Improvement of the Properties Through Monitoring of the Cooling Regimes Applied to Steel for Metal Sculptures

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This work proposed to achieve a statistical analysis and studies the possibility to improve the properties of steel used for elements of metal structures subjected to small requests such as: ornamental elements, metal sculptures, balustrades. An important influence factor is the cooling speed value after heating treatment. It is important to be chooses the optimal cooling regime because the steel was laminated at high temperature or, the steel was heated at high temperature after lamination process. There were considered three groups of samples of the steel, each group had eight samples. Three different mediums for directing of the cooling process were considered and the properties of the steel have been modified. After an experimental program, the values obtained were used to determine a correlation between these variables through an empirical study. A causal connection between two variables such as: the cooling speed (VR) and the hardness of the steel (HB) exists. The main problem of any regression model is to determine the model parameters. This operation can be performed using the least squares approximation method. This paper try to demonstrate that the linear model of unifactorial regression, commonly used in Economics, has applications in the Engineering of the steel.

Keywords: steel; properties; monitoring; correlation; statistical model

This study aimed to identify the best cooling regimes after heat treatment applied to steel used for ornamental elements, metal sculpture or for other elements of metal structures subjected to small requests, which are studied in correlation with the composition of iron artifacts [1-4]. This work wants to find a connection between cooling technological parameters and the hot laminated steel properties and tries to demonstrate that the method of least squares and, respectively, the linear model of unifactorial regression commonly used in Economics has applications in the Engineering of steel. This kind of statistical model can predicts the evolution of the properties of the steel depending by the cooling speed (VR) after heating. Thus, a statistical model was made to investigate the behavior of the steel versus the cooling conditions and the correlation between the cooling speed, structure and properties.

If we study the literature [5, 6], a steel with a low carbon in composition, for example, one steel with 0.05% C, 0.18% Mn, 0.012% Si, is intercritically annealed at temperatures 750, 775 and 800°C [6]. The equilibrated alloys of different amounts of austenite with varying carbon contents are quenched by immersing in iced water [7-10]. The same alloys are sub-critically annealed at 675°C and 700°C for varying periods of times. To realize the sub-critically anneal for alloy samples it is necessary to quenched this alloy with cooling in iced water. The main structural changes that can be obtained through a hot rolling (a hot plastic deformation) of the steel with a low carbon content are: the compacting of the material and the covering of the gaps (murmurs) from casting; the crumbling of the crystalline grain, the forming of the structure in strings that 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.

From the point of view of microstructural aspects, at a sub-cooling of austenite from an eutectoid steel up to 240°C the mobility of carbon atoms is close to zero, having the transformation of austenite without diffusion. In this case, for an eutectoid steel, it's changed just the type of the network crystalline $\gamma \rightarrow \alpha$ and the entire amount of carbon dissolved in network fully austenite remains in the ferrite network even if the concentration of carbon in ferrite does not exceed 0.006% at room temperature, resulting a interstitial supersaturated solid solution by carbon in Feα, called Martensite. The degree of supersaturation in ferrite (F) together with carbon content in martensite (M) varies with the process parameters. The martensite was found to be highly dislocated as lattice (needle) invariant deformed and the hardness test results shown that the hardness values for different phases differ appreciably with the process parameters [6]. Major microstructural parameters which determine the mechanical properties of this class of steel are the size and the shape of ferrite grains which- in general- constitute it microstructure [6, 11-13].

For steels with 0.11% C, 0.48% Mn, 0.24% Si, the microstructural parameters which determine the mechanical properties of this class of steel are the size and the shape of pearlitic and ferritic grains which -in general- constitute its microstructure. These types of steels, for metal sculptures and machine building, for elements of metal structures subjected to small requests, are used current without chemical treatments. The steel with low carbon has high plasticity properties below 550°C, the thermal stresses will not leads to the formation of cracks. Damage in the case of materials means the progressive or sudden deterioration of their mechanical strength due to loading, thermal or chemical effects [14-17]. .It is important to know how it is possible to improve the properties of the steels [18, 19]. 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

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Table 1
CHEMICAL COMPOSITION OF THE STEEL

Steel grade/AISI/SAE/DIN 10025	C (%)	Mn (%)	Si (%)	P (%)	S (%)	Al (%)
OL 37/ S284 Gr D (Fe 360-D1) Amount	0.11	0.48	0.24	0.01	0.01	0.0038

Table 2
INFLUENCE OF THE COOLING CONDITIONS ON THE MECHANICAL PROPERTIES OF THE STEEL [22]

Cooling conditions	Initial temperature [°C]	Ψ [%]	HB	Cooling Speed values (VR) - Average [°C /min]	KV (20 °C)	A5 [%]	Rm [N/mm^2]
(1)	1000	74	124	4.67	155.5	43.5	391
(1)	950	74.3	128	5.81	149.5	39.5	399
(1)	900	76	128	6.06	149.5	43	400
(1)	850	77.4	134	7.55	148	37.3	398
(2)	1000	73.8	131	3.63	111	38	388
(2)	950	77.5	140	3.73	80.5	40.2	398
(2)	900	71.8	125	4.23	70.5	39.5	393
(2)	850	77	152	4.37	63.5	41.8	410.2
(3)	1000	73.7	119	17.82	116.5	43.8	415.4
(3)	950	77.4	139	18.6	178.5	37	412
(3)	900	75.2	140	19.13	177.5	40.3	402
(3)	850	78.14	139	19.76	167.5	41.2	400.16

this causal relation between variables it was applied the method of least squares, taking into account a unifactorial regression.

Experimental part

Experimental program

There were considered three groups of samples of the steel and each group had eight samples. Chemical composition of the material was presented in table 1.

Three cooling regimes [22] were applied: (1) cooling regime in normal conditions; (2) cooling regime in metallic box; (3) cooling in air flow (using a jet of air). The initial temperatures were: T1 = 850°C (for the first batch of samples), T2 = 900°C (for the second batch of samples), T3 = 950 °C (for the third batch of samples) and T4 = 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 air, the speed of the cooling will be the highest. Tensile tests related to room temperature were carried out according to ASTM: E8M-11 standard [20, 21], while those related to elevated temperatures were carried out according to ASTM: E21-09 [20-23]. Charpy impact tests for resilience determination were carried out according to ASTM: E23-07ae1 standard [24].The preparation of metallographic specimens was conducted according to ASTM E3-11 standard [18, 25, 26]. All of aforementioned standards can be found in the Annual Book of ASTM Standards (2012).

Results and discussions

The evolution of the cooling speed (VR) depending by temperature and cooling time were represented using the Matlab program. Table 2 presents the cooling speed values for three different cooling conditions and the mechanical properties evolutions corresponding to these cooling regimes. The evolution of the cooling speed (VR), depending by cooling time (T1) and temperature, for three different cooling regimes were represented in figures 1-3.

Simultaneously with the modifications of the cooling process, the properties of the steel will be changed.

For example, the hardness of the steel increases when the speed of the cooling process has a higher value, considering the initial temperature as 1000°C (figs. 4, 5 and 6).

According with table 2 and studying the figures 4 - 8, the cooling in metallic box determines a low resilience. In this case, the speed of the cooling regime has the lowest values and the hardness has the best values. The cooling in air flow process (3) determines better values for cooling speed and

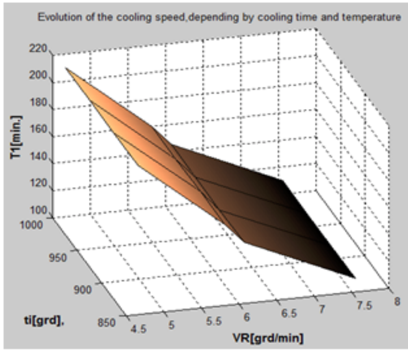

Fig. 1. Cooling speed (VR) versus cooling time (T1) and temperature (ti), for normal conditions (1)

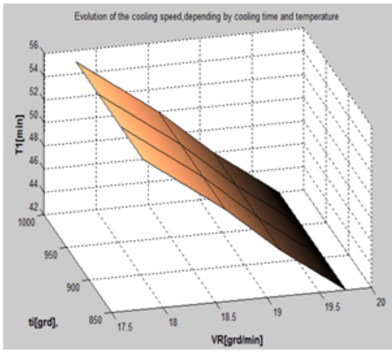

Fig. 2.Cooling speed (VR) vs. cooling time (T1) and temperature (ti), for cooling in jet of air (3)

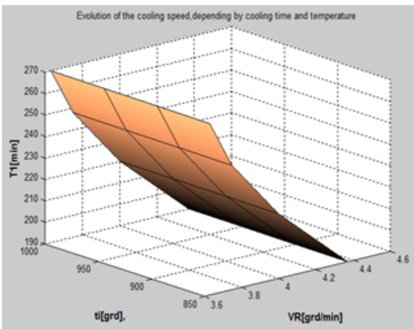

Fig. 3. Cooling speed (VR) vs. cooling time (T1) and temperature (ti), for cooling in metal box (2)

better values for resilience and hardness. For hardness (HB), the best results were obtained in the case of cooling in air flow (in jet of air) from 850 and 950°C (initial temperature) and in the case of cooling in metallic recipint from 850°C initial temperature. Thinning of the samples ψ (Z) during the tensile tests has the best values in the case of the initial temperature by 850°C (fig. 7).

In figures 8 and 9 were presented some microstructural aspects of the steel according to initial temperature and cooling speed [22]. Each cooling regime changes the grain size or the mechanical mixture ratio.

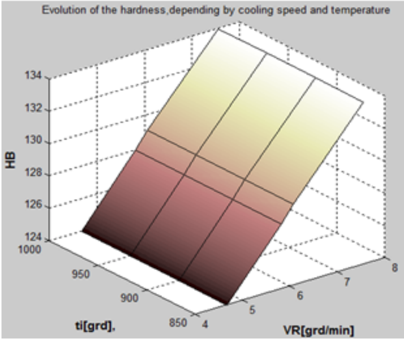

Fig. 4. Hardness (HB) vs. cooling speed (VR) and temperature (ti), for normal conditions (1)

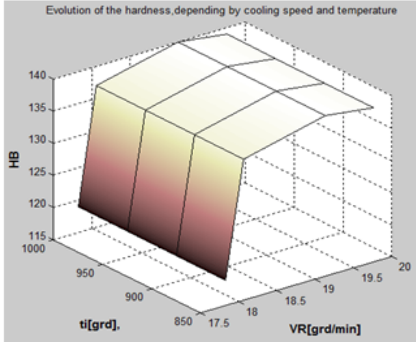

Fig. 6. Hardness (HB) vs. cooling speed (VR) and temperature (ti), for cooling in metallic Box (2)

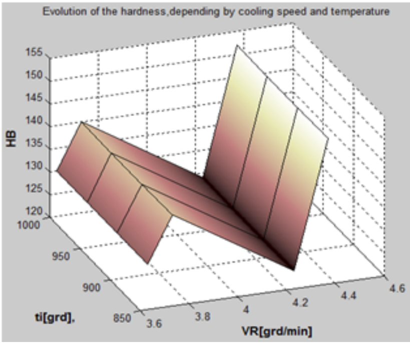

Fig. 5. Hardness (HB) vs. cooling speed (VR) and temperature (ti), for cooling in jet of air (3)

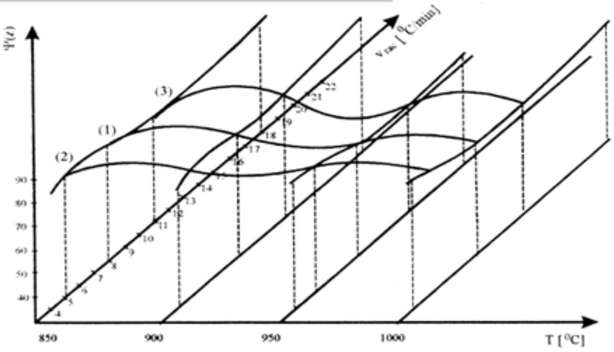

Fig. 7. Thinning of the samples (Z) during the tensile tests

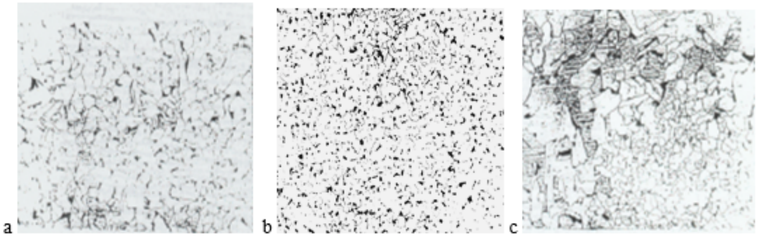

Fig. 8. Microstructural aspects in the case of cooling from the initial temperature T1 = 900°C: a) cooling in metallic box (P/F = 10% /90%, size 4/5) 100× Nittal Atack 2%; b) cooling in normal condition (P/F = 5%/95%, size 7/8) 100× Nittal Atack 2%; c) cooling in jet of air (P/F = 10%/90%, size7/4) 100× Nittal Atack 2%

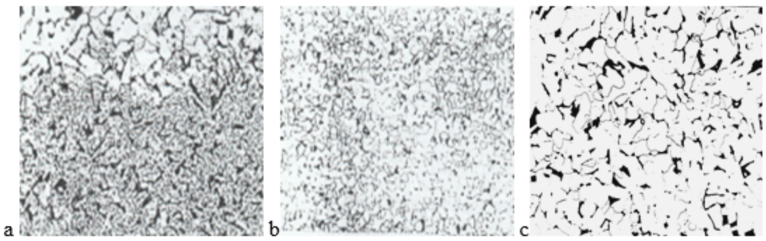

Fig. 9. Microstructural aspects in the case of cooling from initial temperature T1 = 1000°C: a) cooling in jet of air (P/F = 20% /80%, size 5/9) 100×, Nittal Atack 2%; b) cooling in normal conditions (P/F = 10% /90%, size 3/4) 100× Nittal Atack 2%; c) cooling in metallic box (P/F = 10% /90%, size 4/4) 200×, Nittal Atack 2%

Pearlite zone has lamellar aspect being a mechanic mixture with cementite (11…12%) in the ferrite mass. The distance between pearlite lamella depends by the sectional angle on metallographic plan. The real distance is visible just in the moment when the sectional plan is perpendicular on the lamella plan. The pearlite lamella can be observed for large images (>500×). On Nittal Atack (2%), ferritic grains are dissolved and the cementite (Fe_3C_{III}) remains on relief. The steels with 0.1…0.4% C have ferritic polyhedric grains and pearlite (P) in their structures. Cementite can't be observed very well in this case.

Analytical Methods

Adjusted values of the resulting features

For an initial temperature Ti = 900°C, the cooling speed values for these three different cooling regimes were presented in table 3 [22].

In figure 10 was represented the evolution of the hardness of the steel, cooled from 900°C, versus the type of the cooling regime.

To determine the model parameters can be applied the least squares approximation method. It starts from the regression equation of a simple linear model. For example, to prove the causal relation between the cooling speed (VR) and the hardness of the steel (HB) in the case of the initial temperature Ti = 900°C, resort to statistical methods for checking the next assumption: We assume that there is a causal relation between the independent variable *VR* and a dependent variable *HB* and between these variables should be a direct connection.

Application of analysis model of regression and the correlation implies some steps [27]. For the first step, it is necessary to make 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 HB (the hardness) will be the dependent variable *y* (the efficient variable, experimental obtained). We consider HB = f (VR). The second step means to find the existence of the connection between *x* and *y*. Third step establish the mathematical form of the connection: the development

Table 3
HARDNESS RESULTS OBTAINED FOR COOLING FROM THE INITIAL TEMPERATURE T1 = 900°C

Speed of cooling VR [°C /min]	HB	Cooling regime	Code samples
4.23 (cooling regime in metallic box)	125	(2)	1.7
6.06 (cooling regime in normal conditions)	128	(1)	1.3
19.13 (cooling regime in jet of air)	140	(3)	1.12

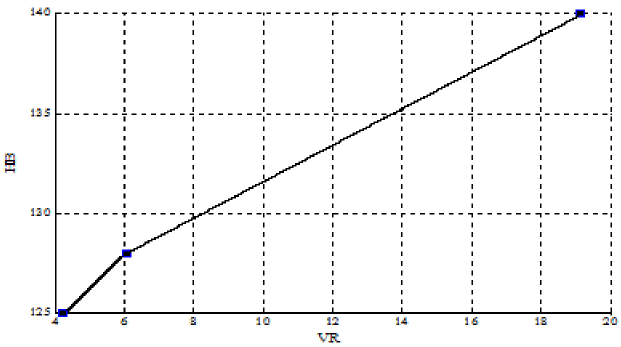

Fig. 10. Variation of the hardness (HB) according to cooling speed (VR)

of the regression equation corresponding to this regression model. The Method of least squares assumes the minimization of the following function [27-30]:

$$F(\hat{a},\hat{b}) = \min\sum_{t=1}^{n}(y_t - \hat{y}_t)^2 = \min\sum_{t=1}^{n}(y_t - \hat{a} - \hat{b}x_t)^2 \quad (1)$$

A minimum condition of this function implies the system of two equations with two unknowns [27, 28, 32]:

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

$$\hat{a}\sum_{i=1}^{n} x_i + \hat{b}\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_i y_i, \quad (3)$$

For this case, n = 3. One can write the following system of equations (4):

3×a+ b×(4.23 + 6.06 + 19.13) = 125 + 128 + 140 = 393
a×(4.23 + 6.06 + 19.13) + b x 420.57 = 775.68 + 528.75 + 2678.20 = 3982.63 (4)

The system of equations has the following results: b = 0.9738 > 0 and a = 121.45.

The final equation is:

$$y = 0.9738x + 121.45, \quad (5)$$

were y is the adjusted value of the resulting features.

In figure 11 was represented the correlation between x and w, were w is the adjusted values for resulting feature. It is estimated that the bond between these two variables (VR and HB) is represented by the equation of straight line.

Table 4
ADJUSTED VALUES FOR RESULTING FEATURE $\hat{y}$

x	Ŷ
4.23	125.5691
6.06	127.3512
19.13	140.07878

Table 5
VALUES COMPARED

ŷ	ŷ − y
125.5691	0.5691
127.3512	0.3512
140.07878	0.07878

On the base of the regression equation (5) were calculated the adjusted values of the characteristic resulting.

Parametric method of measuring the intensity of connections between phenomena

Characterization of the connection intensity between two variables using the correlation coefficient $r_{x,y}$ and the correlation ratio were made with the following relations, according to [31]:

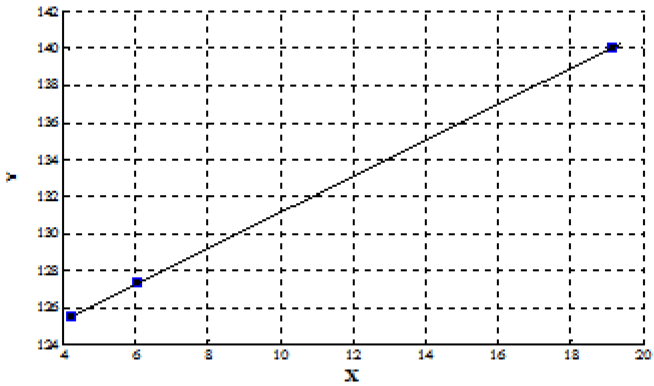

Fig. 11. Graphic representation for equation $\hat{y} = 0.9738\,x + 121.45$

$$\bar{y} = n^{-1}\sum x_i \cdot y_i, \quad (6)$$

The above relation, for *covariance coefficient*, can be written in the following form [28]:

$$M(x \cdot y) = n^{-1}\sum_{i=1}^{n} x_i y_i, \quad (7)$$

for n = 3, $\bar{y}$ = M(x y) = 3982.63/3 = 1327.54

The simple correlation coefficient "r" will be, according to Literature [27, 28]:

$$r = \frac{n\sum x_t y_t - \left(\sum x_t\right)\left(\sum y_t\right)}{\sqrt{n\sum x_t^2 - \left(\sum x_t\right)^2} * \sqrt{n\sum y_t^2 - \left(\sum y_t\right)^2}} \quad (8)$$

After calculation, we obtained the following result:

r = 385.83 / 386.98 = 0.99

This result determines the correlation, a direct connection between these two variables considered (VR and HB).

Theoretically, if the value is closed to 1, a very good connection between the variables exists (if 0.95 ≤ r ≤ 1). In this case, we can talk about a relative deterministic connection because $r_{x,y}$ = 0.99 and it is a value which is very close by 1. For the interpretation of nonzero values for coefficients of correlation, an explanation graphics is much more suggestive in mathematical statistics [22, 32].

The value of the correlation coefficient is in the dependency pairs (x_i, y_i) with the distribution of the values in a rectangular XOY references.

The simple ratio of correlation (Rx,y) [33] was calculated taking into account the multiple ratio of correlation.

$$R_{y(x1\ldots xm)} = \sqrt{1 - \frac{\sum_{i=1}^{k}(y_i - y^{*}_{x1\ldots xm})^2}{\sum_{i=1}^{k}(y_i - \bar{y})^2}} \quad (9)$$

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:

$$|r_{x,y}| = R_{x,y} \quad (10)$$

In our case,

$$|r_{x,y}| = R_{x,y} = 0.99 \quad (11)$$

The obtained value is very close to 1. Mathematically and graphically was demonstrated that between these variables – initially considered – a strong connection exists. There is a direct relation of interdependence and we can talk about a relative deterministic connection. The evolution of the properties of the steel depends by the cooling speed values [34-36].

Conclusions

This work shown that the method of least squares and, respectively, the linear model of unifactorial regression commonly used in Economics has applications in the Engineering of the steel.

It has been confirmed statistically the direct linear connection between two variables: the Cooling speed regime and the hardness of the steel, for an initial temperature T1 = 900° C.

The correlation is positive because the graph of correlation is represented by a linear ascending. It is a linear correlation.

In this case, we can talk about a relative deterministic connection between the cooling speed and the hardness of the steel because $r_{x,y} = 0.99$. This value is very close to 1.

The hardness test results have shown that the hardness values differ appreciably according to process parameters (for example, VR). Different cooling regimes determine changes in the structure of the steel and modify the crystalline grain size.

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