DESIGNING OF NUMERICAL MODEL APPLICATION TO PREDICT FINAL HYDROGEN CONTENT AT END OF VACUUM DEGASSING TREATMENT

DOSTÁL Miroslav

VSB-Technical University of Ostrava, Faculty of Materials Science and Technology, Ostrava, Czech Republic, EU, miroslav.dostal@vsb.cz

Abstract

The main topic discussed in this work is the reduction of hydrogen content in high grades of steel for the production of seamless pipes using processes of secondary metallurgy and vacuum degassing. The aim of thispaper is the statistical analysis of operational data with a follow-up to the preparation of a statistical model for calculating the final hydrogen content in steel after processing in a vacuum. The preparation of the model consisted in the analysis of operating conditions from available production data, statistical evaluation of individual input parameters and their mutual dependence and impact on melt processing. From the results of the analytical part, the necessary inputs for the preparation of a prediction model were obtained, which enables the simulation of the resulting values of the final hydrogen content in the melting on the key´s input parameters defined by the analysis. The result of the predictive statistical model is the approximate expected final hydrogen content, including the values of the other variables that enter into the process.

Keywords: Hydrogen removal, vacuum degassing, statistical model

1. INTRODUCTION

At Liberty Ostrava, a.s. (formerly ArcelorMittal Ostrava, a.s.) a vacuum station (VD) was built in 2013 as a part of the modernization of the continuous steel casting equipment (Continuous caster No. 1), which is part of the secondary metallurgy of the steel plant. This equipment is currently unique in the Czech Republic due to its dimensions and ability to use the ladles weighing up to 220 tons of steel [1]. The equipment enables the removal of non-metallic inclusions, modification of the chemical composition of steel, thermal and chemical homogenization. With its parameters, the device will ensure a reliable possibility of producing microalloyed and special steels with strict requirements for chemical composition, including steel degassing and precise alloying in the required time and with minimal heat loss. Part of the overall reconstruction of the facility was also the construction of a new continuous steel casting technology enabling the increased production of cast formats depending on the customer's requirements, thereby increasing competitiveness on the market. The newly introduced grades and formats are primarily intended for the production of seamless pipes not only for the high demanding operating conditions of various industries [1]. The main goal was to analyse the start-up of the new vacuum station and subsequently define the key parameters for the processing of steel in a vacuum, both from the point of view of current theoretical knowledge and operational experience. Target was to develop on the basis of the analyses carried out from the tracked operational key input parameters of the steel processing process in a vacuum a statistical model for calculating the final hydrogen content. Statistical model works with the possibility of variation of individual input parameters for possible simulation and prediction itself.

2. THEORETICAL PART

Hydrogen has a significant effect on the mechanical properties of steel [2]:

- degradationof plastic properties, and to a lesser extent its strength and notch toughness,

- is the main cause of hydrogenflakes presence, porosity and micro cracks,

- increased hydrogen content in steel causes red-hot embrittlement of steel, and thus an increase in the number of surface defects on forgings and rolls [3].

Changes in the mechanical properties of cast steel were investigated in detail at different time intervals. The main sources of hydrogen in steel include [4]:

- moisture in raw materials (in ore, lime, bauxite, lignite, metal charge and ferroalloys),

- hydrogen and water vapor content in the furnace atmosphere and in the air,

- humidity of the lining of the tapping part, pouring ladle and pouring systems,

- leaks associated with poor equipment condition (water-cooled parts of the furnace) [4].

2.1   Principle of removal of hydrogen from molten steel

The removal of hydrogen from steel melts during out-of-furnace refining takes place in a ladle in a caisson-type device through bubbles of blown inert gas and a free surface exposed to the effect of reduced pressure, or by means of so-called vacuuming [5]. If a carbon reaction is also caused by the reduced pressure above the steel level in the ladle, then the resulting CO bubbles also ensure the release of hydrogen from the melt [6]. The basic thermodynamic condition for steel degassing is therefore a lower partial pressure of hydrogen in the gas phase (in the atmosphere above the bath or gas bubble in the metal bath) than the equilibrium pressure of these gases corresponding to their content in the steel [6]:

$$P_{H2} < P_{H2,\,r} \tag{1}$$

The beneficial effects of steel vacuuming consist mainly not only in reducing the content of gases dissolved in steel, but also in influencing the course of the carbon reaction, the product of which is gas phase - carbon monoxide [7].

3.   EXPERIMENTAL PART

The aim of the experimental part was to create a statistical model of hydrogen reduction (melt degassing) by vacuum technology in highly demanding grades of steel intended for the production of seamless pipes. On the basis of theoretical knowledge, a partial goal was to verify process observations in industrial plant and to define key parameters as important inputs for the second part of experimental part. Furthermore, the goal was to use these data for statistical evaluations and to create a simple statistical model of the final hydrogen content in the melt from the obtained dependencies. The primary goal was to create a statistical model that is based on the key parameters of the process, i.e. those that are verified by statistical evaluation within the variables [8].

3.1.   Regression analysis

The results of measuring the hydrogen content were processed for the period 7/2014 to 6/2015. In total, the file for the above period contained data for 199 meltings. As part of data file preparation, data that do not correspond to the actual process state (e.g. measurement error, system malfunctions) were removed. The partial correlation output shows the significance of other process parameters on the final hydrogen content after VD [8]. According to the result of the processed data, the processing time in a deep vacuum, the maximum achieved negative pressure, the amount of blown argon and the total processing time at VD were identified as key parameters. The input variables and the dependence between them, as well as the number of evaluated statistics along with the maximum, minimum and average value of the given variable are shown in **Table 1** [8]**.**

Table 1 Variables input entering into the regression statistics of hydrogen content and important parameters[8]

Parameters - variable	Nr. of values	Typ	Min.	Max.	Average	Unit
Total treatment time (min)	199	Regressor	24	98	53.6	min
Hydrogen content	199	Regressant	0.72	5.7	2.02	ppm
Maximum of the vacuum (mBar)	199	Regressor	0.01	1.29	0.72	mbar
Hydrogen content	199	Regressant	0.72	5.7	2.02	ppm
Vacuum treatment (min)	199	Regressor	7.6	30.2	20.4	min
Hydrogen content	199	Regressant	0.72	5.7	2.02	ppm
Amount of blowed Ar (Nm/l)	199	Regressor	551	23,965	9,754	Nm/l
Hydrogen content	199	Regressant	0.72	5.7	2.02	ppm

3.2 Results of regression statistics of hydrogen content and important parameters

An important result of the regression curve is primarily the correlation coefficient R, which cantake on the values (0;1>; the closer it is to one, the more the dependence can be considered linear). The coefficient of determination R^2 expresses the percentage of cases affected by a given addiction, hence the reliability of this addiction. A certain degree of linear dependence can be considered from the value of the correlation coefficient R of 0.2. The p-value is the probability that the test statistic takes on values that are "worse" (more against the hypothesis being tested) than the observed value of the statistic. For a variable to be included in the regression equation, the P value should be within 0.1, preferably within 0.05. The α value indicates the angle that the regression line makes with the x-axis. The closer the absolute value of this quantity is to the angle α = 45°, the more intensively the regressor affects the hydrogen content. The values of individual parameters are shown in **Table 2**, which are the results of regression statistics [8].

Table 2 Results of regression statistics of hydrogen content and important parameters [8]

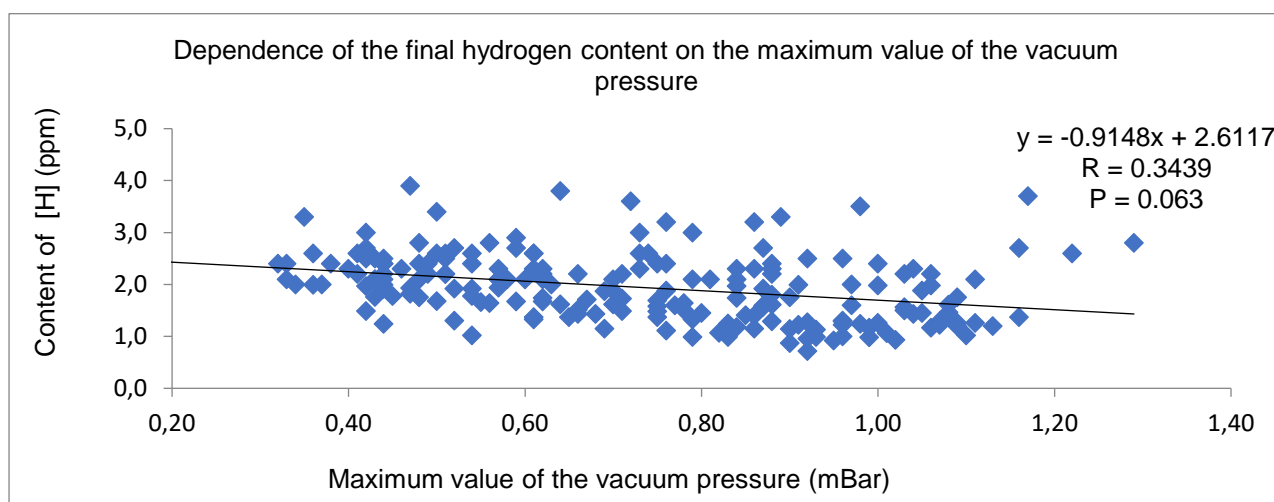| Content of [H]	R	P	α
Duration of total treatment time	0.0574	0.05	-3.5°
Duration of vacuum treatment	**0.5490**	0.071	-9.8°
Maximum value of the vacuum pressure	**0.3439**	0.063	-8.3°
Amount of blowed Ar	**0.2555**	0.120	9.2°

Figure 1 Dependence of the final hydrogen content on the maximum value of the vacuum achieved [8]

3.3. Evaluation of the influence of key process parameters on the final hydrogen content

Figure 1 shows an example of the resulting linear regression with a significant dependence of the final hydrogen content on the maximum value of the negative pressure achieved at the vacuum station [8].

The maximum value of vacuum achieved is a key parameter together with the vacuuming time for the effective removal of hydrogen in steel. It is known from practice that the maximum depth of vacuum should be achievable below 1mBar in the tank, with a duration of processing in deep vacuum of at least 15 minutes. In this process mode, the input hydrogen content is not decisive, as its decrease is very significant at the beginning of the vacuum processing [8]

3.4. Preparation a statistical model for calculating the final hydrogen content

The results of the previous analyses were subsequently used to create a prediction of individual operating conditions with the aim of calculating the final theoretical value of hydrogen at the end of the vacuum treatment for a given combination of key parameters. The input value of hydrogen is defined by a constant of 8 ppm for easier entry of the mathematical calculation. The effectiveness of the degassing process at VD in our conditions is greatly influenced by the time of vacuuming, together with the maximum value of vacuum pressure achieved and the amount of blown argon. The model simulation reflects the evolution of the resulting hydrogen in the melt according to the default setting of the input parameters. While always one of the parameters serves as a constant quantity for generating the range for graphic display [8]. The individual steps of calculating the statistical model can be seen in **Figure 2.** For the purposes of implementing the mathematical model, the option of the open MS VBA environment (as a licensed Microsoft Office product) was used. As a part of the implementation, the algorithm described above can be divided into parts: Initialization after opening the model, Calculation for the current settings, Elements of the graphic environment, Dataset for integration into external applications (PowerBI dashboards, PowerToolkit) and Dynamic matrix generation for displaying the resulting curve [8]. Furthermore, software graphic elements were used to create a user-friendly interface for calculating the final hydrogen content under operating conditions [8].. Among the application elements of the model were included:

- Initialization after opening the model - the "Workbook_Open" method serves to initialize the model itself and perform optional settings of individual quantities. It also serves to set user access to individual elements of the model [8],

- Calculation for the current setting - in this case, a quick calculation is performed for the set input parameters, always with regard to the required resulting hydrogen [8].

- Elements of the graphic environment - built-in GUI elements on the ActiveX platform, serve for more user-friendly parameter settings [8].

- Dataset for integration into external applications - external connection using a data model to external applications - e.g. PowerBI, or other tools on the MS platform [8],

Dynamic matrix generation to display the resulting curve - an element to create the input data for the resulting graph - here it is a set of dynamic links / formulas - in this case they proved to be a suitable approach for this solution, without the need for Event Management while maintaining a solid calculation speed. Visual Basic for Application is a procedural programming language widely used in Microsoft products [8]. It is based on the then quite widespread Basic interpreter, which was originally part of many operating systems. A modernized version of this environment has become part of the MS Office product, where it provides the possibility of development with a high degree of compatibility between individual versions. Another advantage is a stable monolithic core that uses standard data types and libraries. Thanks to this, it also offers the possibility of using functions and methods of other libraries of the .NET platform [8]. For these reasons, as well as the fact that there are no other license restrictions, the VBA environment was also used for the purpose of writing the numerical simulation user interface for this work. Graphic User Interface (GUI) is a user interface that allows

you to control a computer using graphical controls. In the self-created statistical model for calculating the final hydrogen content, it serves for an easier option of setting the input parameters and also for the interpretation of the results [8]. The interactive elements used are part of the ActiveX library and use the VBA environment to run numerical code. ActiveX is an extensive platform supplied by Microsoft, mainly within its own products. The platform includes a set of controls, libraries for communication between applications and other plug-ins. It was primarily intended for the web and web browsers, however, it is no longer used as often here, mainly for security reasons. On the contrary, it still fulfills its purpose as part of the MS office package. The statistical model uses ActiveX platform controls as part of the GUI. Primarily, these are all interactive components (sliders, buttons). Power BI is a software product designed for working with data, subsequent analysis and development of dashboards [8]. The product is developed by Microsoft and primarily focuses on the field of BI (Business Intelligence). In this work, it is mentioned rather marginally, as a possibility of further possible integration of the model. Like most products in the MS family, it offers a number of different data connectors for retrieving data from a source. The numerical model uses data sets that are compatible with this platform from the ground up, so all outputs can be easily integrated [8]. The user interface (GUI) for setting up the numerical model contains the basic parameters used for the simulation. It also contains ActiveX controls for easier operation/change of parameter range (sliders) and choice of simulated parameter settings (RadioButton module) [8]. In a simplified way, we can describe entering model input data in connection with the images below. In **Figure 3**, we can see the basic interface of the model, where it is important to mention two parts, including entering input values for a specific example of model calculation. In the first part, it is necessary to choose a variable parameter, that is, a parameter that we want to influence and define input value [8]. When marking one of these parameters, we can go to the second step, which is setting the values within the limit ranges. It should be mentioned here that the statistical model works with a data set of 199 melts, i.e. the same one that was used for the statistical analysis in the previous chapter. It is therefore important to mention that the theoretical limits of the calculation are based on the collected process data. The area for entering input values simply indicates the possibility to choose the required value for an individual parameter with a sliding button [8]. An example of a model calculation was chosen with a defined constant parameter "argon consumption (12,845 Nm/l)". The combination of values entered by us for the maximum value of the negative pressure (0.61 mbar) and the time of the deep vacuum (12 min) also participates in the calculation, when we arrive at the calculated final hydrogen value of 2.18 ppm using the numerical model [8].
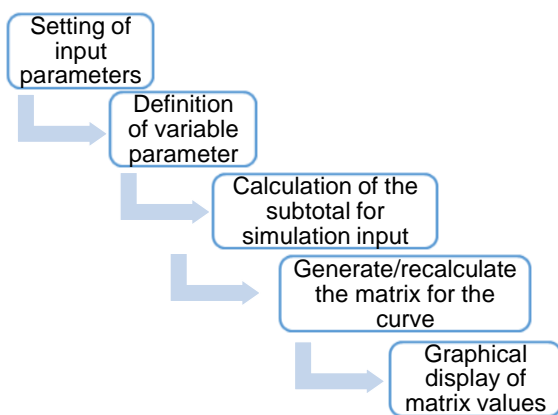

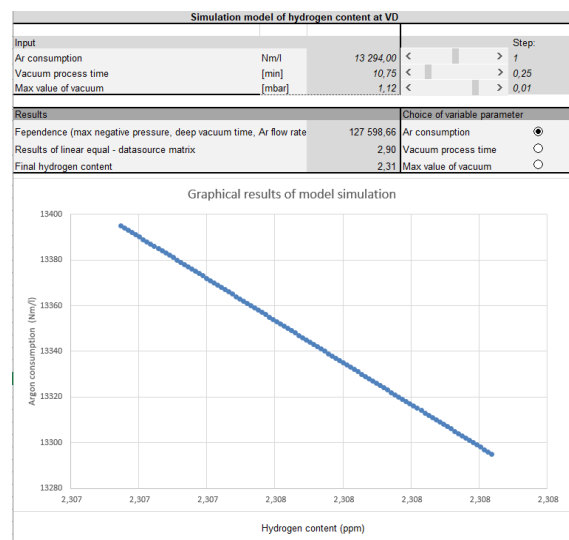**Figure 2** Process steps of statisticalmodelcalculation[8]

Figure 3 Model calculation of the dependence of the final hydrogen content [8]

4.   CONCLUSION

This article wasfocused on using vacuum metallurgy with the aim of controlling the hydrogen content with using of numerical model. The aim of the work consisted in comparison of influence of selected parameters on final content of hydrogen at steel refining in the VD tank to prepare reliable data source for the preparation of statistical model to calculate and predict final hydrogen content in steel. On the basis of these analyses and model examples, it is possible to see the significance of the inert gas blowing intensity in combination with a shorter processing time in a deep vacuum, a maximum value of the vacuum achieved, when the individual values of the calculated final hydrogen contents are not very different. Still according to the expected specifications for the quality of steel produced. Therefore, questions arise as to how the degassing process in operation can be designed with regard to the speed of degassing, and the associated energy and economic demands. The implementation and understanding of the statistical model itself is very simple for any user. At the same time, it gives a very good opportunity to define a combination of limit conditions for these key input parameters. You can immediately see where the course of the process can move us. In the case of expansion of the data set, we can very easily add additional input parameters from new operational results, thus the model can be functionally expanded and statistically refined. It is in no way a substitute for numerical models for the purposes of automatic regulation, which can react online to operating conditions without human intervention. The model gives the opportunity for real-time and past-time data verification with regard to possible theoretical optimization of the process. The actual calculation of the final result is based on the source file, which compares all the collected data with each other for an optimal estimate of the resulting value. In our case, it is the final hydrogen content at the end of the vacuum treatment. By the fact that it is a closed data file without random generation of additional input variables, it is always guaranteed that the progress is based on the combination of our key values prepared in the data file. Therefore, it is not possible to get outside the defined limits of the data file.

REFERENCES

[1]   VÁLEK, L., MAREK, A., TKADLEČKOVÁ, M., KOCIÁN, L., PACHLOPNÍK, R., GUMULEC, T., HINTERREITER R., SVIŹELOVÁ, J. Nové možnosti výroby kruhových sochorů na modernizovaném ZPO č.1 v Arcelormittal Ostrava a.s. In: *31. ročník konference o teorii a praxi výroby a zpracování oceli- Oceláři*, Rožnov p. Radhoštěm: Tanger, 2015, pp. 73-79. ISBN: 978-80-87294-56-7.

[2]   BROŽ, L. a kol. *Hutnictví železa.*1. vydání. Praha: SNTL, 1988, p. 460.

[3]   MOROZOV, A.N. *Vodík a dusík v oceli*. Praha: Státní nakladatelství technické literatury, 1953, p. 203.

[4]   FRUEHAN, R. J., ed. *The making, shaping and treating of steel*. 11th ed. Pittsburgh: AISE Steel Foundation, 1998. ISBN 0-930767-02-0.

[5]   KASZPERYDES, A. *Parametry ovlivňující odplynění oceli v podmínkách vakuovací stanice RH*. Ostrava, 2012. Bachelor thesis. VSB - Technical University of Ostrava.

[6]   KEPKA, M. *Rafinace oceli*. 1. vydání. Praha: SNTL, 1989, p. 211.

[7]   ADOLF, Z. Sekundární metalurgie, Studijní opora, VŠB – TU Ostrava, FMMI, 2012.
       Dostupné na http://www.vsb.cz/618-ADOLF-SEKUNDÁRNÍ-METALURGIE.pdf.

[8]   DOSTÁL, M. *Zpracování náročných jakostí oceli pomocí vakuové metalurgie s cílem řízení obsah uvodíku výpočtovým modelem.* Ostrava, 2023. Dissertation thesis. VSB - Technical University of Ostrava.