Research regarding the vacuuming of liquid steel on steel degassing

M Magaon¹, M Radu¹, S Şerban¹ and L Zgripcea²
¹Politehnica University of Timisoara, Engineering and Management Department, Revolutiei str., no. 5, 331128 Hunedoara, Romania
²S.C Hydromatic Sistem S.R.L, Calea Buziasului Street, no. 11, Timisoara, Romania
E-mail: miruna_magaon@yahoo.com

Abstract. When the liquid steel comes in contact with the atmosphere of the elaboration aggregates, a process of gas diffusion into the metal bath takes place on the one hand, and on the other hand, a process that allows them to pass from the metal bath into the atmosphere. The meaning of these processes is determined by a number of factors as follows: the quality of raw and auxiliary materials (moisture content, oils, etc.), the boiling intensity, the evacuation duration, the properties of used slags, the values of the casting ladle processing parameters (bubbling, vacuuming, etc.). The research was carried out at an electrical steelwork, equipped with an electric arc furnace type EBT (Electric Bottom Tapping) capacity 100t, LF (Ladle-Furnace) and VD (Vacuum Degassing) facilities, establishing some correlations between the vacuuming parameters from the V.D. facility and the amounts of hydrogen and nitrogen removed from the metal bath, as well as their removal efficiency, were taken into consideration. The obtained data was processed in MATLAB calculation program, the established correlations form was presented both in analytical and graphical form. The validity of these correlations was verified in practice, being particularly useful in research.

1. Introduction

When the liquid steel comes in contact with the atmosphere of the elaboration aggregates, on one hand, a process of gas diffusion into the metal bath takes place and, on the other hand, a process that allows them to pass from the metal bath into the atmosphere. The meaning of these processes is determined by a number of factors such as: the quality of raw and auxiliary materials (moisture content, oils, etc.), the boiling intensity, the evacuation duration, the parameters compliance with the casting ladle processing (LF/VD), the properties of used slags, the values of the casting ladle processing parameters.

In steel manufacturing process, besides non-metallic inclusions, gases like hydrogen, nitrogen, and oxygen remain trapped in its structure.

The hydrogen represents an impurity for steel products, its negative influence is manifested especially in steel because: it is one of the causes of sulphides in ingots and calmed steel castings, it decreases the elasticity and toughness of the steel, it contributes to the occurrence of the defect called "flakes" in steels alloyed with chromium and nickel, which substantially reduces fatigue strength of steel parts and affects the electrical and magnetic properties of steels. In order to produce steel with low hydrogen content, a series of measures must be applied to the manufacturing flow such as [1-4]: the cargo used must be of good quality, without moisture, oils, plastic materials, calcinated additions, freshly burnt limestone; the treatment of steel under vacuum; the adequate heating of the casting
machine (the ladle and the distributor). The negative influence of nitrogen in steel is manifested in the following considerations [1], [2], [5]: it reduces the plasticity and toughness of the steel; in combination with hydrogen contributes to the appearance of sulphides in the cast steel; it causes the ageing phenomenon of the steel by depositing nitrides at the structural grains limits.

During the steel elaboration process, boiling the metal bath has a very important role in the degassing process, caused by the release of the carbon monoxide bubbles.

When these carbon monoxide bubbles are formed, the partial pressure of hydrogen and nitrogen is practically null and, therefore, the gases diffuse inside these bubbles under the action of concentration gradients, and then disposed outside the bath [4], [6].

In order for the speed of the gas removal from the steel bath to be higher than the passing speed through the slag in the metal bath and thus the nitrogen content to fall, the speed of decarburization needs to be high enough to overcome a certain critical value, in order to cause pressure in the carbon monoxide bubble above the ferrostatic pressure [5], [6].

Regarding the electrical steelworks equipped with electric arc furnaces type EBT, very good conditions to reduce gas absorption in the steel bath (high-speed boiling of the metal by the intense blowing of oxygen, the foaming of slag and the possibility of bubbling with argon in the oven) were provided [3], [5], [6].

The introduction of the so-called "Metallurgy into the pot" into the steel elaboration technological flow produced a genuine technical revolution in steel industry, some of the processes that took place in aggregates elaboration were transferred to the casting ladle, particularly in LF (Ladle-Furnace) facilities and vacuum facilities without heat input (R. H., V.D.) and with heat input (V.A.D., V.O.D. etc.) [1], [2], [5], [6].

2. Industrial experiments. Data processing

In the research conducted, the possibilities to reduce the hydrogen and the nitrogen content from steels designed for pipes manufacturing were investigated. The obtained results are presented in this paper.

The research was carried out on an electrical steelwork, equipped with an electric arc furnace type EBT (Electric Bottom Tapping) capacity 100t, LF (Ladle-Furnace) facility, VD (Vacuum Degassing) facility and a 5 wires continuous casting (ITC) facility. On the flow presented a total of 20 steel batches were followed, S 275 JOH (EN 10216-1) type steel, circular rolled with a diameter of Ø180mm. The 20 batches were monitored throughout the technological flow, stage by stage, as follows:

- Elaboration in the furnace: loads of good quality, without scrap with oil, moisture, rust under about 2%, freshly burnt limestone, calcined iron ore, adequately heated casting ladle;
- LF and VD treating facility: respecting the limits of variation of technological parameters (heating, bubbling), additions without moisture (for slag formation and alloying), mixing chemical and thermal by bubbling with argon followed by treatment in the vacuum facility without VD heat input, in the casting process the ladle and the distributor were heated adequately;
- The continuous casting compliance parameters: the casting speed correlated with the casting temperature, flow rate and pressure of cooling water in each cooling zone.

Based on the the hydrogen and nitrogen content before and after vacuuming, the quantities of removed gases were calculated (ΔH [ppm] and ΔN [ppm]), respectively their removal efficiency (ηH [%] and ηN [%]), which are considered to be the dependent parameters. The independent parameters considered are: the total duration of vacuuming Dtv [min]; the duration of ultra-high vacuuming Dva [min] and the pressure in the vacuum facility under ultra-high vacuuming Pva[mBar].

By processing the obtained data in the MATLAB calculation program, multiple correlation equations have resulted between the independent and dependent parameters, the results being presented both in the analytical and graphical form in figures 1-15.

In order to obtain these correlations (z- dependent parameter, x and y - independent parameters), the following equations forms were used:
Equation 1
\[ z = a_1 + a_2 \cdot x + a_3 \cdot x^2 + a_4 \cdot x^3 + a_5 \cdot y + a_6 \cdot y^2 + a_7 \cdot y^3 + a_8 \cdot y^4 + a_9 \cdot y^5 \] (1)

Equation 2
\[ (z = a_1 + a_2 \cdot \log(x) + a_3 \cdot \log(x)^2 + a_4 \cdot \log(x)^3 + a_5 \cdot \log(y) + a_6 \cdot \log(y)^2 + a_7 \cdot \log(y)^3 + a_8 \cdot \log(y)^4 + a_9 \cdot \log(y)^5) \] (2)

In the following figures are presented the most significant correlations obtained both in terms of values for correlation coefficients, as well as for technological direction.

The graphical and analytical representation of the obtained data using the first equation:

Figure 1. Correlation $\Delta H = f(D_{tv}, D_{va})$: a) the correlation surface; b) level curves

\begin{align*}
D &= 705116.851244; \\
H &= -99565.85323; \\
R^2 &= 0.4418765; \\
a_1 &= -49782.926616; \\
a_2 &= -3.540957; \\
a_3 &= 0.104587; \\
a_4 &= -0.000967; \\
a_5 &= 16750.070210; \\
a_6 &= -2240.456339; \\
a_7 &= 149.06927; \\
a_8 &= -4.93461; \\
a_9 &= 0.0650288. 
\end{align*}

Figure 2. Correlation $\Delta H = f(D_{va}, P_{va})$: a) the correlation surface; b) level curves

\begin{align*}
D &= 584969.633965; \\
H &= 7208.758343; \\
R^2 &= 0.662044; \\
a_1 &= -3604.379171; \\
a_2 &= -40.573961; \\
a_3 &= 2.474023; \\
a_4 &= -0.049264; \\
a_5 &= 12556.088689; \\
a_6 &= 16350.753277; \\
a_7 &= 10470.281392; \\
a_8 &= 3323.588525; \\
a_9 &= 417.124588; \\
y_1 &= x^2x^3
\end{align*}
D=114505539.5218; H=-90741.47209; R^2=0.6842; a1=-45370.73604; a2=-630.952437; a3=39.5767; a4=-0.8156; a5=161252.2037; a6=-211002.2892; a7=136512.1858; a8=43666.7105; a9=5524.3698.

**Figure 3.** Correlation $\eta_H = f(D_{va}, P_{va})$: a) the correlation surface; b) level curves

D= -50936586.7253; H= -298348.3767; R^2 = 0.4537469; a1= -149174.1883; a2= 85.36426; a3= -3.0903; a4= 0.0369; a5= 49257.1978; a6= -6497.2367; a7= 425.80702; a8= -13.8673; a9= 0.1795.

**Figure 4.** Correlation $\Delta N = f(D_v, D_{va})$: a) the correlation surface; b) level curves
\(D = -143127.630479; \quad H = -648.1332002; \quad R^2 = 0.772582; \quad a_1 = -324.0666001; \quad a_2 = 110.376649; \quad a_3 = -7.077384; \quad a_4 = 0.1501739; \quad a_5 = -1530.507378; \quad a_6 = 3526.358771; \quad a_7 = -3602.854107; \quad a_8 = 1676.1338907; \quad a_9 = -290.3976957; \quad Y_3 = x_2 x_3\)

**Figure 5.** Correlation \(\Delta N = f(D_{va}, P_{va})\): a) the correlation surface; b) level curves

\(D = -11520280.645924; \quad H = -97947.685681; \quad R^2 = 0.4076934; \quad a_1 = -48973.842842; \quad a_2 = 58.808314; \quad a_3 = -2.0189403; \quad a_4 = 0.0228829; \quad a_5 = 15766.0797; \quad a_6 = -2035.283404; \quad a_7 = 130.203671; \quad a_8 = 4.127074; \quad a_9 = 0.051839.\)

**Figure 6.** Correlation \(\eta = f(D_{tv}, D_{va})\): a) the correlation surface; b) level curves
Figure 7. Correlation $\eta_N = f(D_{va}, P_{va})$: a) the correlation surface; b) level curves

The graphical and analytical representation of the obtained data using the second equation:

$$D = -2271528.789341; H = -4291.142356; R^2 = 0.8268917; a1 = -2145.571177; a2 = 264.641941; a3 = -17.213466; a4 = 0.369775; a5 = 2922.322108; a6 = -3644.849781; a7 = 1964.816843; a8 = -426.285141; a9 = 20.1586318;$$

Figure 8. Correlation $\Delta H = f(D_{tv}, D_{va})$: a) the correlation surface; b) level curves

$$D = 211034332.035952; H = 141201.0480609; R^2 = 0.4421996; a1 = 70600.5241; a2 = 747.4977; a3 = -246.1921; a4 = 26.8182; a5 = -5403329.0948; a6 = 162957468.5082; a7 = -2445846673.9457; a8 = 18265542497.9899; a9 = 54285159029.6510.$$
\[ R^2 = 0.69051; \quad a_1 = 38765.73730; \quad a_2 = -61629.34808; \quad a_3 = 22304.67077; \quad a_4 = -2684.798405; \]
\[ a_5 = 111192.7945116; \quad a_6 = -266863.828855; \quad a_7 = 306915.8584278; \quad a_8 = -166257.084709; \]
\[ a_9 = 32774.859651; \]

**Figure 10.** Correlation \( \eta_H = f(D_{va}, P_{va}) \): a) the correlation surface; b) level curves

\[ R^2 = 0.4596777; \quad a_1 = 84423.7519; \quad a_2 = 21774.374948; \quad a_3 = -6590.29533; \quad a_4 = 664.32948; \quad a_5 = -8554613.52623; \]
\[ a_6 = 267878925.313956; \quad a_7 = -4159978032.23881; a_8 = 32039478846.2628; \quad a_9 = -97909697827.6924 \]

**Figure 11.** Correlation \( \Delta N = f(D_{tv}, D_{va}) \): a) the correlation surface; b) level curves
R^2=0.7712696; a1=-15128.621905; a2=10627.85422007; a3=-3873.1318372; a4=469.9147357; a5=36905.8670319; a6=-98389.2377431; a7=128597.8130189; a8=-82499.246152; a9=20828.695835;

**Figure 12.** Correlation ΔN = f(D_{va}, P_{va}): a) the correlation surface; b) level curves

D=-1459235866.36140; H=-59400.56406; R^2=0.410592; a1=-29700.28203; a2=12173.443148; a3=-3607.920043; a4=356.1214758; a5=930120.193999; a6=-19966438.3295872; a7=185770804.328888; a8=-592499637.225002; a9=-435401682.323592

**Figure 13.** Correlation η_N = f(D_{tv}, D_{va}): a) the correlation surface; b) level curves
D = -2753858029.17180; H = 48780.7745931; R² = 0.8272189; a1 = -24390.387296; a2 = 27205.9563839; a3 = -9980.1191003; a4 = 1218.552021; a5 = -3175.214067; a6 = 13171.984069; a7 = -25368.699896; a8 = 22854.023043; a9 = -7758.362733;

**Figure 14.** Correlation \( \eta_N = f(D_{va}, P_{va}) \): a) the correlation surface; b) level curves

D = 0.550274; a1 = 63736.280833; a2 = 49403.656749; a3 = -14701.351024; a4 = 1457.077641; a5 = -853705.21048; a6 = 2431071.365372; a7 = -3434032.851742; a8 = 2406387.735273; a9 = -669292.604992085.

**Figure 15.** Correlation \( \eta_H = f(D_{va}, P_{va}) \): a) the correlation surface; b) level curves

### 3. Results analysis

From the results obtained in the Matlab calculation program, the correlation surfaces and the level curves in flat projection are presented in graphical form and the correlation equation in analytical form in order to achieve their technological analysis.

From figures 1, 4, 6, 8, 11 and 13, it clearly appears that the total duration of vacuuming and the duration of ultra-high vacuuming has a combined effect on the quantities of hydrogen and nitrogen removed from the metal bath during vacuuming, as well as on their removal efficiency.

Values for the total duration of vacuum of 28-32 minutes and for the duration of ultra-high vacuuming of 13-18 minutes can ensure the hydrogen reduction content of more than 3.5ppm, the average nitrogen reduction content of 12ppm, for \( \eta_H \) more than 70% and for \( \eta_N \) an average of 15%.

Analysing figures 2, 3, 5, 7, 9, 10, 12 and 14, it also appears that the duration of ultra-high vacuuming and the pressure in the vacuum facility under ultra-high vacuuming has the same combined
effect as mentioned above. Values for the duration of ultra-high vacuuming of 13-18 minutes and the pressure in the vacuum facility under ultra-high vacuuming of under 1.7 mBar can ensure the hydrogen reduction content of more than 3.5ppm, the average nitrogen reduction content of 12ppm, for $\eta_H$ more than 68% and for $\eta_N$ an average of 16%.

The analysis of the correlation regarding the cumulative influence of the total duration of vacuuming and of the pressure in the vacuum facility under ultra-high vacuuming on the hydrogen removal efficiency (figure 15) confirms the validity of the above assertions, meaning that values for $\eta_H$ of more than 70% can be obtained.

4. Conclusion
From the results obtained by processing the data in the MATLAB calculation program, one can conclude the following:

- there is a large dispersion of the values for the amounts of hydrogen ($\Delta H$) and nitrogen ($\Delta N$) removed from the metal bath, as well as for the hydrogen and nitrogen removal efficiency ($\eta_H$ [%] and $\eta_N$ [%]), depending on the vacuuming parameters ($D_v$, $D_a$ and $P_{va}$);
- if the values for $P_{va}$ are under 1.4 mBar the obtained values for the hydrogen and nitrogen removal efficiency are $\eta_H$ $\geq$ 70% and $\eta_N$ $\geq$ 15%;
- the ultra-high vacuuming duration has a significant influence on the hydrogen removal efficiency ($\eta_H$), its desired duration is 18 even 20 min.

By using in practice the obtained diagrams, values for the vacuuming parameters can be established in order to obtain estimated values both for the removed quantity and the removal efficiency of gases.

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