

Non-Metallic Inclusions in Steel in the Process of Deoxidation. Theory

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Equations for removal of oxygen and non-metallic inclusions in the process of steel deoxidation in steelmaking unit, ladle pouring and out-of-furnace treatment are obtained.

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Results and Discussion

The surface of exogenous non-metallic inclusions becomes a place of reaction of element-deoxidant (E) with oxygen during steel deoxidation. C. H. Herty (USA) was the first who has determined that at addition of ferrosilicon in the open-hearth bath the content of non-metallic inclusions reaches the maximum after a while (τ_{max}) and then, as a result of removal of non-metallic inclusion, it reaches the minimum (τ_{min}). Understanding of deoxidizing dynamics regularities and content of nonmetallic inclusions in steel enables to find out processing methods for its minimization.

Addition of reduction alloy into steel-making unit bath kills steel. If deoxidation rate is limited by oxygen transfer to surface of exogenous non-metallic inclusions in metal, it is possible to accept the value of Sherwood number $Sh = 2$ from which oxygen transfer coefficient $\beta_0 = 2D_0/d$, where D_0 - factor of oxygen molecular diffusion, d - size of non-metallic inclusion. Then, the mass of oxygen $dm_0 = \beta_0(0-0^*)\pi d^2\rho_1/100$ will be transferred to non-metallic inclusion surface during time $d\tau$, where $0, 0^*$ - actual and equilibrium with reduction alloy concentration of oxygen, ρ_1 - metal density. At amount of non-metallic inclusions in bath $N = 6M^*HB/100\rho_2\pi d^3$, where M - its weight, HB - content of non-metallic inclusions in metal and density of ρ_2 inclusions, change of oxygen concentration will be $dO = -Nd_{m0}100/M$.

Having substituted and integrated obtained equation within the limits $O = O_i$ at $\tau = 0$ and

$O = O_f$ at $\tau = \tau$, where O_i, O_f - initial and final content of oxygen, we will obtain:

$$\ln[(O_i-O^*)/(O_f-O^*)] = 2HB(\rho_1/\rho_2)D_0\tau/100\rho_2d^2 \quad (\text{Eq. 1})$$

At limitation of deoxidation by transfer of element - reduction alloy for reaction $x\mathfrak{A}+yO\rightarrow\mathfrak{A}_xO_y$ we will find out that change of oxygen content during deoxidation will make:

$$\Delta O \equiv O_i-O^* = 2(y/x)(M_0/M_E)(\rho_1/\rho_2) \times D_EHB(E-E^*)\tau/100d^2 \quad (\text{Eq. 2})$$

where M_0, M_E - molar weights of oxygen and element, D_E - molecular diffusion coefficient of element. If removal of oxygen from metal takes place at the rate U , under condition of complete mixing of bath we will obtain:

$$\ln[(O_i-O^*)/(O_f-O^*)] = U\tau/\bar{h} \quad (\text{Eq. 3})$$

where h - bath depth.

As the rate of non-metallic inclusion floating is its size function, deoxidation dynamics is defined by value d in all three equations (1) - (3) all other things being equal. It is minimum when defined from equation (3) with the use of form resistance coefficient by Schlichting $C_f = 18.5/Re^{3/5}$, where Re - Reynolds number [1] and a little more by Stoks $C_f = 24/Re$. So, removal of oxygen in the process of steel-making unit bath deoxidation is limited by floating of non-metallic inclusions. At steel deoxidation in the ladle the mass of nonmetallic inclusions $dm = UF\rho_1Cd\tau/100$

is removed during time $d\tau$ which changes concentration of nonmetallic inclusions to $dC = -100dm/V\rho_1$, at the changing volume of metal in the ladle $V = M\tau/\rho_1\tau_{\text{tapping}}$, where M - weight of melt; τ_{tapping} - duration of tapping. After substitutions and integration within the limits $C = C_1$ at $\tau = \tau_1$ and $C = C_2$ at $\tau = \tau_2$ we will obtain:

$$\ln(C_1/C_2) = U\tau_{\text{tapping}}\ln(\tau_2/\tau_1)/\bar{h} \quad (\text{Eq. 4})$$

Removal of nonmetallic inclusions is characterized by equation (3) at steel soaking in the ladle after tapping. If steel is blown by inert gas in the ladle, deoxidation by carbon on the surface of bubbles, partial pressure of carbon monoxide P_{CO} in which is originally equal to zero, is possible according to reaction $E_xO_y + yC \rightarrow xE + yCO$ which causes transfer of O and C to their surface.

Mass-transfer coefficient is:

$$\beta_i = (D_i U / D) \quad (\text{Eq. 5})$$

where D_i - molecular diffusion coefficient of transferable substance; D , U - size and rate of bubble floating. Amount of bubbles in the ladle bath $N_D = 6hI / U\pi D^3$, where I - blowing intensity, and their surface square $F = \pi D^2$. Concentration of oxygen will change by value $dO = \beta_0 O \rho_1 F N d\tau / M$ during time $d\tau$. After integration of this value within the limits $O = O_i$ at $\tau = 0$, $O = O_f$ at $\tau = \tau$, we will obtain:

$$\ln(O_i / O_f) = 3 \times 2^{5/4} \rho_1 g^{1/10} D_0^{1/2} \times \frac{\bar{h}}{h\tau}^{3/10} (T/273) / K_D^{7/4} M \quad (\text{Eq. 6})$$

where K_D - coefficient of proportionality in dependence D on I [1], T - bath temperature. For carbon transfer we will obtain:

$$(C_i - C_f) = 2^{5/4} \times 3(M_O / M_C) \rho_1 D_C^{1/2} (T/273)^{5/12} \times g^{1/10} \frac{\bar{h}}{h\tau}^{3/10} [C] / K_D^{7/4} M \quad (\text{Eq. 7})$$

where M_O , M_C - atomic weights of oxygen and carbon; D_c - molecular diffusion factor of carbon.

If oxygen removal process is limited by transfer of CO in the bubble, than according to Hendlos-Baron's model [1] $\beta_{CO} = 0.00375U$, and specific intensity of CO transfer is $i_{CO} = \beta_{CO} P_{CO} / RT$, where R - absolute gas constant. For reaction $C+O \rightarrow CO$ $P_{CO} = K_{CaO}$,

where K - equilibrium constant, the process of internal mass exchange is presented as follows:

$$\ln(O_i / O_f) = 100M_o (0.00375)g^{1/5} k_{a_c} I^{3/5} \times h\tau / 6MRk_D 273^{2/3} T^{1/3} \quad (\text{Eq. 8})$$

If the process of steel deoxidation by carbon reaches the balance:

$$\ln(O_i / O_f) = 100M_o V_g K [C] / V_m \quad (\text{Eq. 9})$$

where V_g - specific charge of inert gas; V_m - volume of one mole of gas. Comparison of calculation results with the use of equations (6) - (8) shows that steel deoxidation by carbon with jet degassing is defined, most likely, by external transfer of carbon. According to experiment data balance is not reached when blowing through a stopper and through the lance - actual results exceed equilibrium ones which is related to more intensity of blowing, size of bubbles and, accordingly, their reduction range in the latter case that is not considered by model (9).

Conclusions

The models of formation and removal of non-metallic inclusions at deoxidation at the different stages of steelmaking are created.

References

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Получены выражения для удаления кислорода и неметаллических включений при раскислении стали в сталеплавильном агрегате, на выпуске в ковш и при внепечной доводке.