable):

$$A5 = f\,(VR) \qquad (2)$$

The second Step consists in **v**erification of the existence of the connection between x and y. We consider the following notations: x = VR and y = A5. Based on the graph from figure 6, we can say that between these two variables a direct connection exists.

The third Step is represented by the establishment of the mathematical form of the connection; we develop the regression equation corresponding to this regression model. In the case of uni-factorial linear regression, it is considered that on a resulting characteristic w acts the only variable factor ***x*** and the others can have a constant and negligible action:

$$y = f(x) \qquad (3)$$

Considering that, the function f(x) has a graph evolution as a straight line and results a linear model of the simple regression.

The function of estimation is given by the expression:

$$\hat{y} = a + bx \qquad (4)$$

Modeling function is given by the expression: $y_x = a + bx_i$, (5) for the linearity of connection and it means an additive interaction scheme of variables, in conditions by uniform changing with constant amounts of characteristic x [7].

The parameter a is the value of the regression function at the point x = 0. This parameter a is the ordinate by

Table 3

EXPERIMENTAL RESULTS, FOR INITIAL TEMPERATURE 850°C [6]

Speed of cooling VR (average values calculated) [°C/min]	HB [daN/mm²] Average values (experimental)	A5 [%] (exp.)	Z [%] (exp.)	KV [J] (exp.)	Cooling regime	Code samples
4.61 (cooling in metallic box)	162.5	31.05	77	81	(2)	2.8
7.35 (cooling in normal conditions, in air)	181.5	32.5	77	89	(1)	2.4
21.84 (cooling in jet of air)	184	33.2	77.8	90	(3)	2.13

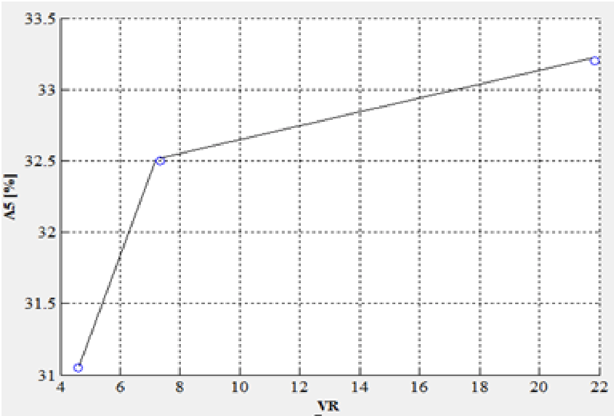

Fig. 6. Evolution of the Elongation (A5) versus cooling speed (VR)

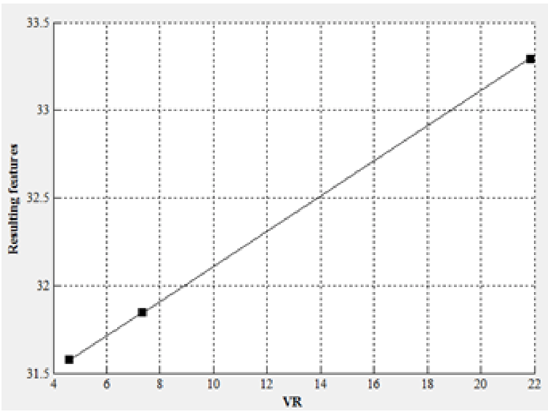

Fig.7. The representation of the equation $\hat{y} = 0.09x + 31.13$

origin, meaning the point where the regression right intersects the 0y axis. The parameter b called the regression coefficient, shows the amount with which you can modify the variable **y**, at the modifying of the variable with one unit. (7)

The method of least squares assumes the minimization of the following function [2, 7, 8]: (8)

$$F(\hat{a},\hat{b}) = \min\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 = \min\sum_{i=1}^{n}(y_i - \hat{a} - \hat{b}x_i)^2 \quad (6)$$

The minimum condition of this function implies the formation of the system of two equations with two unknowns:

$$F(a^{\wedge}) = 0 \text{ and } F(b^{\wedge}) = 0 \rightarrow$$

$$n\hat{a} + \hat{b}\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i\,,$$

$$\hat{a}\sum_{i=1}^{n} x_i + \hat{b}\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_i y_i,$$

For this case, n = 3. One can write the equations from the following system of equations:

$$3a + b(4.61+7.35+21.84) = 31.05 + 32.5 + 33.2$$

x	$\hat{y}$
4.61	31.58
7.35	31.85
21.84	33.29

Table 4

RESULTING FEATURES $\hat{y}$

x	$y - \hat{y}$
4.61	0.5
7.35	-0.65
21.84	0.09

Table 5

COMPARED VALUES

$$33.8a + b(4.61^2 + 7.35^2 + 21.84^2) = 4.61 \times 31.05 + 7.35 \times 32.5 + 21.84 \times 33.2$$

Or, one can write the results from the system of equations: b = 0.09 > 0.Results: a = 31.13

It was obtained the following equation:

$$\hat{y} = 0.09x + 31.13 \quad (9)$$

Comparing the real values of **y** with the adjusted values for resulting feature ($\hat{y}$), there are small differences. Using Matlab Program, it was obtained the graphic corresponding to the equation (9), for some values corresponding to the adjusted values for *resulting feature* $\hat{y}$ presented in table 4.

In table 5 are presented the differences between the experimental values for y and the calculated values $\hat{y}$.

Parametric method of measuring the intensity of connections between variables

The fourth step is represented by the characterization of the connection intensity between the two variables using the correlation coefficient $r^{x,y}$ and the correlation report.

$$\bar{y} = n^{-1}\sum x_i \cdot y_i, \quad (10)$$

The above relation, for *covariance coefficient*, can be written in the following form [7, 12, 14]:

$$M(x \cdot y) = n^{-1}\sum_{i=1}^{n} x_i y_i, \quad (11)$$

For n = 3, **y = M(x y)** = $\frac{1}{3}$ x 1107.09 = 369.03**.**

One can write the simple correlation coefficient r [2, 8, 12, 14]:

$$r = \frac{n\sum^{n} x_i y_i - (\sum^{n} x_i)(\sum^{n} y_i)}{\sqrt{n\sum^{n} x_i^2 - (\sum^{n} x_i)^2} * \sqrt{n\sum^{n} y_i^2 - (\sum^{n} y_i)^2}} \quad (12)$$

r = 51.12/ 58,76 = **0.85** > 0

A direct connection between these two variables (VR and A5) exists. Theoretically, if the value is closed to 1, exists a very good connection between the variables. For the interpretation of nonzero values for coefficients of correlation, an explanation graphics is much more suggestive in mathematical statistics. The value of the correlation coefficient is in the dependency pairs (x_i, y_i) with the distribution of values in rectangular (XOY) references [2]. It is calculated the simple ratio of correlation (Rx,y) taking into account the multiple ratio of correlation [10]:

$$R_{y(x1...xn)} = \sqrt{1 - \frac{\sum_{i=1}^{k}\left(y - y^{*}_{x1...xn}\right)^2}{\sum_{i=1}^{k}\left(y_i - \bar{y}\right)^2}} \quad (13)$$

Rx,y is approximately equal with the simple coefficient of correlation r. To confirm the linearity of the connection, the following relation must be met:

$$\left| r_{x,y} \right| = R_{x,y} = 0.85 \quad (14)$$

It follows that a direct linear connection between two variables: the speed of the cooling regime (VR) and a characteristic of plasticity (A5) exists.

Conclusions

The experimental program shown that the plasticity characteristics differ appreciably according to process parameters (for example, VR). The microstructures show that different cooling regimes determine changes in the structure of the steel and modify the crystalline grain size. The elongation of break (A5) of the steel during the traction tests increases when the speed of the cooling process is higher.

The simple correlation coefficient is positive: r x, y > 0 and it shown that a direct connection between the variables (VR and A5) exists. This result indicates the correlation, a direct connection between these two variables. This confirmation was made statistically-using the linear unifactorial regression. The correlation is positive because the graph of correlation is represented by a line ascending and is strong enough because the points are close. This work proved that a linear correlation between the variables exists.

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