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The Degassing Laws for Railway Wheel Steel in a Vacuum Tank Degasser

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Abstract. The research presents the results of data analysis on degassing of wheel grades of steels in a tank degasser with a capacity of 120 tons, operated at the JSC "Ural Steel". The volume of the analyzed sample included 754 steels for railway wheels (steel grades "2" and "T" according to State standard GOST 10791-2011) weighing more than 80 thousand tons received in November-December 2019.

It was established that in order to guarantee the production of hydrogen content of less than 1.5 ppm and nitrogen before 0.007%, it is necessary to carry out vacuum treatment of metal with overheating of 110-130°C at the residual pressure of up to 3 mbar for 20-25 minutes and argon flow rate of at least 0.05 m^3/ton.

The regression equation was obtained, which allows to predict the results of degassing, as well as select the values of vacuum treatment parameters in order to achieve a given content of dissolved gases - hydrogen and nitrogen.

The Overview of the Problem

The steels for the manufacture of railway wheels are subject to increased requirements for the content of dissolved gases - hydrogen and nitrogen. Thus, in accordance with the specifications for the manufacture of railway wheel steel (according to State standard GOST 10791-2011), the mass fraction of hydrogen in liquid steel should not exceed 2 ppm [1], and the requirements for nitrogen content are determined based on the conditions for ensuring regulated mechanical properties. Since nitrogen reduces plastic properties and contact-fatigue strength during the operation [2-5], its content in wheeled steels is usually limited to 0.006-0.008%.

The restrictions on nitrogen content are also due to its negative effect on hot ductility of steel, which can lead to transverse cracking during continuous casting [6-10]. Therefore, wheel grades of steel (according to State standard GOST 10791-2011) are necessarily evacuated.

As it is known, vacuum results are influenced not only by technological parameters of processing, but also by a large number of technological and organizational factors [2-5, 10-20]. Therefore, despite a large number of studies on the effects of hydrogen and nitrogen in vacuuming [10-20], the study of the results of steel degassing in specific production conditions allows us to obtain new patterns and improve the production technology.

The Purpose and Object of the Study

The study of the laws of degassing of wheel steel grades was carried out on the basis of the production data on the results of vacuum metal treatment at the installation vacuum tank degasser (VTD) SIEMENS-VAI with a capacity of 120 tons, operated since 2012 in an electric steel shop of the JSC "Ural Steel". According to the current technology, which has been in operation since 2019, steel smelted in a flexible modular furnace (FMF) and processed at the ladle-furnace installation is subjected to treatment at VTD [21].

The Basic Data

To study the patterns of steel degassing at the VTD, an analysis of the production data on the smelting of wheel steel grades for November-December 2019 was carried out. In total, 754 of melting for railway wheels (steel grades “2” and “T” according to GOST 10791-2011) weighing more than 80 thousand tons were smelted during the study period. The averaged data on process parameters and the results of steel degassing of the studied steels are given in Table 1.

Table 1. The averaged data on process parameters and the results of steel degassing

The parameter	Parameter value * during steel processing			
	Steel 2		Steel T	
Smelting mode **	EAF	BOF	EAF	BOF
Steel wt., [ton]	82.0-141.6 109.0	74.5-119.2 105.7	83.5-136.6 109.2	86.8-129.0 108.0
The processing duration at the VTD, [min]	32.0-84.0 51.4	23.0-78.0 52.6	41.0-91.0 56.4	31.0-71.0 55.9
Deep vacuum treatment time (<0.5 kPa), [min]	10.0-33.0 22.1	10.0-35.0 23.2	15.0-30.0 21.0	11.0-30.0 22.0
Minimum pressure in a vacuum chamber, [mbar]	0.40-3.30 0.62	0.45-6.20 1.35	0.50-2.60 1.05	0.44-3.80 1.10
Argon flow rate, [m^3/ton]	0.022-0.175 0.080	0.025-0.167 0.089	0.036-0.173 0.093	0.044-0.184 0.110
The overheating temp. before VTD, [°C]	76-142 112	82-142 116	94-143 115	94-175 122
The slag level in the ladle, [mm]	101.9	99.3	100	100
Freeboard, [mm]	500-950 559.6	350-950 577.7	500-800 561.0	500-800 579.3
[N] before degassing, [%]	0.009-0.011 0.0095	0.005-0.008 0.0076	0.008-0.011 0.0094	0.006-0.009 0.0082
[N] after degassing, [%]	0.004-0.008 0.0062	0.004-0.008 0.0060	0.005-0.008 0.0065	0.005-0.008 0.0062
[H] before degassing, [ppm]		3.1-9.5 6.1		2.9-9.2 5.6
[H] after degassing, [ppm]	0.70-2.00 1.24	0.70-2.00 1.22	0.90-2.00 1.28	0.90-1.80 1.24

The notes:
* in numerator - the range of change; in denominator - average value.
**the mode of an electric arc furnace (EAF) and the mode of an basic oxygen furnace (BOF) without electric power

As a result of the vacuum treatment, in the vast majority of cases, it is possible to reduce the content of hydrogen and nitrogen to the required levels [18, 20]. The minimum and average values of hydrogen and nitrogen content in steels are much lower than the required values, which indicates unsustainable evacuation modes and leads to an increase in vacuum treatment costs [22]. Therefore, an urgent task is to improve the technology of evacuation of steel.

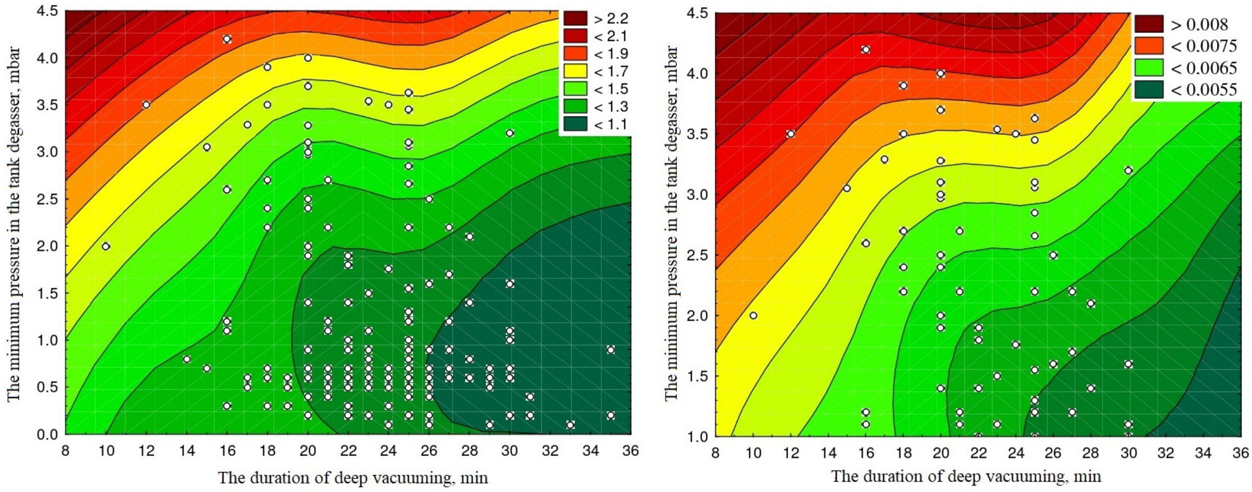
The Results of the Study and their Discussion

The detailed study of the laws of vacuumization was carried out according to the production of steel grade “2” (the most mass) melted in the BOF mode, which provides minimal nitriding of the metal.

For the studied VTD, the main process parameters that determine the degassing results include the depth and duration of vacuuming, argon flow rate, metal temperature, slag layer thickness and freeboard value. At the same time, according to the practice of operating the VTD at the JSC “Ural Steel”, the thickness of the slag layer is stably maintained at 100 mm, and the value of the freeboard in more than 90% of cases is 500-600 mm. Therefore, for further processing from the initial production data, the dropouts of melting was screened with a freeboard value of more than 600 mm, and the influence of the slag layer thickness, visually estimated, was not taken into account.

To illustrate the effect of vacuuming parameters on the residual hydrogen and nitrogen content of steel, three-dimensional dependencies were constructed:

- the dependence of [H] and [N] on the pressure in the vacuum chamber and the duration of vacuumization (Fig. 1) during metal overheating in the range of 100-130°C;
- the dependence of [H] and [N] on the pressure in the vacuum chamber and metal overheating (Fig. 2) with a vacuum duration of 15-25 minutes;
- the dependence of [H] and [N] on the pressure in the vacuum chamber and the flow rate of argon (Fig. 3) with a vacuum duration of 15-25 minutes.



a) b)

Fig. 1. The dependence of the residual content of hydrogen (a) and nitrogen (b) on pressure in the vacuum chamber (VC) and the duration of the deep evacuation during metal overheating in the range of 100-130°C

From the diagrams presented in pictures 1-3, it follows that in order to guarantee a hydrogen content of less than 1.5 ppm and nitrogen up to 0.007%, it is necessary to carry out a vacuum treatment of steel at the following parameters:

- the residual pressure in the vacuum chamber up to 3 mbar;
- the duration of the treatment at deep vacuum not less than 20 minutes;
- argon flow rate for blowdown is not less than 0.05 m^3/ton;
- metal overheating from 110 to 130°C.

The revealed rational range of steel overheating before the start of vacuumization ensures optimal temperature conditions of steel casting. So, with a total duration of the vacuum treatment of 50-55 minutes, the metal temperature loss is 70-75°C. Then, at optimum overheating of metal in a steel ladle before pouring of 35-45°C and the losses of the temperature of metal while transporting from VTD before pouring up to 5°C (up to 15 min.), the optimum temperature of overheating of metal at the beginning of processing on VTD will be 75+ (35-45) +5 ~ 115-125°C that corresponds to optimal conditions of steel degassing at vacuumization.

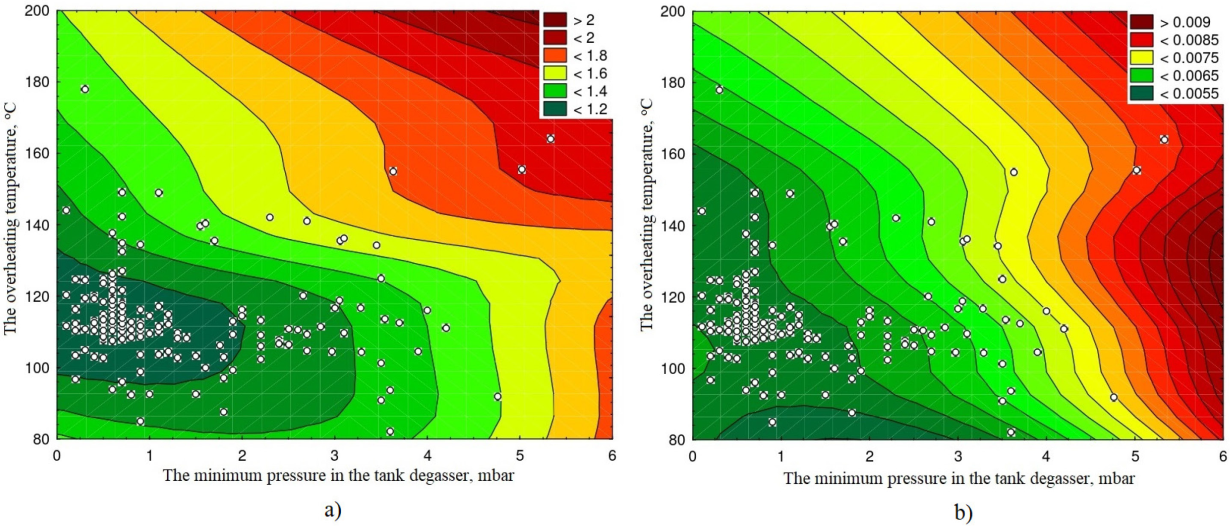


Fig. 2. The dependence of the residual content of hydrogen (a) and nitrogen (b) on pressure in the VC and metal overheating at vacuumization duration of 15-25 minutes

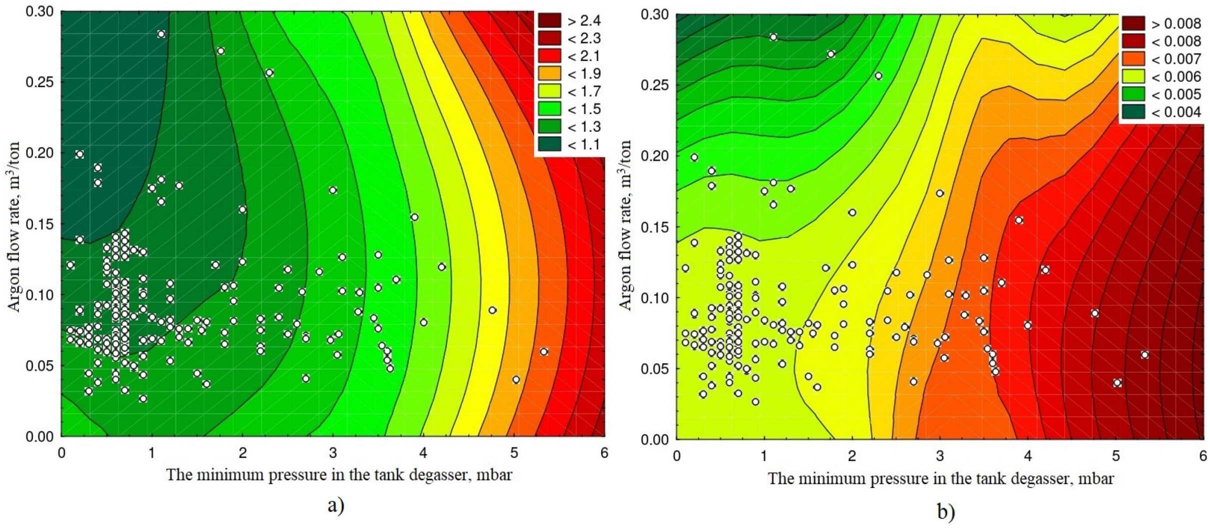


Fig. 3. The dependence of the residual content of hydrogen (a) and nitrogen (b) on pressure in the VC and argon flow rate at vacuumization duration of 15-25 minutes

To quantify the joint effect of vacuumization parameters on the removal of hydrogen and nitrogen, a regression analysis of production data was carried out and the regression equations were obtained:

$$[H] = 0.616 - 0.0101 \cdot \tau_v + 9.8 \cdot 10^{-5} \cdot \tau_v^2 + 0.1 \cdot p_{min} - 0.011 \cdot p_{min}^2 + 0.0087 \cdot t_{over} - 1.6 \cdot 10^{-5} \cdot t_{over}^2 - \\ - 0.141 \cdot v_{ar}, \quad R = 0.49 \tag{1}$$

$$[N] = 0.0023 - 7.2 \cdot 10^{-5} \cdot \tau_v + 2.56 \cdot 10^{-7} \cdot \tau_v^2 + 6.06 \cdot 10^{-5} \cdot p_{min} + 4.62 \cdot 10^{-5} \cdot p_{min}^2 + 7.78 \cdot 10^{-5} \cdot t_{over} - \\ - 2.8 \cdot 10^{-5} \cdot t_{over}^2 - 0.0025 \cdot v_{ar}, \quad R = 0.55 \tag{2}$$

where [H] – the residual content of hydrogen, ppm;
[N] – the residual content of nitrogen, %;
τ_v – the duration of the deep vacuum at the VTD, min;
p_{min} – the minimum vacuum chamber pressure, mbar;
t_{over} – the temperature of overheating at the VTD, °C;
v_{ar} – argon flow rate, m^3/ton.

The obtained regression equations make it possible to predict the residual hydrogen and nitrogen content at the current vacuuming parameters for the operating conditions of the VTD at the JSC "Ural Steel", as well as to quantify the degree of influence of each technological parameter (with the constancy of other factors) on the residual hydrogen and nitrogen content in steel:

- the increase of the duration of deep vacuuming from 15 to 25 minutes helps to reduce hydrogen content by 0.14 ppm and nitrogen content by 0.0006%;
- the reduction of the minimum pressure in the vacuum chamber from 5 to 2 mbar contributes to the reduction of hydrogen content by 0.07 ppm and nitrogen content by 0.0011%;
- the decrease of the overheating temperature from 150 to 110°C helps to reduce hydrogen content by 0.18 ppm and nitrogen by 0.00022%;
- the increase of argon flow rate from 0.05 to 0.15 m^3/ton contributes to the reduction of hydrogen content by 0.014 ppm and nitrogen content by 0.00025%.

Thus, all vacuum parameters included in the regression model have an effect on hydrogen and nitrogen removal. Actual and rational (according to technological and economic criteria) evacuation parameters, as well as degassing results are presented in Table 2.

Table 2. Current and rational evacuation parameters at the JSC "Ural Steel"

Evacuation parameters	Parameters values	
	Actual	Rational
The duration of processing at VTD, [min]	52.6	45
The duration of deep vacuuming at VTD, [min]	22.93	15
The minimum vacuum chamber pressure, [mbar]	1.35	3.0
The overheating temperature at VTD, [°C]	116	120
Argon flow rate, [m^3/ton]	0.089	0.05
Nitrogen content, [%]	0.006	0.007
Hydrogen content, [ppm]	1.22	1.45

Thus, by selecting the evacuation parameters with account of technological capabilities and rational levels, it is possible to predict the level of hydrogen content in steel according to the regression equations obtained earlier, as well as to determine a rational combination of processing parameters when obtaining the required depth of hydrogen and nitrogen removal.

Conclusion

The main parameters of steel vacuuming are determined, which show the efficiency of hydrogen and nitrogen removal from wheel grades of steels in a tank degasser operated at the JSC "Ural Steel".

The quantitative influence of vacuumizing parameters was revealed, which allows to predict its results, as well as select parameter values in order to achieve a given content of dissolved gases in steel.

Economically and technologically rational levels of vacuumizing parameters are defined, which guarantee the production of steel with hydrogen content up to 2 ppm and nitrogen content up to 0,008%.

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