Half-hard cast-iron rolls: statistically research on the manufacturing technology for increase their quality and safety in exploitation

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Abstract. The regression analysis provides an opportunity to specify hypotheses concerning the quality assurance of cast–iron rolls, as well as explanatory factors in their manufacturing practice. When the analysis is correctly executed, having on base the statistically valid adjustment, this can produce quantitative effects on the quality assurance process. In the practice of the rolling rolls manufacturing by casting many variables interact with each other simultaneously (the iron properties, the casting equipment and they execution, the casting temperature, the cooling and solidification and so on). Multivariate research and visualization comes to the fore when the engineers have difficulties in comprehending many dimensions at one time, especially in the iron melting and alloying stages. In order to establish the optimal condition for hardness assurance in the cast–iron rolls manufacturing we proposed a statistical modelling study by using the multivariate regression. Our research propose to analyse the half–hard cast–iron rolls, an analysis defined by the statistically analyse of the cast rolls manufacturing technology, using the modelling phenomenon and the mathematical approach. The optimization model is based on industrial data, obtained from half–hard cast–iron rolls. Their analysis shall lead to the optimization pattern, through the prism of the multicomponent correlations, expressed by mathematical formulae.

1. Introduction

The rolls represent the deforming support in the hot rolling process, being among the most expensive parts of the rolling sectors. By coming into direct contact with the hot material and taking over the deformation effort, the rolls are subjected to heavy working conditions (temperature, pressure, friction) [1-7]. In order to withstand the multiple and complex demands to which they are subjected, the requirements imposed on the rolls are resistance to dynamic and static demands, wear resistance in durability conditions and resistance to high temperature [1-7]. In addition, it must ensure satisfactory catching of the laminate and a convenient surface [5], [7].

Some of the conditions imposed are more difficult to achieve. Thus, if the mechanical resistance and the shock resistance are at odds with the wear resistance, a compromise is required that is made according to the specifics of the steel laminates [1-7]. These properties can be obtained by a suitable choice of the material and technology of rolls manufacturing in accordance with their destination [5], [7-24]. The technological manufacturing process of the cast rolls (Figure 1), as well as the quality of material used in manufacturing them, can have a different influence upon their quality and safety in exploitation [1-7].
Within the foregoing compositional ranges, particularly desired combinations of properties can be produced in cast--iron rolls by relatively minor adjustments or corrections in the chemical composition [7-24]. In fact, when it is desired to emphasize properties in the cast--iron rolls, especially the alloying elements (i.e. Nickel |Ni|, Chromium |Cr| and Molybdenum |Mo|) are maintained in the special ranges, in the alloying stages [7-24]. Also, the basic chemical composition (i.e. Carbon |C|, Silicon |Si|, Manganese |Mn|, Phosphorous |P| and Sulphur |S|) can be maintained in the proper ranges, in the melting and alloying stages [7-24]. In the same way, the control of Magnesium |Mg|, necessary to control the occurrence of graphite therein to the spheroidal/nodular form, in accordance with the compositional ranges, is possible in the additional treatment of the roll's destined iron [7-24].

2. Modelling – a key concept

Modelling of iron making process and casting technologies in the cast rolls production can be used to predict the rolls performance and to optimize the combination or ratio of main chemical components during the iron making process (melting, alloying, additional treatments etc.) [7-24]. In this sense, the chemical composition is an important cumulative parameter [7-24]. Therefore, the statistical approach can be used to provide insights into quality control strategies that may improve the hot rolling performance [7-15].

Many studies have been reported on mathematical modelling of cast iron rolls. Our research team developed in the last 20 years a general steady state mathematical model using the multivariate regression analysis for several rolls type (i.e. nodular cast iron rolls [7-19], indefinite chilled cast iron rolls [21], [22], bimetallic cast iron rolls [20] and hyper--eutectoid steel rolls [23], [24]), based on industrial data. The problem of good correlation between the irons chemical composition and the cast iron rolls hardness has been studied for its importance in the assuring the high--qualities rolls and their safety in the rolling mills exploitation [7-22].

Most of the studies reviewed above worked on modelling of cast iron rolls mechanical properties (like hardness) and their safety in exploitation, based on the rolls materials, their chemical composition and the good guidance of the iron making process (melting, alloying, additional treatments etc.) [7-24]. In all the above studies, the combined effect of basic chemical elements in addition to the main alloying chemical elements has been considered simultaneously, in various combinations [7-15]. Here we have made an attempt to study the chemical composition effects on a rolls hardness [7-24]. Therefore, we presented in several scientific works the modelling of a the cast iron [7-22] and the hyper--eutectoid steel [22], [23] rolls technologies using a multivariate regression analysis model [7-24]. The governing equations couple with the pertinent boundary conditions are solved by the multivariate regression analysis, in the four-- and three--dimensional Matlab environment and in the three--dimensional Matlab mesh [7-24].

Primarily, the individually effect of main basic elements (i.e. Carbon |C|, Silicon |Si|, Manganese |Mn|) and the main alloying elements (i.e. Nickel |Ni|, Chromium |Cr| and Molybdenum |Mo|) on the rolls hardness was investigated by our research team [7-24]. Because these primarily experiments did not prove relevant for the industrial area, they only trace trends of broader influences, we opted to a multivariate analysis, which takes into account the simultaneous influence of several elements.
Therefore, the simultaneous effect of the main basic elements on the rolls hardness was studied, followed by the simultaneous effect of the alloying elements [7-24]. Additional, the effect of graphitizing forming elements (defined by one of the main basic element – Silicon |Si| and one of the main alloying element – Nickel |Ni|, under the presence of the Carbon |C|) was studied [7], [18], [22], [23]. Another research has in view to obtain correlations between the hardness and the carbide forming elements (defined by another basic element – Manganese, and another alloying element – Chromium |Cr|), under the presence of the Carbon |C| [7], [19], [22], [24]. All performed research have generated a number of multi–component regression equations and correlation coefficients, determined to the 3rd and 4th dimensions spaces [7–24]. Now, in this study, the relationship between the hardness and the chemical composition of the investigated half–hard nodular cast iron rolls was presented.

Our research propose to analyse the half–hard cast–iron rolls, an analysis defined by the statistically analyse of the cast rolls manufacturing technology, using the modelling phenomenon and the mathematical approach. The optimization model is based on industrial data, obtained from half–hard cast–iron rolls [7-15]. Their analysis shall lead to the optimization pattern, through the prism of the multicomponent correlations, expressed by mathematical formulae [7-24]. Our research is fixed to analyse the half–hard cast–iron rolls hardness on the working surface (barrel or body of rolls), according to the Figure 2 [7-15].

![Figure 2. Technological parts of the cast rolls](image)

3. Results of statistically analyse
The proposed statistical approach establishes a standard methodology for the determination of the iron’s chemical composition values, for which the cast–rolls hardness has the desirable values which assure their quality and safety in the rolling process during their exploitation. Because we disposed of real technological data, the mathematical model is based on industrial data, collected from cast–iron rolls manufacturing [7-15].

The variation limits of the variables in Table 1, Table 3 and Table 5 are presented. According to our statistical research, the average values of variables and the deviations of variables are calculated and presented in Table 2, Table 4 and Table 6.

| Table 1. The variation limits of the variables – basic elements and hardness [7] |
| --- |
| Carbon | C | Silicon | Si | Manganese | Mn | Hardness | HB_(surface) |
| 3.14 | 3.52 | 1.48 | 1.92 | 0.42 | 0.73 | 355 | 486 |

| Table 2. The average values and deviations of variables – basic elements and hardness [7] |
| --- |
| Carbon | C | Silicon | Si | Manganese | Mn | Hardness | HB_(surface) |
| 3.2861 | 0.0851 | 1.7191 | 0.1309 | 0.5682 | 0.0755 | 421.22 | 36.8652 |

| Table 3. The variation limits of variables – alloying elements and hardness [7] |
| --- |
| Chromium | Cr | Nickel | Ni | Molybdenum | Mo | Hardness | HB_(surface) |
| 0.3 | 0.97 | 0.81 | 2.68 | 0.18 | 0.71 | 355 | 486 |

| Table 4. The average values and deviations of variables – alloying elements and hardness [7] |
| --- |
| Chromium | Cr | Nickel | Ni | Molybdenum | Mo | Hardness | HB_(surface) |
| 0.4978 | 0.1314 | 1.3535 | 0.4779 | 0.3722 | 0.1502 | 421.22 | 36.8652 |
Table 5. The variation limits of variables – permanent and additional elements and hardness [7]

| Sulphur | S | Phosphorus | P | Magnesium | Mg | Hardness | HB (surface) |
|---------|---|------------|---|-----------|----|----------|-------------|
| 0.008   | 0.032 | 0.106      | 0.141 | 0.021     | 0.031 | 355      | 486         |

Table 6. The average values and deviations of variables – permanent, additional elements and hardness [7]

| Sulphur | S | Phosphorus | P | Magnesium | Mg | Hardness | HB (surface) |
|---------|---|------------|---|-----------|----|----------|-------------|
| 0.0192  | 0.0063 | 0.1199     | 0.0075 | 0.0256    | 0.0029 | 421.22   | 36.8652     |

4. Modelling results & graphical addenda

The equations of regression hypersurfaces, which describes the mathematical dependency between the above–mentioned cast–iron chemical elements and the half–hard rolls hardness, are determined.

In the first statistical experiment, the cumulative effect of Carbon [C], Silicon [Si] and Manganese [Mn] on Hardness [HB (surface)] is analyzed. The optimal form of modeling in the case of [HB] = f([C], [Si], [Mn]) is given by the regression equation (1), where the correlation coefficient is rf (1) = 0.7689. The deviation from the regression surface is sf (1) = 32.5612.

The cumulative effect of Chromium [Cr], Nickel [Ni] and Molybdenum [Mo] on Hardness [HB (surface)] in the second statistical approach is analyzed. The optimal form of modeling in the case of HB = f([Cr], [Ni], [Mo]) is given by the regression equation (2), where the correlation coefficient is rf (2) = 0.7067. The deviation from the regression surface, in the case of HB = f([Cr], [Ni], [Mo]), is sf (2) = 26.0834.

The cumulative effect of Magnesium [Mg], Phosphorous [P] and Sulphur [S] on Hardness [HB (surface)] in a third experiment is analyzed. The optimal form of modeling in the case of HB = f([Mg], [S], [P]) is given by the regression equation (3), where the correlation coefficient is rf (3) = 0.7472. The deviation from the regression surface, in the case of HB = f([Mg], [S], [P]), is sf (3) = 24.5054.

\[
\text{[HB (surface)] = 638.1423[C]^{2} - 241.4879[Si]^{2} + 1975.1556[Mn]^{2} - 687.6853[C][Si] + 310.4432[Si][Mn] + 142.3547[Mn][C] - 2995.1496[C] + 3009.1012[Si] - 3135.5616[Mn] + 363.0033} \tag{1}
\]

The correlation coefficient, rf (1) = 0.7689 deviation from the regression surface, sf (1) = 32.5612

\[
\text{[HB (surface)] = -449.6316[Cr]^{2} + 63.5482[Ni][Cr]^{2} + 660.0506[Mo]^{2} - 253.5251[Cr][Ni] - 184.7047[Ni][Mo] + 177.7449[Mo][Cr] + 817.3641[Cr] - 13.6043[Ni] - 291.2341[Mo] + 620.6273} \tag{2}
\]

The correlation coefficient, rf (2) = 0.7067 deviation from the regression surface, sf (2) = 26.0834

\[
\text{[HB (surface)] = -330892.5517[S]^{2} + 88300.1159[P]^{2} + 1888372.8722[Mg]^{2} + 469491.1429[S][P] - 793301.6885[P][Mg] - 774022.0622[Mg][S] - 23637.7292[S] - 10470.2929[P] + 17388.8114[Mg] + 1028.5067} \tag{3}
\]

The correlation coefficient, rf (3) = 0.7472 deviation from the regression surface, sf (3) = 24.5054

These surfaces, described by the general equations (1–3), cannot be represented in the 3–dimensional space. Therefore, the independent variables (Carbon [C], Silicon [Si] and Manganese [Mn], see Table 1) were successively replaced with their average values (Carbon [C]_{med}, Silicon [Si]_{med} and Manganese [Mn]_{med}, see Table 2). These regression surfaces belonging to the 3–dimensional space, described by the equations (1.1–1.3), can be represented graphically, resulting several correlation charts (Figures 3–5).

\[
\text{[HB (surface)]_{med} = -241.4879[Si]^{2} + 1975.1556[Mn]^{2} + 310.4432[Si][Mn] + 749.3075[Si] - 2667.7716[Mn] + 411.5766} \tag{1.1}
\]

\[
\text{[HB (surface)]_{med} = 1975.1556[Mn]^{2} + 638.1423[C]^{2} + 142.3547[Mn][C] - 2601.8695[Mn] - 4177.3703[C] + 7822.3452} \tag{1.2}
\]
Similarly, the independent variables which represent the alloying elements (i.e. Chromium $|\text{Cr}|$, Nickel $|\text{Ni}|$ and Molybdenum $|\text{Mo}|$, see Table 3) were successively replaced with their average values (Chromium $|\text{Cr}|_{\text{med}}$, Nickel $|\text{Ni}|_{\text{med}}$ and Molybdenum $|\text{Mo}|_{\text{med}}$, see Table 4). These regression surfaces, belonging to the 3–dimensional space, described by the equations (2.1–2.3), can be represented graphically, resulting several correlation charts (Figures 6–8).

\[ |\text{HB}|_{\text{(surface)}} |\text{Mn}|_{\text{med}} = 638.1423|\text{C}|^2 - 241.4879|\text{Si}|^2 - 687.6853|\text{C}||\text{Si}| - 2914.2552|\text{C}| + 3185.5138|\text{Si}| + 2219.0044 \]  

(1.3)
\[ |HB|_{\text{surface}} |Ni|_{\text{med}} = 660.0506|Mo|^2 - 449.6316|Cr|^2 + 177.7449|Mo||Cr| - 541.228|Mo| \\
+ 474.2232|Cr| + 358.6283 \]  
(2.2)

\[ |HB|_{\text{surface}} |Mo|_{\text{med}} = - 449.6316|Cr|^2 + 63.5482|Ni|^2 - 253.5251|Cr||Ni| + 883.516|Cr| \\
- 82.3466|Ni| + 243.6635 \]  
(2.3)

Figure 6. The contour lines of domain \(|HB|_{\text{surface}}(|Cr|_{\text{med}}, |Ni|, |Mo|)\)

Figure 7. The contour lines of domain \(|HB|_{\text{surface}}(|Cr|, |Ni_{\text{med}}, |Mo|)\)

Figure 8. The contour lines of domain \(|HB|_{\text{surface}}(|Cr|, |Ni|, |Mo_{\text{med}}|)\)

Similarly, the independent variables which represent the iron's permanent and additional elements (i.e. Phosphorous \(|P|\) and Sulphur \(|S|\), respectively Magnesium \(|Mg|\), see Table 5) were successively replaced with their average values (Magnesium \(|Mg|_{\text{med}}\), Sulphur \(|S|_{\text{med}}\) and Phosphorous \(|P|_{\text{med}}\), see Table 6). These regression surfaces, belonging to the 3–dimensional space, described by the equations (3.1–3.3), can be represented graphically, resulting several correlation charts (Figures 9–11).
\[|\text{HB}_{\text{surface}}|_{\text{med}} = 88300.1159|P|^2 + 1888372.8722|Mg|^2 - 793301.6885|P||Mg| - 1529.5485|P| + 2648.7391|Mg| + 458.3626 \quad (3.1)\]
\[|\text{HB}_{\text{surface}}|_{\text{med}} = 1888372.8722|Mg|^2 - 330892.5517|S|^2 - 774022.0622|Mg||S| - 77738.4084|Mg| + 32660.3828|S| + 1042.6616 \quad (3.2)\]
\[|\text{HB}_{\text{surface}}|_{\text{med}} = -330892.5517|S|^2 + 88300.1159|P|^2 + 469491.1429|S||P| - 43425.7713|S| - 30751.223|P| + 2707.2588 \quad (3.3)\]

Figure 9. The contour lines of domain \(|\text{HB}_{\text{surface}}|_{|S_{\text{med}},P_{\text{med}},Mg|}\)

Figure 10. The contour lines of domain \(|\text{HB}_{\text{surface}}|_{|S_{\text{med}},P_{\text{med}},Mg|}\)

Figure 11. The contour lines of domain \(|\text{HB}_{\text{surface}}|_{|S_{\text{med}},P_{\text{med}},Mg|}\)
5. Concluding remarks
In the foundries practices of the rolling rolls manufacturing by static casting many variables interact with each other simultaneously (the iron characteristics and properties, melting, alloying and additional treatments, the casting equipment parts and they execution, the casting temperature, the cooling and solidification and so on). In fact, the mechanical properties of irons destined to cast–iron rolls are determined by the combined effect of its chemical composition, processing technique in the foundry, and the solidification and cooling rates. Although, the cast–iron rolls hardness is affected by the irons processing stages (melting, alloying and additional treatment) as well as the composition because these factors influence the microstructure, the chemical composition of these irons are not commonly specified in requirements and technical standards and it does not assure obtaining specific mechanical properties. However, for special applications such the rolls manufacturing, some aspect of chemical composition may be specified to assure the suitability of the iron for a specific need, in accordance with the steels rolling process. Therefore, an alloy content range may be specified in this case to provide a proper strength characteristics or to assure an adequate rolls hardness.

The regression analysis provides an opportunity to specify hypotheses concerning the quality assurance of cast–iron rolls, as well as explanatory factors in their manufacturing practice. When the analysis is correctly executed, having on base the statistically valid adjustment, this can produce quantitative effects on the quality assurance process. The statistically multivariate research comes to the fore when the engineers have difficulties in comprehending many dimensions at one time, especially in the iron melting, alloying and additional treatment stages. In order to establish the optimal condition for hardness assurance in the cast–iron rolls manufacturing we proposed a statistical modelling study by using the multivariate regression.

Based on the presented statistically experiments we concluded that obtaining of the proper chemical compositions of the cast–iron destined to the rolls casting can constitute a technical efficient way to assure the rolls hardness, in particular, and the exploitation properties, in general. In this sense, the cast–iron from which the rolling rolls are manufactured by casting have an important role in assuring their quality and safety in exploitation. We believe that a chemical composition within acceptable limits, correlated with the general requirements on all stages of cast–iron rolls manufacturing process, can give the required or proper exploitation properties. A three–dimensional regression surfaces, presented graphically in this research (Figures 3–11), are a common way to illustrate multivariate cast–iron rolls manufacturing data and the correlation diagrams can be a good guide for the technologists the proper domains being easily highlighted.

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