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STATISTICAL CORRELATIONS BETWEEN CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF A516 GRADE 65 STEEL

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ABSTRACT

In order to respond to required demands associated to certain operation conditions, the steels used in petroleum, petrochemical and chemical processing industries must have significant improved mechanical properties. These can be obtained by constant monitoring and controlling of parameters of steelmaking process. The determining factors responsible for improving the mechanical properties of steel are chemical composition, purity and the technological parameters. The injection of an inert gas or by vacuum exposure is effective in reducing non-metallic inclusions and for chemical composition control. These treatments are comprised in the secondary metallurgy and require special installations. It is cheaper to create a modeling tool that can be used for the prediction of mechanical properties, directly in the steel production process by variating its chemical composition. In this paper, by using the linear regression technique, the relationships between certain mechanical properties and the chemical composition of steel A516 Grade 65 have been determined.

KEYWORDS: steel, mechanical characteristics, chemical composition, statistical correlation

1. Introduction

In standard specification, A516 steel, with grades 55, 60, 65, and 70, refers to a range of steels used to produce pressure vessels [1-4]. These steels are mainly used to manufacture pressure vessels and boilers for the petrochemical industry that work at moderate and lower temperature. The steels have good weldability and excellent notch toughness. A516 Grade 65 has greater specified tensile and also higher yield strength. The chemical composition of steel plates may vary for different products thicknesses so as to meet particular mechanical properties requirements. These ask for high levels of purity and the precise control of chemical composition. The mechanical properties are in direct relation with parameters of steel produced in traditional furnace. Also, special processing of steel bath, like the vacuum degassing for control of inclusions and chemical composition, is a solution to obtain improved mechanical properties [5-7]. Today, there are many techniques available in the steelmaking industry for correction and control of the characteristics of non-metallic inclusions. The secondary treatment of melted steel is carried out in special metallurgical installations with supplementary costs [8]. It is cheaper to create a modeling tool able to predict the mechanical properties of steels directly, during the steel making process by varying their chemical composition [9-11]. In this paper the linear regression technique was used to determine relationships between certain mechanical properties and the chemical composition of steel A516 Grade 65.

2. Method and materials

Sample size of industrial heats of A516 Grade 65 steel were made using the traditional method in an electric arc furnace. All steels were poured into ingots and then were rolled into slabs than finally as plates. The material properties were improved by normalization treatment, applied in accordance with the specifications required for this steel. The data regarding the mechanical properties and chemical composition of steel from the monitored heats were obtained from the laboratory of a steel integrated plant.

3. Experimental data and discussion

The data set comprising measurements of the parameters for 93 sample from 31 industrial heats of A516 Grade 65 steel were statistically processed. The variables taken into consideration concerned the element content: carbon, manganese, phosphorus, sulfur, silicon and nickel. Figure 1 below shows statistical distributions of data regarding chemical composition of steel obtained in electric arc furnace.

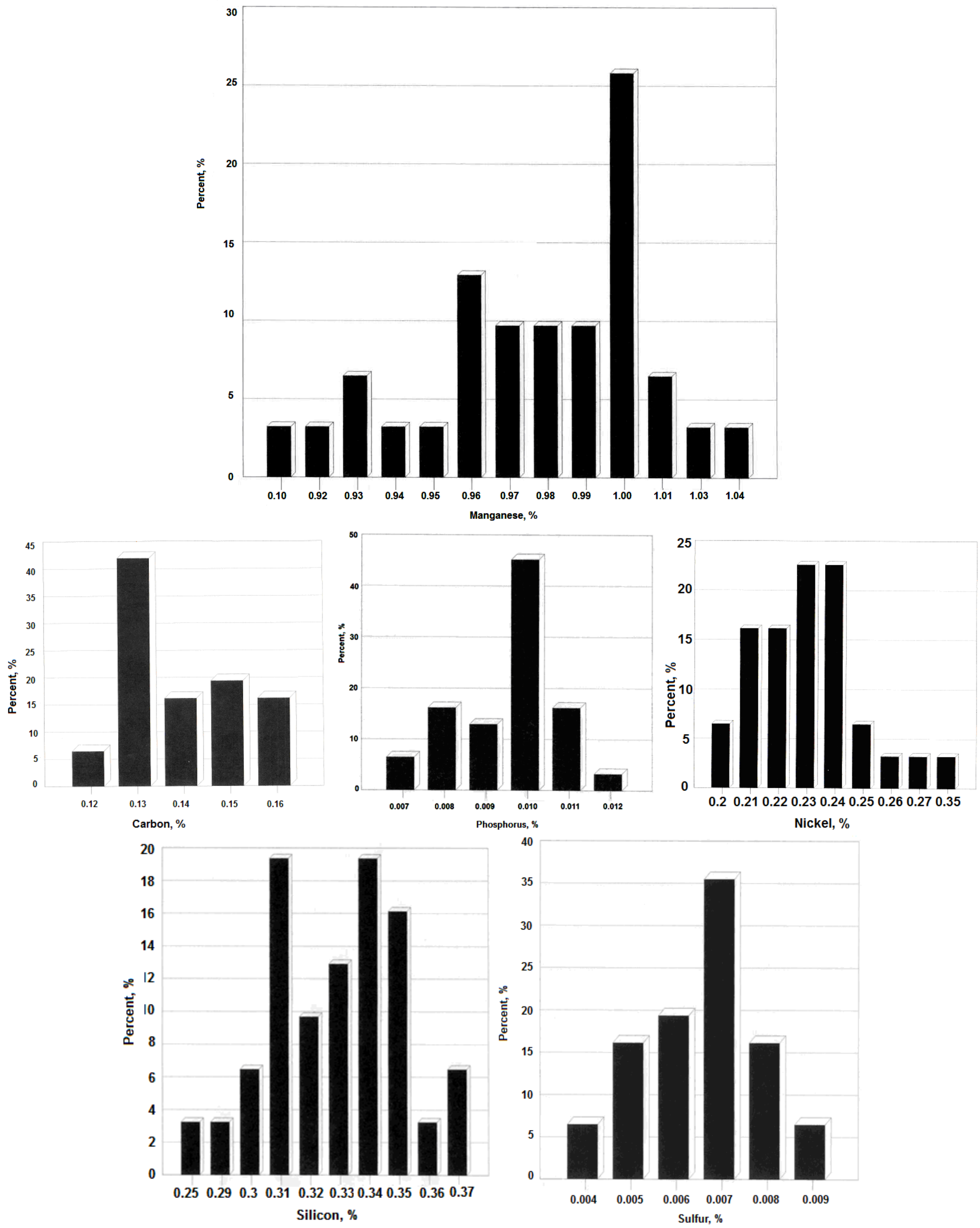

Fig. 1. *Distribution of elements content in the steel*

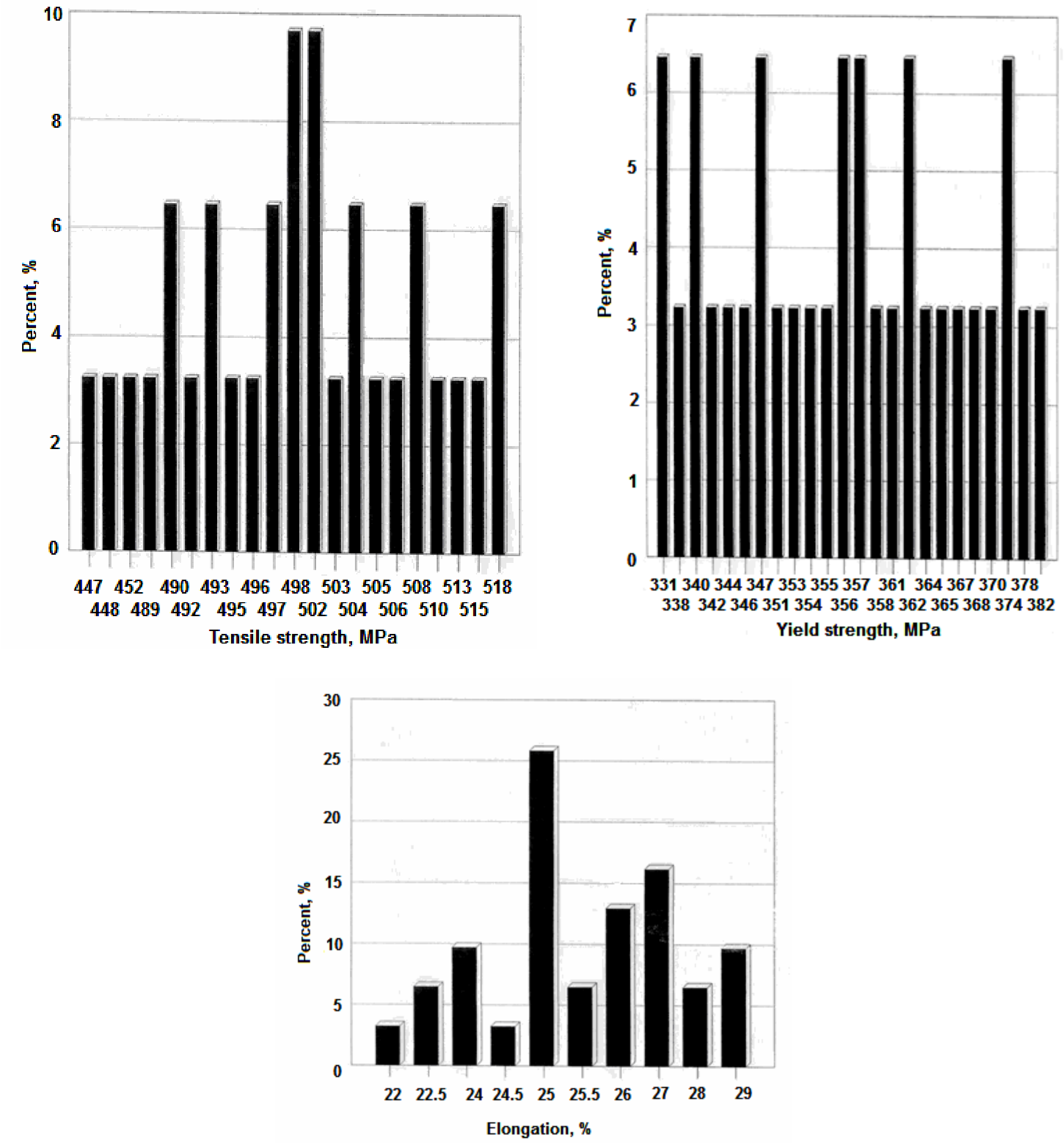

Fig. 2. *Distribution of mechanical properties of monitored steel (measured data)*

The distribution of the data used for the mechanical properties of steel from the monitored heats are shown in Figure 2.

The data calculated for correlation and regression analysis are listed in Table 1. There, ″Mean″ is the arithmetic mean of distribution and ″Standard_dev″ is the standard deviation of distribution.

Regarding the range (minimum, maximum or the smallest and largest content of element), carbon varied from 0.12% to 0.16%, manganese from 0.92% to 1.04% (with the exception of a single value, namely 0.1%, which in fact also explains the greater standard deviation of 0.025 from Table 1), phosphorus from 0.007% to 0.012%, sulfur from 0.004% to 0.009%, silicon from 0.25% to 0.37% and nickel from 0.2% to 0.35%. Equally, the tensile strength varied from 447 MPa to 518 MPa, yield strength from 331 MPa to 382 MPa and elongation from 22% to 29%.

In order to determine the correlation between the final elements content of the steel analyzed and their mechanical properties we determined the individual correlation coefficient between the parameters analyzed. The sign (+) or (-) in front of the coefficient indicates direct or inverse relationship between parameters.

***Table 1.** Statistical data for correlation and regression analysis*

Parameter	Mean	Dispersal	Standard_dev
Carbon, %	0.140	0.012	0.000
Manganese, %	0.952	0.158	0.025
Phosphorus, %	0.010	0.001	0.000
Sulfur, %	0.007	0.001	0.000
Silicon, %	0.328	0.025	0.001
Nickel, %	0.233	0.027	0.001
Tensile Strength, MPa	496.484	17.387	302.314
Yield Strength, MPa	355.806	13.005	169.124
Elongation, %	25.694	1.799	3.237

The equation is a function of the range of the chemical composition considered

$$Y = f(x_1, x_2, \dots x_n)$$

were $x_1, x_2, \dots x_n$ are input random variables.

The linear relation between chemical composition of steel and each mechanical property of A516 Grade 65 steel are described as the equation

$$Y_{1\dots3} = f(c_0+c_1 x_1+c_2x_2+c_3x_3+c_4x_4+c_5x_5+c_6x_6)$$

where Y_1 is tensile strength (MPa), Y_2 yield strength (MPa) and Y_3 elongation (%), while $c_0 \dots c_6$ are regression coefficients corresponding to the chemical element from steel, and $x_1 \dots x_6$ are, respectively, the content of C, Mn, P, S, Si and Ni.

Finally, we obtained the following results for steel A516 Grade 65:

$Y_1 = f(x_1, x_2, x_3, x_4, x_5, x_6) = 553.937 - 71.658 * (\%C) + 1.423 * (\%Mn) - 1553.289 * (\%P) + 49.549 * (\%S) - 87.86 * (\%Si) - 23.277 * (\%Ni)$; $c_0 = 553.937$, $c_1 = -71.658$, $c_2 = +1.423$, $c_3 = -1553.289$, $c_4 = +49.549$, $c_5 = -87.86$, $c_6 = -23.277$ and $R^2 = 0.3015$

$Y_2 = 371.686 - 66.142 * (\%C) + 4.486 * (\%Mn) - 1859.868 * (\%P) + 1453.264 * (\%S) - 23.565 * (\%Si) + 21.777 * (\%Ni)$; $c_0 = 371.686$, $c_1 = -66.142$, $c_2 = +4.486$, $c_3 = -1859.868$, $c_4 = +1453.264$, $c_5 = -23.565$, $c_6 = +21.777$ and $R^2 = 0.4853$

$Y_3 = 28.219 - 7.694 * (\%C) - 4.458 * (\%Mn) + 560.673 * (\%P) + 13.628 * (\%S) + 5.886 * (\%Si) - 19.75 * (\%Ni)$; $c_0 = 28.219$, $c_1 = -7.694$, $c_2 = -4.458$, $c_3 = +560.673$, $c_4 = +13.628$, $c_5 = 5.886$, $c_6 = -19.75$ and $R^2 = 0.36678$.

The coefficient of R^2 determination (square multiple correlation coefficient) which has values within the range [0,1] was calculated. The values of R^2 can be interpreted as meaning that about 30%, 48.5% and respectively 367% of the variation of Y (tensile strength, yield strength or elongation) can be determined by the independent variables x (content of C, Mn, P, S, Si and Ni).

The ductility, as well as weldability properties of the steel decrease if the amount of carbon increases. Manganese has effects similar to those of carbon and also it is necessary in hot rolled steels for its role to form combinations with oxygen and sulfur. Phosphorus is generally regarded as an undesirable impurity because of its embrittling effect. Also, sulfur is normally regarded as an impurity and has an adverse effect on impact properties when steel is high in Sulphur and low in manganese. Elements such as silicon and nickel were also found to be beneficial to the strength properties. Silicon increases strength and hardness but to a lesser extent than manganese. The decrease of ductility could induce cracking problems. Ni is added to steels to increase hardenability. Nickel enhances the low temperature behavior of the material by improving the fracture toughness. The weldability of the steel is not decreased by the presence of this element. The nickel drastically increases the notch toughness of the steel [12].

From the regression analysis, carbon was found to reduce ductility (the elongation at fracture is a measure of ductility of the steel), which is probably related to the pearlite content and the strain hardening rate. Analyses of equations show that manganese improves the tensile strength and yield strength, but have an adverse effect on ductility. This influence is caused by grain refinement and by hardening of solid solution. Also, this effect can be put in relation with the role of manganese as deoxidiser in the steel bath. However, it adversely affects elongation. Silicon has negative effect on steel strength but not on elongation. The alloying of steel with nickel was beneficial to yield strengthening and harmful for tensile strength and elongation.

The effects of the monitored elements can be explained by the following considerations. The regression equations have derived from the available data and so, they have statistical significance only for the samples that were utilized. The equations are functions of the range of chemical composition considered. These linear equations enable the predictions of mechanical properties for steel A516 Grade 65 at the production of plates with variations in their chemical composition.

The accuracy of the regression analysis could be affected by the low number of data processed. Consequently, the regression analysis carried out based on available data is of lower significance level and can be misleading. They must be substantially improved by increasing the number of data and by using a relatively largest range of values for parameters.

4. Conclusions

Mechanical properties of steel plates are determined firstly by the chemical composition of steel. To obtain steels of adequate strength levels, the elements content can be constantly monitored and controlled. By means of regression analysis were obtained simple linear equations used to obtain some mechanical properties of steels by variation in chemical composition (C, Mn, Si, S, P, Ni). The relationships between mechanical properties and chemical composition of A516 Grade 65 Steel assist the specialists' control process to choose the optimum conditions during steel production. The statistically significant correlation between the analyzed parameters and the good correspondence with practical knowledge concerning how parameters affect behaviour of steel in service condition, create the suggestion concerning the practical applicability of the developed statistical models.

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