Statistical research using the multiple regression analysis in areas of the cast hipereutectoid steel rolls manufacturing

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Abstract. The cast hipereutectoid steel (usually named Adamite) is a roll manufacturing destined material, having mechanical, chemical properties and Carbon [C] content of which stands between steel and iron, along with its alloy elements such as Nickel [Ni], Chrome [Cr], Molybdenum [Mo] and/or other alloy elements. Adamite Rolls are basically alloy steel rolls (a kind of high carbon steel) having hardness ranging from 40 to 55 degrees Shore C, with Carbon [C] percentage ranging from 1.35% until 2% (usually between 1.2–2.3%), the extra Carbon [C] and the special alloying element giving an extra wear resistance and strength. First of all the Adamite roll’s prominent feature is the small variation in hardness of the working surface, and has a good abrasion resistance and bite performance. This paper reviews key aspects of roll material properties and presents an analysis of the influences of chemical composition upon the mechanical properties (hardness) of the cast hipereutectoid steel rolls (Adamite). Using the multiple regression analysis (the double and triple regression equations), some mathematical correlations between the cast hipereutectoid steel rolls’ chemical composition and the obtained hardness are presented. In this work several results and evidence obtained by actual experiments are presented. Thus, several variation boundaries for the chemical composition of cast hipereutectoid steel rolls, in view the obtaining the proper values of the hardness, are revealed. For the multiple regression equations, correlation coefficients and graphical representations the software Matlab was used.

1. Introduction
The hot rolling is a highly complex engineering process, with interactions of the multiple process variables, which extremely dependents by the operating conditions. Within the framework of the hot rolling operations predominate the wear, it is necessary that rolls to have good hardness [1–3]. All of the rolls must have high exploiting qualities, which are determined by hardness, wear resistance and stability at high temperatures [1–3]. When the roll hardness is higher, the wear resistance is greater [1–3]. Since the properties of any cast alloy parts are determined by microstructure which are formed during solidification in the casting mould and under the influence of cooling rate, the criterion that determines the basic physic–mechanical properties of the rolls is the structure. Therefore, the composition of the alloy is an important parameter [1–3]. In case of Adamite hyper–eutectoid steel rolls the hardness depends on the degree of alloying elements and the special high temperature heat treatment process (annealing) followed by tempering cycle which determine the microstructure [4].

The intensification of rolling processes influences, directly, the durability of rolls, they being the most important components in the metal rolling [1–3]. The efficiency of rolling primarily depends by
the quality of rolls, which durability in exploitation is determined by the features of material they are manufactured, the features of material that is laminated, and, not least, the exploitation conditions. Decreasing durability in exploitation of the rolls, which work in variable requests conditions due to the deformation process (requests that repeat cyclically, to certain intervals), represent one of the most actual problems met in the rolling sectors [1–3]. Therefore, the current work wants to answer to more of the problems linked by this aspect, having in focus the Adamite hyper–eutectoid steel rolls, creating a connection bridge between the casting manufacturing factors and the rolling exploitation conditions.

![Figure 1. The cast hipereutectoid steel roll (usually named Adamite)](image)

Prediction of the properties of the resulting cast alloy is a prerequisite for the management of metallurgy, especially in materials destined to the cast rolls (irons or steels). Required metallurgical quality of a particular type of alloys (irons and steels) and its properties are determined by chemical composition and a proper melting processing. Control of microstructure and high exploiting properties of cast alloy destined to rolling rolls is in perfect control of the melting process and the metallurgical melt processing [3], [5–12].

In the manufacturing rolls for hot rolling the roll makers are engaged in the production of various rolls including cast iron rolls and steel rolls (including Adamite steel). The best way for roll makers to achieve better rolls is to ensure that better materials and improved manufacturing processes are used and that roll users take account of rolling conditions and improved rolling processes. The problem of roll selection is complicated by the fact that mill conditions vary widely [3], [5–12]. In order to secure superior quality and durability characteristics, the main problem was and is the optimal chemical composition assurance. Therefore the roll grade is very important on roll properties. However, rolling conditions are important factors [1–3], [5–12].

2. Technological area of research: Adamite hyper–eutectoid steel rolls

Cast steel base rolls (or semi–steel base rolls) are classified into Adamite rolls and graphitic steel rolls. Cast steel rolls are available in wide of chemical compositions varying from hypo–eutectoid to hyper–eutectoid steels. Steel base rolls are heat treated in various ways and have no hardness drop [4].

The Adamite steel rolls typically have great strength, good thermal properties and high wear resistance. Unlike other metal rolls, these have uniform hardness from depth to the surface which makes them very special. Hardness of the Adamite steel rolls is maximum amongst the steel based rolls. Adamite steel rolls are stronger than cast iron rolls and harder than other steel rolls. The biggest advantage of these rolls is almost no hardness gradient in the working layer. These rolls show a low hardness drop from surface layer to the cross sectional centres and possess a high friction coefficient good for biting. Therefore, the Adamite hyper–eutectoid steel rolls are acknowledged for superior finish, durable life, wear resistance, strength and toughness [4], [13–15].

Adamite steel rolls are widely used for hot rolling applications in the different type of pre–roughing and roughing stands and also different positions in the section mills as well. Adamite hyper–eutectoid steel rolls are suitable for rolling medium and heavy sections where resistance is very important along with considerable amount of strength and toughness. Good biting is usually required for rolls for
roughing stands, for which anti-heat cracking properties and high toughness are also required. These rolls are used in roughing mills and front stands of the hot strip mills. Also, they are used in roughing stands, intermediate stands and pre-finishing stands for bar mills [4, 13–15].

Figure 2. Hardness gradient in the working layer of Adamite hyper-eutectoid steel rolls (Hardness: 45–50 Shore / 308–344 Brinell)

Figure 3. Hardness gradient in the working layer of Adamite hyper-eutectoid steel rolls (Hardness: 50–55 Shore / 345–381 Brinell)

Figure 4. Microstructure of Adamite hyper-eutectoid steel rolls (Hardness: 45–50 Shore / 308–344 Brinell)

Figure 5. Microstructure of Adamite hyper-eutectoid steel rolls (Hardness: 50–55 Shore / 345–381 Brinell)

Figure 6. The technological domain of the Adamite hyper-eutectoid steel rolls
Adamite Rolls are special hyper–eutectoid steel rolls alloyed with Nickel, Chromium and Molybdenum. In fact, the Adamite is a material, mechanical properties and Carbon content of which stands between steel and iron [4], [13–15]. The extra Carbon – between 1.0 and 2.2% – and special alloys give it extra wear resistance and strength. Adamite steel rolls are mainly composed of fine pearlitic matrix with some cementite in the structure. The structure consists of well broken up and dispersed carbides in a pearlitic matrix complementing the hardness and wear resistance imparted by highly alloyed matrix [4], [13–15]. Depending on the primary requirements there are varieties of grades with a series of carbon content and alloying elements used considering the rolling mill operational conditions such as wear, strength, thermal cracks etc.

| Table 1. Typical compositions of Adamite hyper–eutectoid steel rolls |
|---------------------------------------------------------------|
| Adamite hyper–eutectoid steel rolls | Class 1 | Class 2 | Class 3 |
| Composition (%) | | | |
| Carbon [C] | 1.40–1.60 | 1.50–1.80 | 1.60–2.00 |
| Silicon [Si] | 0.40–0.70 | 0.30–0.70 | 0.30–0.70 |
| Manganese [Mn] | 0.50–0.80 | 0.50–1.00 | 0.50–1.00 |
| Nickel [Ni] | 0.40–1.00 | 0.70–1.10 | max 1.50 |
| Chromium [Cr] | 0.80–1.20 | 1.00–1.40 | 1.10–1.60 |
| Molybdenum [Mo] | 0.20–0.40 | 0.20–0.40 | 0.25–0.50 |
| Mechanical Properties | | | |
| Hardness (Shore) | 40–45 | 45–50 | 50–55 |
| Hardness (Brinell) | 270–308 | 309–344 | 345–381 |

Alloying combinations of different element like Nickel, Chromium and Molybdenum are normally used to achieve the desired physical and mechanical properties. In view of the demanding end use requirements these rolls cannot be used in an as cast condition. When a coarse grain pearlitic structure with cementite and ferrite in a continuous network is normally obtained. The rolls are subject to specially designed heat treatment cycles to arrive at the optimum microstructure configuration with fine pearlite and uniformly distributed suitable for the final application [4], [13–15].

Adamite hyper–eutectoid steel rolls are statically cast and undergo a special high temperature heat treatment process (annealing) followed by tempering cycle to give a microstructure consisting of fine pearlitic matrix with spherodised/broken carbide [4], [13–15]. This multi–stage heat treatment process followed by tempering phases are very important operations in order to develop the combination of hardness, toughness and wear resistance required for heavy duty wear applications [4], [13–15]. Owing to its alloy elements such as Nickel, Chromium and Molybdenum, there are some amounts of carbides in the matrix and because of certain special heat treatment technology, high wearability, good toughness and excellent resistance to fire crack is obtained [4], [13–15].

![Figure 7. The static casting (bottom pour casting) of Adamite hyper–eutectoid steel rolls](image-url)
The static casting is widely used to produce rolls for roughing mills, section mill, as well as universal mills [3]. The bottom pour casting is applied in the analysed Adamite hyper–eutectoid steel rolls production. By the control of the cooling speed techniques by combined casting forms (sand for the necks and chill for the body) and the future heat treatment process, the static roll can get the performance requested on entire cast steel roll. The moulding practices, chill properties and casting specifications of the hyper–eutectoid steel are carefully controlled to achieve proper solidification rates across the full range of produced rolls. Exceptional care is needed during the casting process [3].

3. Methodology: the regression analysis

Modelling of cast rolls technologies by multivariate regression analysis are used to predict the rolls performance and to optimize the chemical composition components during the manufacturing process (i.e. melting and casting processes) and also to provide insights into control strategies that may improve the rolls exploitation properties [3], [5–12].

Many studies have been reported on mathematical modelling of cast rolls. Most of the studies reviewed above worked on modelling of cast iron rolls and their technological components which assure the proper hardness by the chemical composition variation, but not reviewed the cast steel–base rolls [3], [5–12]. We developed a general steady state mathematical model for cast iron rolls that can be applied to the hyper–eutectoid steel rolls too. The governing equations coupled with pertinent boundary conditions are solved by the correlation diagrams generation, in the Matlab environment. In all the above studies, the combined effect of basic chemical composition in addition to the proper alloying elements has been considered separate or simultaneously, in case of the cast iron rolls.

Here we have made an attempt to study the combined effects on the hardness, in case of the Adamite hyper–eutectoid steel rolls. We implemented into the research several lots of industrial data analyses, by the way of the statistical experiment, in two separate series. This analysis gathers within the framework of research, the cast Adamite rolls and aims to characteristics of the material (i.e. hyper–eutectoid steel). The analyses concern the influence of main basic and alloying elements in the chemical composition of the Adamite hyper–eutectoid steel, as well as the conditions under which the hardness is affected by the cumulative influence of the chemical components.

As results of the applied mathematical modelling, we described a number of multi–component regression equations, determined to the 3rd and 4th dimensions spaces. Also, we generated several regression surfaces and matrices of the level curves, which can be represented and interpreted by the roll makers and may be considered as correlation charts between the analyzed variables [3], [5–12]. For the multiple regression equations, correlation coefficients and graphical representations the software Matlab was used [3], [5–12].

4. Multicomponent relations determination

The variables and the hardness variation limits are presented in Table 2. The average values for the variables and the hardness, necessary for the calculation of the proper form of modelling are presented in Table 3.

| Table 2. The variation domains of variables (basic and alloying elements) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Carbon, [C] | Silicon, [Si] | Manganese, [Ni] | Nickel, [Ni] | Chromium, [Cr] | Molybdenum, [Mo] | Hardness, [HB] |
| min | max | min | Max | min | max | min | max | min | max | min | max |
| 1.52 | 2.02 | 0.54 | 0.72 | 0.60 | 0.92 | 1.17 | 1.66 | 1.04 | 1.37 | 0.24 | 0.45 | 311 | 412 |

| Table 3. The average values of variables |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Carbon, [C] | Silicon, [Si] | Manganese, [Ni] | Nickel, [Ni] | Chromium, [Cr] | Molybdenum, [Mo] | Hardness, [HB] |
| Med | med | med | med | Med | med | med |
| 1.73 | 0.62 | 0.76 | 1.31 | 1.22 | 0.32 | 356 |
The optimal form of modeling in the case of basic elements ([C], [Si], [Mn]) effect is given by the equation (1), where the correlation coefficient is $R^2 = 0.9322$. The modeling in the case of alloying elements ([Ni], [Cr], [Mo]) effect is given by the equation (2), where the correlation coefficient is $R^2 = 0.9330$. The polynomial coefficients have the values presented in Table 4.

$$[\text{HB}] = a_1 [\text{C}]^2 + a_2 [\text{Si}]^2 + a_3 [\text{Mn}]^2 + a_4 [\text{Ni}] [\text{Si}] + a_5 [\text{Ni}] [\text{Mn}] + a_6 [\text{Mn}] [\text{C}] + a_7 [\text{C}] + a_8 [\text{Si}] + a_9 [\text{Mn}] + a_{10} \quad (1)$$

$$[\text{HB}] = a_1 [\text{Ni}]^2 + a_2 [\text{Cr}]^2 + a_3 [\text{Mo}]^2 + a_4 [\text{Ni}] [\text{Cr}] + a_5 [\text{Ni}] [\text{Mo}] + a_6 [\text{Cr}] [\text{Mo}] + a_7 [\text{Ni}] + a_8 [\text{Cr}] + a_9 [\text{Mo}] + a_{10} \quad (2)$$

| Table 4. The polynomial coefficients of equations (1)–(2) |
|---------------------------------------------------------|
| The polynomial coefficients                     | $\text{HB}=f([\text{C}], [\text{Si}], [\text{Mn}])$ | $\text{HB}=f([\text{Ni}],[\text{Cr}],[\text{Mo}])$ |
| the second–degree terms coefficients          | $a_1 = 277.3852$ | $a_1 = 69.9558$ |
|                                           | $a_2 = 1001.5596$ | $a_2 = 133.2416$ |
|                                           | $a_3 = 318.0048$ | $a_3 = -436.2808$ |
| the product terms coefficients               | $a_4 = -827.4239$ | $a_4 = 433.7566$ |
|                                           | $a_5 = -324.6609$ | $a_5 = 155.5801$ |
|                                           | $a_6 = -146.7932$ | $a_6 = 923.9556$ |
| the first–degree terms coefficients           | $a_7 = -69.9044$ | $a_7 = -669.3177$ |
|                                           | $a_8 = 300.0813$ | $a_8 = -1331.4557$ |
|                                           | $a_9 = 285.3223$ | $a_9 = -976.6554$ |
| the constant term                            | $a_{10} = 56.4979$ | $a_{10} = 1780.7491$ |

Because the two surfaces described by the equations (1)–(2) cannot be represented graphically, the independent variables were successively replaced with their average values ([C]$_\text{med}$, [Si]$_\text{med}$, [Mn]$_\text{med}$, [Ni]$_\text{med}$, [Cr]$_\text{med}$ and [Mo]$_\text{med}$). Therefore, in the case of basic elements correlation, the equations (3)–(5) were obtained. The correlation coefficient are $R^2$ at [C]$_\text{med}$ = 0.8195, $R^2$ at [Si]$_\text{med}$ = 0.9122 and $R^2$ at [Mn]$_\text{med}$ = 0.8940. The polynomial coefficients of equations (3)–(5) in Table 5 are presented.

$$[\text{HB}] \text{ at } [\text{C}]_\text{med} = b_1 [\text{Si}]^2 + b_2 [\text{Mn}]^2 + b_3 [\text{Si}] [\text{Mn}] + b_4 [\text{Si}] + b_5 [\text{Mn}] + b_6 \quad (3)$$

$$[\text{HB}] \text{ at } [\text{Si}]_\text{med} = c_1 [\text{C}]^2 + c_2 [\text{Mn}]^2 + c_3 [\text{C}] [\text{Mn}] + c_4 [\text{C}] + c_5 [\text{Mn}] + c_6 \quad (4)$$

$$[\text{HB}] \text{ at } [\text{Mn}]_\text{med} = d_1 [\text{C}]^2 + d_2 [\text{Si}]^2 + d_3 [\text{C}] [\text{Si}] + d_4 [\text{C}] + d_5 [\text{Si}] + d_6 \quad (5)$$

| Table 5. The polynomial coefficients of equations (3)–(5) |
|---------------------------------------------------------|
| The polynomial coefficients                     | $\text{HB}=f([\text{C}], [\text{Si}], [\text{Mn}])$ |
| the second–degree terms coefficients          | $b_1 = 1001.5595$ | $c_1 = 277.3851$ |
|                                           | $b_2 = 318.0048$ | $c_2 = 318.0048$ |
|                                           | $b_3 = -146.7932$ | $c_3 = -324.6609$ |
| the product terms coefficients               | $b_4 = -1135.3614$ | $c_4 = -583.4589$ |
|                                           | $b_5 = -277.9103$ | $c_5 = 194.2126$ |
| the constant term                            | $b_6 = 770.0567$ | $c_6 = 628.5762$ |

Similarly, in the case of alloying elements correlation, the equations (6)–(8) were obtained. The correlation coefficient are $R^2$ at [Ni]$_\text{med}$ = 0.8358, $R^2$ at [Cr]$_\text{med}$ = 0.8048 and $R^2$ at [Mo]$_\text{med}$ = 0.9160. The polynomial coefficients of equations (6)–(8) in Table 6 are presented.
\[ [HB] \text{ at } [Ni]_{med} = b_1[Cr]^2 + b_2[Mo]^2 + b_3[Cr][Mo] + b_4[Cr] + b_5[Mo] + b_6 \]  
\[ (6) \]

\[ [HB] \text{ at } [Cr]_{med} = c_1[Ni]^2 + c_2[Mo]^2 + c_3[Ni][Mo] + c_4[Ni] + c_5[Mo] + c_6 \]  
\[ (7) \]

\[ [HB] \text{ at } [Mo]_{med} = d_1[Ni]^2 + d_2[Cr]^2 + d_3[Ni][Cr] + d_4[Ni] + d_5[Cr] + d_6 \]  
\[ (8) \]

### Table 6. The polynomial coefficients of equations (6)–(8)

| The polynomial coefficients | HB=f([Ni],[Cr],[Mo]) |
|-----------------------------|-----------------------|
| the second–degree terms     |                       |
| coefficients                |                       |
| \( b_1 = 133.2416 \)        | \( c_1 = 69.9558 \)   |
| \( b_2 = -436.2808 \)       | \( c_2 = -436.2808 \) |
| \( d_1 = 69.9558 \)         | \( d_1 = 133.2416 \)  |
| the product terms coefficients |                       |
| \( b_3 = 923.9556 \)        | \( c_3 = 155.5801 \)  |
| \( d_3 = 433.7566 \)        |                       |
| the first–degree terms       |                       |
| coefficients                |                       |
| \( b_4 = -765.4032 \)       | \( c_4 = -137.0983 \) |
| \( b_5 = -773.6233 \)       | \( c_5 = 157.0382 \)  |
| \( d_4 = -618.6764 \)       | \( d_5 = -1030.7081 \)|
| the constant term            |                       |
| \( b_6 = 1026.4262 \)       | \( c_6 = 347.6522 \)  |
| \( d_6 = 1416.6237 \)       |                       |

5. Generating the correlation diagrams

The regression surfaces described by equations (3)–(5), respectively equations (6)–(8) can be represented graphically, resulting several correlation diagrams. Therefore, the correlation of two independent variables can be made, so that the dependent variables can be obtained in between the requested limits. The correlation diagrams are presented in the Figures 8–13.

\[ \text{Figure 8. Correlation diagrams in case } HB=f([C], [Si], [Mn]), \text{ when } [C]=[C]_{med} \]
Figure 9. Correlation diagrams in case $\text{HB} = f(\{C\}, \{\text{Si}\}, \{\text{Mn}\})$, when $[\text{Si}]=[\text{Si}]_{\text{med}}$

Figure 10. Correlation diagrams in case $\text{HB} = f(\{C\}, \{\text{Si}\}, \{\text{Mn}\})$, when $[\text{Mn}]=[\text{Mn}]_{\text{med}}$
Figure 11. Correlation diagrams in case HB=f([Ni],[Cr],[Mo]), when [Ni]=[Ni]med

Figure 12. Correlation diagrams in case HB=f([Ni],[Cr],[Mo]), when [Cr]=[Cr]med
6. Discussions

The optimal values of the chemical composition of hyper–eutectoid steel rolls are to be found on the correlation diagrams presented in Figures 8–10, respectively Figures 11–13. According to them, the optimal values in the concentration of each element can be noticed, values that can assure the adequate hardness of the rolls. Thus the optimal additions can be determined in these elements to assure the proper hardness’s.

If, according to a preferred material variant, the roll material has a composition:

- Carbon [C] = 1.5 to 2.0 %, preferably 1.7 to 2.0 %
- Silicon [Si] = 0.5 to 0.7 %, preferably 0.54 to 0.7 %
- Silicon [Si] = 0.7 to 2.0 %, preferably 1.0 to 2.0 %
- Chromium [Cr] = 0.6 to 1.5 %, preferably 0.7 to 1.4 %
- Nickel [Ni] = 0.8 to 1.6 %, preferably 1.0 to 2.0 %
- Molybdenum [Mo] = 0.2 to 0.6 %, preferably 0.25 to 0.4 %

with the remainder being iron and impurities.

According to the correlation diagrams, high quality assurance of the Adamite hyper–eutectoid steel rolls is achieved when the alloy contains:

- 1.7 to 1.8 % Carbon [C]
- 0.58 to 0.64 % Silicon [Si]
- 0.65 to 0.85 % Silicon [Si]
- 1.15 to 1.3 % Chromium [Cr]
- 1.3 to 1.5 % Nickel [Ni]
- 0.32 to 0.4 % Molybdenum [Mo]

with the remainder iron and impurities.
7. Conclusions
Hardness is strongly influenced by the roll surface conditions. And the variation of hardness in rolls is very important. For the roll makers the hardness assurance is the control of the roll manufacturing process. For the roll users, the hardness measurement is needed to avoid the roll failure due to surface fatigue. In fact, the hardness is the only property besides dimensions that can be tested by incoming inspections.

Careful investigations on the parameters given by roll users, combined with the vast experience of the roll makers in the rolls materials area, often lead to improved solutions for finding a rolls which gives the best possible technically compromise. Besides the mechanical, physical and chemical properties of the roll materials the process technology and the parameters in the rolling mills are decisive for the roll’s performance.

Roll material is major factors affecting rolling performance and roll life. Therefore, a complex analyses of all the stages of manufacturing and the quality control process are needed. The performed research had in view to obtain correlations between the chemical composition and the hardness of cast steel–base rolls. Adamite hyper–eutectoid steel rolls are basically controlled under actual molding and casting conditions, therefore the desired hardness is obtained by the proper melting process, changing the chemical relationship between basic and alloying element, which is achieved by a close control of chemistry and process parameters. The proper exploitation properties requires extremely careful selection of melting metallic stock, closely controlled melting conditions (charging, temperatures regimes, time) and rigid control of chemical composition (alloying stages, corrections) to obtain the required hardness.

In the processing phase of the Adamite steel, the proper hardness is adjusted through the quality of the metallic charge and of the addition materials (especially the alloying elements addition, as well as through a proper leading of the melting and of the processing. The main chemical composition must be correlated with further addition of alloying elements, respecting the adequate proportions between nickel, chrome and molybdenum, besides an optimal ratio of carbon, silicon and manganese. Also, an optimal proportion between the silicon and the manganese contents is needed both from the basic nickel, chrome and molybdenum and the main chemical composition, in order to obtain the optimal proportion between the silicon and the manganese contents is needed both from the basic nickel, chrome and molybdenum.

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