

Regression Analysis of the Mechanical Properties—Composition Dependencies for Cast Low- and Medium-Carbon Steels

Y. Unigovsky

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One of the principal problems in the production of steel castings is the increase in their mechanical characteristics. To ensure their prediction within the frames of the developed mathematical models, it is rather important to derive the dependencies of "composition-property" type. However, the available data either take into account the influence of one of the components only or are contradictory.

In the present paper, on the basis of correlation analysis of the dependencies of tensile properties and impact strength of carbon steels (0.15 to 0.30% C) produced, using basic and acid processes on the contents of five principal components of (C, Si, Mn, S, and P), we have obtained functional relations of the second order, allowing prediction of mechanical properties of steel at constant parameters of heat treatment as early as at the stage of casting and refining. It is established that at certain combinations of components, we observe trends in the "composition-property" dependencies differing from current notions.

Keywords cast low- and medium-carbon steels, mechanical properties

1. Introduction

Changes in the chemical composition of steel within the limits accepted by standards are known to affect significantly mechanical properties of cast and wrought metals.[1,2] However, the available data either take into account the effect of separate components, without any connection with other ones, or are contradictory. Thus, for carbon steels, the impact of carbon has been mainly studied. For instance, the increase in its content in steel from 0.15 to 0.35% after normalizing leads to ultimate tensile strength (UTS) and tensile yield strength (TYS) growth from 450 to 620 MPa and from 250 to 370 MPa, respectively. Elongation and reduction in area are reduced, respectively, from 35 to 25% and from 60 to 40%. Finally, Sharpy V-notch impact energy decreases from 64 to 30 J.[2]

Meanwhile, to predict metal properties at the stage of its casting and refining, it is rather important to have some correlation of the type "tensile properties-steel composition." The present paper is intended to study the dependencies of tensile and impact properties of cast low- and medium-carbon steels on the contents of five principal components: carbon, silicon, manganese, phosphorus, and sulfur. This study is aimed at the development of a mathematical model allowing prediction of, at constant thermal treatment parameters, mechanical properties of steel as early as at the stage of the steel's casting and refining.

Y. Unigovsky, Department of Material Engineering, Ben-Gurion University of the Negev, Beer Sheva, Israel.

2. Experimental Procedure

Steel was produced in electric arc furnaces using acid and basic processes. Deoxidization by silicon and manganese was performed in the furnace and, partially, in the ladle. Aluminum (1 kg/t) was introduced into the ladle. In the case of the acid process, 1 kg/t of silicocalcium alloy (~17% *Ca*) was additionally introduced into the ladle. Castings with the mass of 0.5 to 1 t were poured in on conveyor lines using bottom pour ladles with the capacity of 8 to 10 t. All the castings were normalized at 900 to 930 °C; castings produced by the acid process were also tempered at 650 to −700 °C.

For the regression analysis, we employed the data of 100 heats (50 for each of the methods of steel production). The component contents in steels produced by basic and acid processes varied, respectively, within the following limits (%): 0.22 to 0.33 and 0.15 to 0.30C; 0.33 to 1.05 and 0.45 to 1.38Mn; 0.21 to 0.62 and 0.28 to 0.54Si; 0.017 to 0.047 and 0.022 to 0.056S; and 0.021 to 0.045 and 0.030 to 0.052P. The effect of aluminum on steel properties was not defined. Its total contents in the metal amounted to 0.04 to 0.08%.

The regression analysis was performed by determining coefficients of the equation of the second order:

$$\begin{aligned} Y = {} & a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 \\ & + a_5X_5 + a_6X_1X_2 + a_7X_1X_3 + a_8X_1X_4 \\ & + a_9X_1X_5 + a_{10}X_2X_3 + a_{11}X_2X_4 + a_{12}X_2X_5 \\ & + a_{13}X_3X_4 + a_{14}X_3X_5 + a_{15}X_4X_5 + a_{16}X_1^2 \\ & + a_{17}X_2^2 + a_{18}X_3^2 + a_{19}X_4^2 + a_{20}X_5^2 \end{aligned} \qquad \text{(Eq 1)}$$

where Y is the value of one of the following mechanical properties: UTS, TYS, elongation (δ), reduction in area (ψ), or U-notch impact energy (I) of the acid steel specimens ($r = 1$

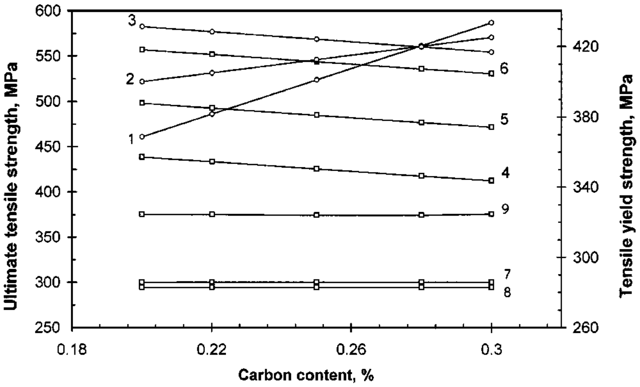

Fig. 1 UTS (1 to 6) and TYS (7 to 9) of the acid (4 to 9) and basic (1 to 3) steels vs carbon and silicon contents. [Si], %: 0.2(1, 4, 7), 0.4(2, 5, 8), and 0.6(3, 6, 9)

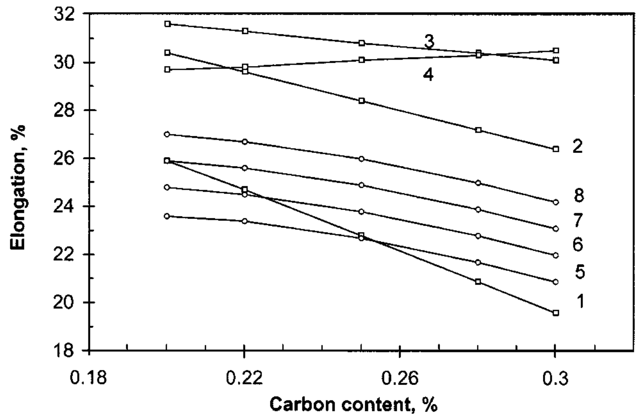

Fig. 3 Elongation of the acid (1 to 4) and basic (5 to 8) steels vs carbon and silicon contents. [Si], %: 0.2(1, 5), 0.3(2, 6), 0.4(3, 7), and 0.5(4, 8)

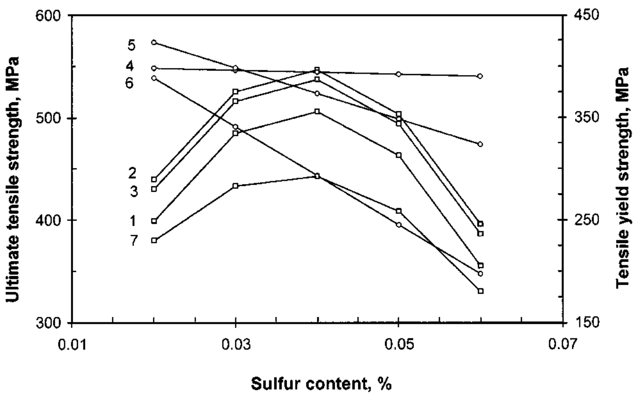

Fig. 2 UTS (1 to 6) and TYS (7) of the basic (4 to 6) and acid (1 to 3, 7) steels vs sulfur and phosphorus contents. [P], %: 0.03(1, 4), 0.04(2, 5), and 0.05(3, 6) (TYS-values are not dependent on the phosphorus content)

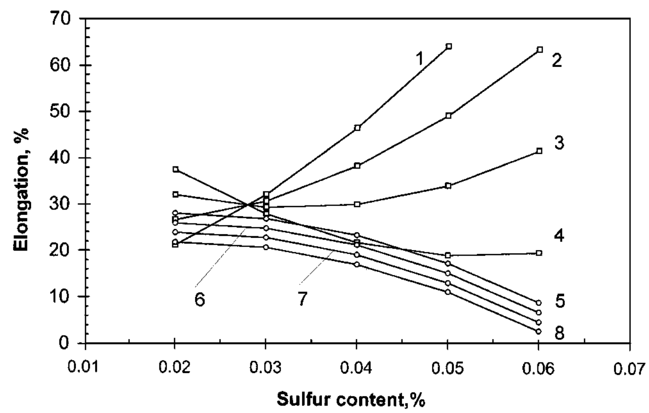

Fig. 4 Elongation of the acid (1 to 4) and basic (5 to 8) steels vs sulfur and phosphorus contents. [P], %: 0.02(1, 5), 0.03(2, 6), 0.04(3, 7), and 0.05(4, 8)

mm, and $F = 8 \times 10$ mm^2) at the testing temperatures 20 °C and −60 °C; X_1, X_2, X_3, X_4, and X_5 are the carbon, silicon, manganese, sulfur, and phosphorus contents in steel, respectively. Correlation coefficients R were computed as well.

3. Results

We present below correlation equations relating tensile and impact properties of steels to their composition. We have not presented above TYS dependencies for basic steel and impact strength of acid steel at −60 °C, because we have obtained low percentages of multiple correlation for these.

To illustrate the effect of separate components on the properties of steel according to Eq 2 to 9, computations are carried out for a specified basic composition of metal, %: 0.25C, 0.4Si, 0.8Mn, 0.03S, and 0.03P. Concentrations of the components varied within the following limits, %: (0.2 to 0.3)C, (0.2 to 0.6)Si, (0.02 to 0.06)S, and (0.02 to 0.06)P. Computation results are presented in Fig. 1 to 8.

3.1 Ultimate Tensile Strength and Yield Strength, MPa

$$(\mathrm{UTS})_a = 947 - 8898.8[\mathrm{C}] + 2228.2[\mathrm{Si}] + 86{,}157[\mathrm{C}][\mathrm{P}] + 201{,}680[\mathrm{C}][\mathrm{S}] - 64{,}399[\mathrm{Si}][\mathrm{S}] - 249{,}780[\mathrm{P}]^2 - 322{,}090[\mathrm{S}]^2, \quad R = 0.868 \qquad \text{(Eq 2)}$$

$$(\mathrm{UTS})_b = -790.5 + 4449[\mathrm{C}] + 57.7[\mathrm{Mn}] + 40{,}414[\mathrm{P}] - 3850.7[\mathrm{C}][\mathrm{Si}] + 16{,}656[\mathrm{Si}][\mathrm{S}] - 80{,}591[\mathrm{C}][\mathrm{P}] + 19{,}169[\mathrm{Si}][\mathrm{P}] - 229{,}120[\mathrm{S}][\mathrm{P}] - 297{,}820[\mathrm{P}]^2, \ \mathrm{MPa}, \quad R = 0.727 \qquad \text{(Eq 3)}$$

$$(\mathrm{TYS})_a = 479.5 - 2489.7[\mathrm{C}] + 60.8[\mathrm{Mn}] + 83{,}083[\mathrm{C}][\mathrm{S}] - 11{,}313[\mathrm{Si}][\mathrm{S}] + 544.8[\mathrm{Si}]^2 - 218{,}710[\mathrm{S}]^2, \quad R = 0.649 \qquad \text{(Eq 4)}$$

The growth of carbon concentration in basic steel from 0.2 to 0.3% increases UTS values at silicon contents up to 0.5%.

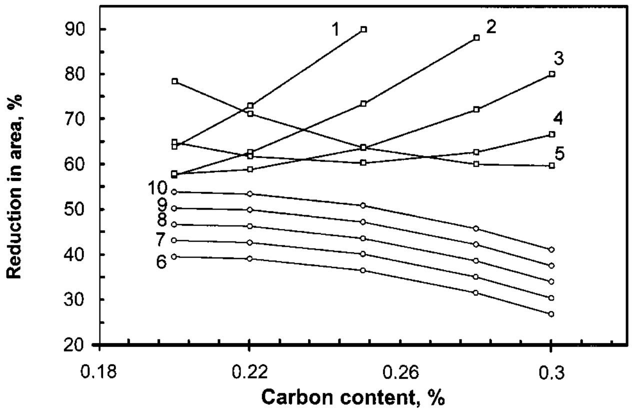

Fig. 5 Reduction in area of the acid (1 to 5) and basic (6 to 10) steels vs carbon and silicon contents. [Si], %: 0.2(1, 6), 0.3(2, 7), 0.4(3, 8), 0.5(4, 9), and 0.6(5, 10)

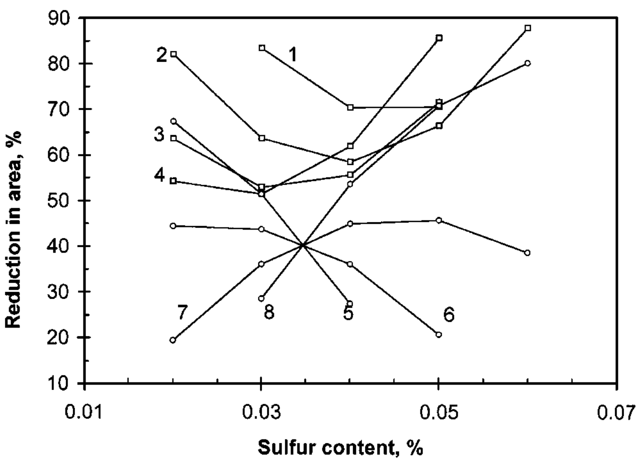

Fig. 6 Reduction in area of the acid (1 to 4) and basic (5 to 8) steels vs sulfur and phosphorus contents. [P], %: 0.02(1, 5), 0.03(2, 6), 0.04(3, 7), and 0.05(4, 8)

With growing concentration of the latter, carbon influence on UTS weakens (Fig. 1). As for acid steel, carbon exerts slight influence on UTS at any concentration of silicon and does not affect TYS value.

Silicon content growth from 0.2 to 0.6% increases UTS of both acid and basic steels, and its growth from 0.3 to 0.6% increases TYS of acid steels.

Sulfur content growth from 0.02 to 0.06% increases UTS of basic steels at $P < 0.03\%$ and decreases UTS at $P \geq 0.03\%$. With sulfur content growth in acid steels from 0.02 to 0.06%, maximum UTS and TYS values are observed at S percentage of 0.04% (Fig. 2).

Phosphorus reduces UTS of basic steel with its content growth above 0.03% (Fig. 2).

3.2 Elongation (δ), %

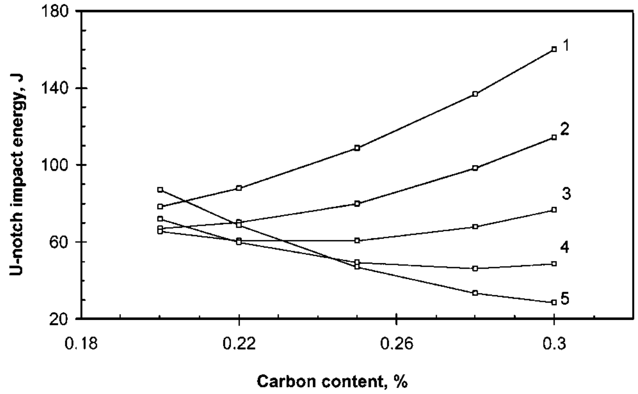

Fig. 7 U-notch impact energy of the acid steel vs carbon and silicon contents. [Si], %: 0.2(1), 0.3(2), 0.4(3), 0.5(4), and 0.6(5)

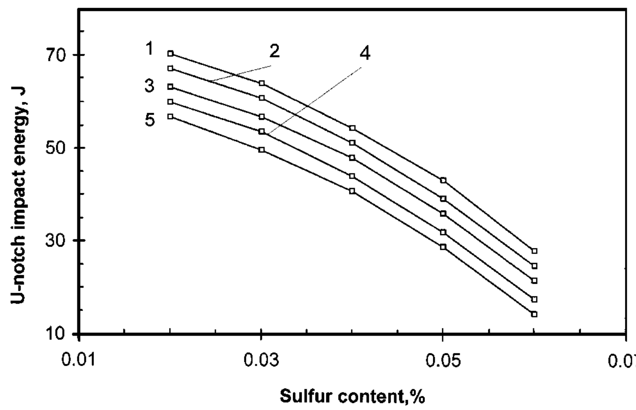

Fig. 8 U-notch impact energy of the acid steel vs sulfur and phosphorus contents. [P], e: 0.02(1), 0.03(2), 0.04(3), 0.05(4), and 0.06(5)

$$\delta_a = -29.6 + 3380.2[P] + 239.6[C][Si] - 138.9[C][Mn] + 94.9[Si][Mn] - 1847.4[Mn][P] + 2014.5[Mn][S] - 68{,}149[S][P] - 159.2[Si]^2 + 16{,}932[S]^2, \quad R = 0.658 \qquad \text{(Eq 5)}$$

$$\delta_b = 63.5 - 45.1[Mn] - 72.3[Si] + 123.7[Si][Mn] + 1990.2[C][S] - 521.5[Si][P] - 175[C]^2 - 12{,}162[S]^2, \quad R = 0.576 \qquad \text{(Eq 6)}$$

With carbon content growth from 0.2 to 0.3%, the elongation of acid and basic steels decreases at %[Si] of 0.2 to 0.4 and 0.2 to 0.6, respectively (Fig. 3). Elongation values are essentially increased with silicon content growth from 0.2 to 0.6% in basic steel and from 0.2 to 0.4% in acid steel (Fig. 3). Sulfur and phosphorus reduce elongation magnitude in basic steel (Fig. 4). In acid steel, on the contrary, sulfur significantly increases elongation at %[P] = 0.02 to 0.04. At phosphorus content of 0.05%, an increase in %[S] leads to a reduction of acid steel elongation.

3.3 Reduction in Area (ψ), %

$$\psi_a = 227 - 9916.2[S] - 2036.3[C][Si] + 709.8[C][Mn] - 20{,}439[C][P] - 1881.1[Mn][P] + 5991.9[Si][S]$$

$$+ 78{,}429[S][P] + 2165.1[C]^2 + 329.8[Si]^2 - 58[Mn]^2 + 45{,}664[P]^2 + 66{,}378[S]^2, \quad R = 0.633 \quad \text{(Eq 7)}$$

$$\psi_b = 214.7 - 9687.1[P] + 348.4[Si][Mn] - 3602.3[Mn][S] + 18{,}160[C][P] + 3399.1[Mn][P] - 8101.1[Si][P] + 163{,}530[S][P] - 1339.1[C]^2 - 83.7[Mn]^2 - 39{,}730[S]^2, \quad R = 0.716 \quad \text{(Eq 8)}$$

With carbon content growing from 0.2 to 0.3%, the ψ value for basic steel decreases, whereas that of acid steel, on the contrary, grows at %[Si] = 0.2 to 0.4 (Fig. 5). In acid steel containing more than 0.5% Si, ψ decreases with growing %[C]. Silicon increases ψ of basic steel and decreases its value for acid steel containing less than 0.5% Si (Fig. 5). Sulfur significantly decreases ψ values of basic steel at phosphorus concentrations up to 0.03%. At further increase in %[P] value, the dependence of ψ on %[S] for basic steel becomes opposite: sulfur essentially increases ψ (Fig. 6). For acid steels, the dependencies of ψ on %[S] have minima that shift toward lower [%S] values with phosphorus content growing from 0.02 to 0.05%. Meanwhile, phosphorus decreases the reduction in area of acid steel (Fig. 6).

3.4 U-Notch Impact Energy of Acid Steel (I)J

$$I_r = 93.6 - 3496[C][Si] - 21{,}224[C][P] + 12{,}392[Si][P] + 4304.8[C]^2 + 436[Si]^2 - 13{,}208[S]^2, \quad R = 0.684 \quad \text{(Eq 9)}$$

If one knows the impact strength value at room temperature I_r, $I_{-60\,°C}$ values can be obtained by the following equation:

$$I_{-60\,°C} = -0.194 + 0.504(I_r) - 0.022(I_r)^2, \quad R = 0.905 \quad \text{(Eq. 10)}$$

Carbon considerably decreases I_r at silicon contents in steel above 0.4%. However, at lower %[Si] values, I_r − %[C] dependencies become opposite: with %[C] growing from 0.2 to 0.3%, the I_r value grows considerably (Fig. 7). Sulfur and phosphorus decrease I_r (Fig. 8).

3.5 Manganese Effect on Steel Properties

With manganese content growth from 0.2 to 1%, elongation of acid and basic steels grows by approximately 20%. The highest values of acid and basic steels reduction in area are observed at Mn contents of 0.8 to 1.0%. Manganese has no effect on the impact properties of acid steel (plots of respective dependencies for Mn are not presented in order to reduce the volume of the present paper).

4. Discussion

According to the above data, the composition of carbon steels, within comparatively narrow ranges of the changes in the contents of separate components, affects significantly their mechanical properties. Therefore, for instance, the ASTM A 148 standard referring to carbon steel castings for structural applications specifies only maximum concentrations of sulfur and phosphorus (0.06% each) and the values of tensile properties UTS, TYS, δ, and ψ.[1]

Table 1 Recommended ratios of carbon and silicon in acid steel satisfying condition $I_{-60\,°C} \geq 20$ J

Carbon content,%							
0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30
Silicon content (%) more than:					**Silicon content (%) less than:**		
0.27	0.35	0.40	0.45	0.55	0.26	0.32	0.36

Notes: (a) the steel contains, %: 0.04S, 0.04P, 0.4 to 1.2Mn, and 0.04 to 0.08A1 (b) heat treatment—normalizing (900 to 930 °C) and tempering (650 to 700 °C)

As an example of using the obtained regularities, let us determine the silicon content in steel at specified carbon contents before the deoxidization required for obtaining U-notch impact energy value at −60 °C, not below 20 J. According to Eq 10, such $I_{-60\,°C}$ value is achieved at $I_r \geq 20$ J. Solving Eq 9 with respect to carbon and silicon concentrations at given values of $I_r = 20$ J, %[S] = %[P] = 0.04, we obtain a nomograph (Table 1). According to this nomograph, say, in acid steel with 0.22% C, silicon content should be no less than 0.40% (Table 1). Since manganese does not affect the impact strength of steel, its content in carbon steel is usually chosen as 0.8 to 1%, unless the standard in force provides some other value.

The results of computing the dependencies of "property-composition" type show that at certain combinations of the components, one can observe some trends inconsistent with current notions on the character of their effect on the properties of steel. Particularly, as for acid steel, this manifests itself by the increase in elongation (%Si ≥ 0.4), reduction in area (%Si ≤ 0.4), and impact strength (%Si ≤ 04), as well as by a certain decrease in UTS and TYS with carbon content growth from 0.2 to 0.3%. In the case of basic steel containing 0.04 to 0.05% P, ψ growth is observed with sulfur content increasing from 0.02 to 0.03 to 0.04 to 0.06% (Fig. 1, 3, and 5 to 7). The mentioned trends are of a particular nature; apparently, to refine the obtained regularities, additional studies are necessary. Meanwhile, using the obtained dependencies, one can predict mechanical properties of normalized carbon steels. These dependencies form the basis of a database for the development of a mathematical model of controlling the quality of steel castings.

5. Conclusions

On the basis of correlation analysis of the data reflecting the influence of five principal components of carbon steels (carbon, manganese, silicon, sulfur, and phosphorus) on their tensile properties and impact energy, we have obtained functional equations of the second order allowing prediction of mechanical properties of steel at constant parameters of heat treatment as early as at the stage of casting and refining. It is established that a certain combination of components, the dependencies of "property-composition" type may differ from current notions on the character of the effect of these components on the metal properties.

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