Statistical analysis using the multiple regression research in areas of the indefinite chilled cast–iron rolls manufacturing

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Abstract. To analyze the metallurgical processes is used, mainly, the statistical fundamental methods that permit to draw conclusions, from the observed values, about the repartition of the frequencies of various parameters, about their interaction, about verification validity of certain premises, and about the research of the dependencies among different parameters. In this sense, the realization of optimum chemical compositions of the cast–iron can constitute a technical efficient way to assure the exploitation properties, the material from which the rolling mills rolls are manufactured having an important role in this sense. This paper reviews key aspects of roll material properties and presents an analysis of the influences of chemical composition upon the mechanical properties of the indefinite cast iron rolls. Now, using the multivariate research, we present some mathematical correlations and graphical interpretations between the hardness and the chemical composition. Using the double and triple correlations variation boundaries for the chemical composition, in view the obtaining the optimal values of the hardness of indefinite cast iron rolls, are obtained. The partial results and evidence obtained by actual experiments are presented. For the multiple regression equations, correlation coefficients and graphical representations the software MATLAB was used.

1. Introductory notes
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. Within the framework of the rolling operations predominate the wear, it is necessary that rolls to have good hardness [1–3]. Since the properties of any cast iron 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]. Hardness on the crust depends on the degree of alloying elements and the mode of distribution of the graphite quantity does the metal mass.

Carrying out the hardness of the cast iron rolls, prescribed by the technology, with the perlite–cementite–graphite type structure, shall be ensured by strict compliance with the chemical composition, conditions of the iron melting and casting, and the thermal cooling applied regime. The hardness variation in the entire section of the roll, it is obtained through the establishment of a precise correlation between the speed of cooling and the chemical composition, after cooling, the hardness on the crust must be greater, due the cementite in the near of the metal chill, i.e. in the area of the roll body [1–3]. In the middle as well as on the necks of roll, the separation shall be in the form of carbon graphite, in increased quantities, and avoid the formation of the cementite in this area, in order to
ensure a high resistance needed into the rolling process. Increasing the graphite, starting with peripheral zone and working toward to core, takes place gradually, through a scheme related the heat technology, which make the hardness to vary gradually, through passing zone, in the case of roll with indefinite crust and by a sudden transition, in the case of the defined crust. In this context, the indefinite chilled cast iron rolls, in which missing a clear and distinct boundary between crust, passing zone and the core area, occupy an important place, and specialized studies in this field are missing almost completely [1–3].

The main structural constituent of cast–iron is the graphite, on the quantity, shape, dimensions and the manner of the distribution of mass basis, depending on the physico–mechanical and wears resistance of the entire rolls [1–3]. Part of the carbon forms flake graphite and the remainder forms carbides. The amount of graphite is less prominent in higher hardness grades and increases towards the centre of the roll. (Figure 1 and Figure 2) Thus, a hardness gradient is developed between the rolls core and the body. The depth of the chilled layer is difficult to define and the hardness decreases gradually towards the centre of the roll. (Figure 1 and Figure 2) The chilled outer surface is very hard and has a white fracture face for a distance beneath the surface (known as the chill zone), signifying that the formation of free graphite in that area had been suppressed by the rapid cooling. The surface layers contain very small particles of graphite and the structure changes smoothly into the grey core. The hardness decreases slowly at first from the surface and more quickly towards the soft core. (Figure 3)

In the cast iron rolls, are to be found all the structural constituents, each of them having its own hardness, well determined. One of the basic factors that determine the structure is the chemical composition of the cast–iron, the basically (C, Si, Mn, P, S) and the alloying (Cr, Ni, Mo) too [1-3]. The non–compliance of the each sort of rolls chemical composition, will lead to rejection of them. If on the crust the hardness is determined by the quantity of cementite, the rolls core must contain
graphite, in order to ensure a high resistance to flexing, which they are subject into the industrial exploitation. Graphitization of cast irons designated for the working layer of rolls occurs under isothermal conditions at high temperatures, which vary over the cross section and resulted from casting the roll core [4].

The rolls must present high hardness at the surface and lower hardness in the core, adequate with the high working regimes. If in the crust the hardness is assured by the quantities of cementite, the core must contain graphite to assure that. While indefinite chill rolls can be produced within large ranges, the composition and resulting properties of the chill roll can be more easily controlled and are more desirable if the compositional ranges are limited to the requirement’s values [1], [3]. The roll casters need to appreciate that minor changes to the chemical ranges and also substitution of comparably active elements can be made to the indefinite chill roll composition, while maintaining the desired exploitation properties. Silicon contributes to the formation of graphite and to maintaining the character of the cast iron. Nickel is added to the indefinite chill roll composition to promote the formation of free graphite in the alloy, having in view that an excess of Nickel will tend to destabilize the iron’s structure. Therefore, the composition of the melt is set using alloying methods by fixing the concentrations of Carbon and Silicon in the presence of Nickel and the effective sum of the carbide forming elements in such a manner that, at its solidification, a microstructure is formed [3], [5].

Control of microstructure and properties of cast iron prediction is in perfect control of the melting process and the metallurgical melt processing. Required metallurgical quality of a particular type of iron and its properties are determined by chemical composition and a proper melting processing. Prediction of the properties of the resulting cast iron is a prerequisite for the management of metallurgy, especially in material destined to the cast rolls.

2. Methodology
The analytical approach aims original line through interdisciplinary aspects, but also through the mathematical analysis approach, the method resulting several equations and graphics. Planning and research on the industrial data, obtained from the rolls manufacturing area, are impressed by creation of a database necessary to the statistical processing, mathematical interpretations, modelling and optimization alike. In this sense, we implemented into the series research by lots of industrial data analyses, by the way of the statistical experiment, in separate series. This analysis gathers within the framework of research, the cast roll material and aims to characteristics of the material. From this point of view a mathematical modelling is made, which is effectuated on the basis of differentiation on parts of the rolls (body and necks), taking account the industrial data [3], [6–11].

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. For the multiple regression equations, correlation coefficients and graphical representations the software Matlab was used.

3. Multicomponent relations determination
The variables and the hardness variation limits are presented in Table 1. The average values for the three variables ([C], [Si], [Ni]) and the hardness (HS), necessary for the calculation of the optimal form of modelling are presented in Table 2 [6].

| Table 1. The variation domains of variables |
|--------------------------------------------|
| Carbon, [C] | Silicon, [Si] | Nickel, [Ni] | Hardness, HS(body) | Hardness, HS(necks) |
| min | max | min | max | min | max | min | max |
| 3.17 | 3.32 | 0.77 | 1.42 | 2.06 | 3.89 | 56 | 78 | 57 | 76 |
The optimal form of modeling in the case of \( HS_{\text{body}} = f([C], [Si], [Ni]) \) is given by the equation (1), where the correlation coefficient is \( r_{f_{\text{body}}} = f([C], [Si], [Ni]) = 0.6462 \) and the average square aberration from the regression surface is \( s_{f_{\text{body}}} = f([C], [Si], [Ni]) = 3.0771 \).

The optimal form of modeling in the case of \( HS_{\text{necks}} = f([C], [Si], [Ni]) \) is given by the equation (2), where the correlation coefficient is \( r_{f_{\text{necks}}} = f([C], [Si], [Ni]) = 0.6499 \) and the average square aberration from the regression surface is \( s_{f_{\text{necks}}} = f([C], [Si], [Ni]) = 2.9500 \).

\[
HS_{\text{body}} = 120.0595 [C]^2 + 99.2622 [Si]^2 - 0.9482 [Ni]^2 - 18.6234 [C][Si] - 1.9188 [Si][Ni] \\
+ 55.4181 [Ni][C] - 918.9241 [C] + 127.6439 [Si] - 166.3666 [Ni] + 1725.0823
\]

\[
HS_{\text{necks}} = -2.9071 [C]^2 + 34.1476 [Si]^2 - 0.7563 [Ni]^2 - 63.8114 [C][Si] - 3.1912 [Si][Ni] \\
+ 43.3294 [Ni][C] - 40.6041 [C] + 286.6411 [Si] - 128.0087 [Ni] + 163.9398
\]

In the technological field, the behavior of these hyper surfaces in the vicinity of the saddle point, or of the point where three independent variables take their average value, can be studied only tabular, which means that the independent variables are attributed values on spheres concentric to the studied point. Because these surfaces, described by the equation (1) and (2), cannot be represented in the three–dimensional space, the independent variables ([C], [Si], [Ni]) were successively replaced with their average values ([C]_{\text{med}}, [Si]_{\text{med}}, [Ni]_{\text{med}}).

Therefore, in the case of \( HS_{\text{body}} = f([C], [Si], [Ni]) \), the equations (3)–(5) were obtained. In the case of \( HS_{\text{necks}} = f([C], [Si], [Ni]) \), the equations (6)–(8) were obtained.

\[
HS_{\text{body}}[C]_{\text{med}} = -29.9622 [Si]^2 - 0.9482 [Ni]^2 - 1.9188 [Si][Ni] \\
+ 67.5632 [Si] + 12.4177 [Ni] + 10.0869
\]

\[
HS_{\text{body}}[Si]_{\text{med}} = -0.9482 [Ni]^2 + 120.0595 [C]^2 + 55.4181 [Ni][C] \\
- 168.3514 [Ni] - 938.1881 [C] + 1825.0583
\]

\[
HS_{\text{body}}[Ni]_{\text{med}} = 120.0595 [C]^2 - 29.9622 [Si]^2 - 18.6234 [C][Si] \\
- 751.3676 [C] + 121.8423 [Si] + 1213.4061
\]

\[
HS_{\text{necks}}[C]_{\text{med}} = -34.1476 [Si]^2 - 0.7563 [Ni]^2 - 3.1912 [Si][Ni] \\
+ 80.7791 [Si] + 11.7762 [Ni] + 2.6921
\]

\[
HS_{\text{necks}}[Si]_{\text{med}} = -0.7563 [Ni]^2 + 2.9071 [C][Si] + 43.3294 [Ni][C] \\
- 131.3097 [Ni] - 106.6105 [C] + 423.9038
\]

\[
HS_{\text{necks}}[Ni]_{\text{med}} = -2.9071 [C]^2 - 34.1476 [Si]^2 - 63.8114 [C][Si] \\
+ 90.4024 [C] + 276.9922 [Si] - 230.0087
\]
Figure 4. The regression surface, case of $HS_{\text{body}} = HS_{\text{body}}([C]_{\text{med}}, [Si], [Ni])$

Figure 5. The matrix of the level curves, case of $HS_{\text{body}} = HS_{\text{body}}([C]_{\text{med}}, [Si], [Ni])$

Figure 6. The regression surface, case of $HS_{\text{body}} = HS_{\text{body}}([C], [Si]_{\text{med}}, [Ni])$

Figure 7. The matrix of the level curves, case of $HS_{\text{body}} = HS_{\text{body}}([C], [Si]_{\text{med}}, [Ni])$

Figure 8. The regression surface, case of $HS_{\text{body}} = HS_{\text{body}}([C], [Si], [Ni]_{\text{med}})$

Figure 9. The matrix of the level curves, case of $HS_{\text{body}} = HS_{\text{body}}([C], [Si], [Ni]_{\text{med}})$
Figure 10. The regression surface, case of $\text{HS}_{\text{necks}} = \text{HS}_{\text{necks}}([C]_{\text{med}}, [\text{Si}], [\text{Ni}])$

Figure 11. The matrix of the level curves, case of $\text{HS}_{\text{necks}} = \text{HS}_{\text{necks}}([C]_{\text{med}}, [\text{Si}], [\text{Ni}])$

Figure 12. The regression surface, case of $\text{HS}_{\text{necks}} = \text{HS}_{\text{necks}}([C], [\text{Si}]_{\text{med}}, [\text{Ni}])$

Figure 13. The matrix of the level curves, case of $\text{HS}_{\text{necks}} = \text{HS}_{\text{necks}}([C], [\text{Si}]_{\text{med}}, [\text{Ni}])$

Figure 14. The regression surface, case of $\text{HS}_{\text{necks}} = \text{HS}_{\text{necks}}([C], [\text{Si}], [\text{Ni}]_{\text{med}})$

Figure 15. The matrix of the level curves, case of $\text{HS}_{\text{necks}} = \text{HS}_{\text{necks}}([C], [\text{Si}], [\text{Ni}]_{\text{med}})$
5. Discussions and technological interpretations
In the interests of an especially good balance of the graphite and carbide distribution during solidification, and in order to further improve the operating characteristics of the indefinite chilled cast iron roll, it has been proven favorable for a final Silicon content of more than 1.0 to 1.2%, preferably 1.05 to 1.15, to be provided.

In the optimization of material properties and material quality, although it is advantageous for the Carbon content of the melt to be set to a value of more than 3.2 to 3.24%, preferably 3.2 to 3.22%.

With regard to a controlled graphite content and an intended assumption of hardness of the material, it is preferred for the irons destined to the indefinite chilled cast rolls to contain 2.6 to 3.4% of Nickel, preferably 3.0 to 3.4%.

When, according to the current approaches described here, the composition of the iron melt is set such that, in the presence of 2.8 to 3.0% Nickel, the concentration ratio of Carbon to Silicon is preferably less than or equal to 2.6, the graphite precipitation and/or the graphite fraction in the material can be held within the desired range with high precision and within tight limits. At a ratio of Carbon content to Silicon content that exceeds this value (2.6), carbides are formed and graphite formation is adversely affected as well.

The Nickel addition leads to the improvement of the mechanical properties (including the of the cast rolls). If we do not allow this element to increase the graphitisation degrees and the white solidification in the peripherical area of the rolling surface, this content can be considerably reduced. Accordingly, the Silicon content of the irons is modified, as this element replaces the Nickel content.

Thus the optimal additions can be determined in these elements to assure the proper hardness’s.

6. Concluding remarks
The rolls requirements may not be fully met, forcing to the granting of priorities in relation to the specific nature of the rolled products, so to compromise. In general, the problem is reduced to choosing the correct roll’s material, relieved the lush experience available in current conditions of production, but complicated by wide diversity of the used materials. By identifying specific needs of manufacture of the indefinite chilled cast iron rolls, the current approaches responds to the identified the rolls casting sector’s needs by increasing the quality of the rolls and contribute to their exploiting satisfaction.

Although the rolls manufacturing is in continuous updating, however requirements to claim to be high–quality rolls are not yet satisfied completely, in many cases, the absence of the quality rolls preventing the optimum quality laminates or to achieve productivities which are capable the rolling mills. The choice of material for the rolling mill rolls is the operation which take into account both their own usage of the rolling process corresponding with the rolled type of products (half–finished or finished laminated products), as well as characteristics of the different materials considered optimal in the manufacturing of the various rolls.

In fact, an essential feature of indefinite chill rolls is the critical balance between alloying elements such as Carbon [C], Nickel [Ni] and Silicon [Si], which promote the formation of graphite and carbide forming elements such as Chromium. The proper balance of graphite and carbides 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 type and distribution of graphite.

The performed research had in view to obtain correlations between the chemical composition (defined by the one of the basic element – Silicon [Si], and one of the main alloying element – Nickel [Ni]) and the hardness of the indefinite chilled cast iron rolls (on the roll’s working surface and on the both necks). Indefinite chilled rolls are basically controlled under actual molding and casting conditions, therefore the desired hardness is obtained by changing the carbide/graphite balance, including the Carbon [C]/Silicon [Si] and Silicon [Si]/Nickel [Ni] ratios or Carbon [C] – Silicon [Si] – Nickel [Ni] relationship, which is achieved by a close control of chemistry and process parameters.
References

[1] Schröder K H 2002 Questions, answers, more questions, Twenty – five years of experience in discussing rolls and rolling technology, ESW Handbook

[2] Schröder K H 1988 Rolling conditions in hot strip mills and their influence on the performance of work rolls, Metallurgical Plant and Technology 4 44-56

[3] Kiss I 2008 Rolling rolls – Approaches of quality in the multidisciplinary research, Mirton Publishing House, Timisoara

[4] Vdovin K N, Zavalishchin A N, Gorlenko D A and Feoktistov N A 2016 Structure and properties of cast iron designated for working layer of rolls, Journal of Materials Science Research 5(1) 77-88

[5] Krawczyk J 2011 Microstructure and tribological properties of mottled cast iron with different chemical composition, Archives of Materials Science and Engineering 51(1) 5-15

[6] Kiss I 2012 Investigations upon the indefinite rolls quality assurance in multiple regression analysis, Revista de Metalurgia, CENIM 48(2) 85-96

[7] Kiss I, Cioata V G and Alexa V 2010 Increasing the rolling–mill rolls quality in some multidisciplinary research, Acta Technica Corviniensis – Bulletin of Engineering III(2) 31-36

[8] Kiss I 2008 Research upon the quality assurance of the rolling–mill rolls and the variation boundaries of the chemical composition, Revista de Metalurgia, CENIM 44(4) 335-342

[9] Kiss I 2013 Investigations on materials used for manufacturing the rolling rolls in few durability experiments, International Journal of Surface Engineering and Interdisciplinary Materials Science 1(1) 46-56

[10] Kiss I, Alexa V, Ratiu S A and Cioata V G 2014 The quality assurance in the rolling industry: Methods, approaches and tendencies, Machine Design 6(4) 131-136

[11] Kiss I, Cioata V G, Alexa V and Ratiu S A 2011 Technological behaviour and interpretations in some multidisciplinary approaches, Annals of F.E.H. – International Journal of Engineering, IX(4) 203-206