PONTIFÍCIA UNIVERSIDADE CATÓLICA
DO RIO DE JANEIRO

Raimundo Augusto Ferro de Oliveira Fortes

Decarburization and Slag Formation Model for the Electric Arc Furnace

Tese de Doutorado

Thesis presented to the Postgraduate Program of the Departmento de Engenharia de Materiais, PUC-Rio as partial fulfillment of the requirements for the degree of Doutor em Engenharia de Materiais e de Processos Químicos e Metalúrgicos .

Advisor: José Carlos D'Abreu
Co-Advisors: Roberto Ribeiro de Avillez
Richard James Fruehan

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Prof. José Carlos D'Abreu
Advisor – Departamento de Engenharia de Materiais-PUC-Rio

Prof. Roberto Ribeiro de Avillez
Co-Advisor – Departamento de Engenharia de Materiais-PUC-Rio

Prof. Francisco José Moura
Departamento de Engenharia de Materiais-PUC-Rio

Prof. Helio Kohler
Departamento de Engenharia de Materiais-PUC-Rio

Prof. André Luiz da Costa e Silva
Universidade Federal Fluminense

Dr. Luis Augusto Colembergue Klujszo
Gerdau Aços Especiais Brasil

Dr. Inigo Unamuno
Sidenor Spain

Prof. José Eugenio Leal
Coordinator of the Centro Técnico Científico da PUC-Rio

Rio de Janeiro
April 19th, 2010

Raimundo Augusto Ferro de Oliveira Fortes

Earned a bachelor's degree in Metallurgical Engineering and Materials Science from UFRJ (Universidade Federal do Rio de Janeiro) in 1981 and a Master of Science title from COPPE UFRJ (Coordenação dos Programas de Pós Graduação em Engenharia) in 1988. He began his career at Gerdau S.A. steelmaking industry in Brazil in 1983, where he progressed through several supervisory positions in the quality control department, ferrous materials and melt shop facilities. From 1990 to 1998 Fortes served as process engineer and melt shop manager in Rio de Janeiro, and from 1999 to 2010 has been serving the Gerdau Industrial Processes headquarter as a senior process manager. Manage the development of optimization systems for meltdown processes. Support technical survey and evaluation of melt shop operations across Gerdau mills in Americas.

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Resumo

Fortes, R.A.F. **Modelo de descarburação e formação de escórias na produção de aço em aciaria elétrica**. Rio de Janeiro, 2010. 319p. – Tese de Doutorado – Departamento de Engenharia de Materiais, Pontifícia Universidade Católica do Rio de Janeiro.

Um modelo de descarburação e formação de escórias foi desenvolvido e aplicado ao processo de fabricação de aço em forno elétrico a arco de 120 ton de capacidade, com carga de ferro gusa e de sucata ferrosa. O carregamento de carbono foi significativamente variado para testar a consistência do modelo, considerando a cinética de oxidação do carbono, oxidação do fósforo e de redução do óxido de ferro. Gusa e coque foram empregados como fontes mais relevantes de carbono, resultando na entrada de 15 a 35 kg carbono/ton. As taxas de fusão do gusa e da sucata governam a disponibilidade dos elementos mais relevantes tais como carbono, fósforo e silício em solução, portanto, afetam as taxas de descarburação e de formação de escórias. A principal fonte de fósforo na carga ferrosa é o gusa. Desta forma, a evolução do teor de fósforo na fase metal mostrou-se importante para as estimativas das taxas de fusão do gusa, uma vez que o fósforo pode ser empregado como traçador adicional ao carbono. Modelos cinéticos envolvendo as reações do fósforo e silício operam simultaneamente com os modelos cinéticos referentes às reações do carbono e do ferro.

Integrações numéricas associadas a um algoritmo de gradientes reduzidos generalizado foi empregado para o sistema não linear com restrições, de forma a determinar a maioria dos parâmetros cinéticos do modelo. A taxa de fusão global da carga de sucata foi maior do que a taxa de fusão aparente do gusa. Supõe-se que, o gusa apesar de ter relações geométricas desfavoráveis à transferência de calor em relação à sucata, poderia fundir mais rapidamente influenciado pelo seu baixo ponto de fusão. Entretanto, devido à formação de camada solidificada a partir da massa líquida na qual é imerso, é provável que mesmo fundido

posteriormente, ocorra um processo de encapsulamento temporário, conferindo-lhe uma taxa aparente de fusão mais baixa. A constante cinética da reação de descarburação quando o teor de carbono é inferior ao carbono crítico de 0.19% em massa e pelo menos 60% da carga ferrosa estão fundidas, foi estimada em 0.74 min^{-1}, taxas comparáveis às obtidas em aciaria a oxigênio.

A principal fonte de oxigênio para oxidação do ferro é disponibilizada por lanças supersônicas. Estima-se que 20% do oxigênio injetado via lanças sejam consumidos para a formação de óxido de ferro. Entretanto, cerca de 31% e 26% do oxigênio oriundo de injetores de pós-combustão podem contribuir na formação de óxido de ferro ou são captados pelo sistema de exaustão de gases, respectivamente. Os resultados indicam que em torno de 15-30% do carbono injetado podem não reagir no forno, sendo removidos com a escória. Adicionalmente ao estado de não-equilíbrio no sistema Fe-C-O observado, a dispersão nas estimativas de carbono solúvel na fase metal também pode ter sido influenciada pela intensidade de penetração da injeção de coque.

O algoritmo proposto se constitui num promissor simulador de práticas que visam otimizar o rendimento metálico do ferro, a partir da dependência da cinética de redução do óxido de ferro com sua atividade química na escória.

Palavras-chave

Forno elétrico a arco; descarburação; desfosforação; formação de escórias; balanço de massa; modelagem.

Abstract

Fortes, R.A.F. **Decarburization and slag formation model for the electric arc furnace**. Rio de Janeiro, 2010. 319p. – Doctoral Thesis – Departamento de Engenharia de Materiais, Pontifícia Universidade Católica do Rio de Janeiro.

A decarburization and slag formation model was developed and applied to a steelmaking process based on scrap and pig iron mixes melted in a conventional AC electric arc furnace (EAF) with 120 ton capacity. The amount of carbon input was varied significantly in order to evaluate the model consistency regarding mainly the kinetics of carbon oxidation, phosphorus oxidation and iron oxide formation and reduction. Pig iron and coke were used as sources of carbon, resulting in variation of total carbon input in the range of 15 to 35 kg carbon/ton. The pig iron and scrap melting rates determine the availability of the most relevant elements such as carbon, phosphorus and silicon in solution in Fe-C melts, and therefore, affecting the decarburization as well the slag formation rates. The pig iron is the main source of phosphorus in the ferrous charge. Hence, the evolution of the phosphorus content in the metal phase is important to predict the pig iron melting rate, since phosphorus can be used as a tracer element in addition to carbon. Kinetic models regarding phosphorus and silicon were applied simultaneously to kinetic models of carbon and iron reactions.

A numerical integration method supported a generalized reduced gradient algorithm for non-linear and constrained system (GRG) was applied to determine most of the kinetic model parameters. The scrap melting rates were found to be higher than pig iron apparent melting rates. This is expected that, even though the heat transfer issues related to significant differences in the area to volume ratio compared to scrap, pig iron may melt faster influenced by its low melting point. However, a solidified shell maybe created from the hot heel where pig iron is immersed, even when further melting occur, Fe-rich carbon melts could be

encapsulated temporarily and present lower apparent melting rate. The decarburization rate parameter, when at least 60% of the charge is melted, was estimated as 0.74 min^{-1}, when carbon content is lower than the critical carbon 0.19 %wt, which is similar to the rate range observed in oxygen steelmaking facilities. Around 31% and 26% of the oxygen input through post combustion injectors were addressed to iron oxidation and to the off-gas system, respectively.

The main source of oxygen taking part of iron oxidation is available from supersonic lances. Approximately 20% of the oxygen input through lancing are consumed to form iron oxide. The results also indicate about 15-30% of the injected carbon may not react and leave EAF during slag-off. In addition to the observed non-equilibrium state in Fe-C-O system, the dispersive behavior of the prediction of soluble carbon content in the metal phase could also be influenced by the intensity of penetration coke.

The model framework is a promising tool to work preliminarily in "what-if" process scenario builder as a static model for iron yield optimization, regarding the kinetics of iron oxide reduction reaction and the proposed dependence on its chemical activity in the slag phase.

Key words
Electric arc furnace; decarburization; dephosphorization; slag formation; mass balance; model development.

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List of symbols

a		Thermodynamic activity
A	m^2	Area
A_S	m^2	Solid phase area
A_{S0}	m^2	Initial solid phase area
B	m/s.N	Mobility
Bi		Biot number
C	mol/m^3	Molar density
c	J/(kg.K)	Heat capacity
	mol/Nm^3	Ideal gas conversion constant ($P/R.T$)
c_p	J/(kg.K)	Heat capacity at constant pressure
C_L^0	%	Initial carbon content at the melt (liquid bulk)
C_S^0	%	Carbon content at the solid phase
C_L^i	%	Carbon content in the liquid phase at Solid-Liquid interface
C_S^i	%	Carbon content in the solid phase at Solid-Liquid interface
D_{AB}	m^2/s	Mass diffusivity or Binary diffusion coefficient of specie A in medium of A and B
D_0	m^2/s	Pre-exponential factor of diffusivity
E	kJ/mol	Activation energy
ΔH_S	J/kg	Enthalpy to heat a solid
ΔH_m	J/kg	Melting enthalpy
ΔH_B	J/kg	Enthalpy available it the melt
ΔH_R	J/kg	Enthalpy of chemical reactions
ΔH_L	J/kg	Enthalpy consumed to heating melt
f		Activity coefficient in respect to Henryan scale
$\vec{f}_\mu$	N/m^3	Shear stress due to viscous fluid
$\vec{g}$	m/s^2	Gravitational field
ΔG^0	kJ/mol	Standard Gibbs Free Energy
h		Henryan activity
h	W/(m^2.K)	Convective heat transfer coefficient
J	Kg/(s.m^2)	Mass flow per unit of area
k_B	J/K.mol	Boltzman constant
k	W/(m.K)	Thermal conductivity
k	m^2/(mol.s)	Rate constant of reaction
k_0	m^2/(mol.s)	Pre-exponential factor of the rate constant
K		Equilibrium constant
		Adsorption coefficient
m	m/s	Mass transfer coefficient
	m/min	
MW	g/mol	Molecular weight
n		Symmetry number or shape number
		Number of moles

N	moles/(m^2.s)	Molar flow per unit of area
p	Pa,N/m^2	Pressure, Partial pressure
Ph		Phase transition number
Pr		Prandtl number
q	W/m^2	Energy rate transferred from or to the system
Q	J	Energy transferred from or to the system
	Nm^3/h	Gas flow rate
r	moles/s	Rate of reaction
	m	Cylindrical coordinate, or sample radius at a time t
R	J/(mol.K)	Gas constant
	W/K	Resistance to mass transfer or to chemical reaction
R_0	m	Initial radius of cylinder solid (sample)
Re		Reynolds number
Sc		Schmidt number
St		Stephan number
T	K	Temperature
T_m	K	Melting temperature
T_δ	K	Temperature at the boundary layer
t	s	Time
u	m/s	Fluid velocity
ϑ	m/s	Interface velocity
V	m^3	Volume
X		Molar fraction
W	kg	Weight
	J	Work done by or on the system
%wt	%	Mass fraction
w		

Greek letters

α	m^2/s	Thermal diffusivity
α_L	m^2/s	Thermal diffusivity of the liquid phase
α_S	m^2/s	Thermal diffusivity of the solid phase
δ	m	Boundary layer thickness
δ_C	m	Concentration boundary layer thickness
δ_T	m	Temperature boundary layer thickness
ε	W/m^3	Average mixing power due to turbulent regime
γ		Activity coefficient
φ		Enthalpy ratio
μ	Pa.s, Poise	Viscosity
	Kg/s.m	
θ		Fraction of surface
ρ	kg/m^3	Mass density
σ	N/m^2	Surface tension
τ_S	N/m^2	Shear stress
τ		Dimensionless time
ν	m^2/s	kinematic viscosity

Indices

(ad)	Adsorbed
(g)	Gas phase
(l)	Liquid phase
0	Initial, at time=0
cg	Carbon-gas interface
cm	Carbon-metal interface
Cr	Critical
eq	Thermodynamic equilibrium
gr	Graphite
i	Interface
	Specie, element, component
L	Liquid
m	Melting point; Melting; Metal phase
mg	Metal-gas interface
S	Solid
sg	Slag-gas interface
μ	Viscous character
∞	At the bulk of a specific phase

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List of acronyms

BOF	Basic Oxygen Furnace (Converter)
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EBT	Eccentric Bottom Tap Hole
GPMT	Gas phase mass transfer
HBI	Hot Briquette Iron
LD	Linz-Donawitz converter technology by VAI
LET	Converter
LPMT	Liquid phase mass transfer
LWS	Loire-Wendel-Sprunk converter
OBM	Oxygen Bottom Blowing Maxhute
OSM	Oxygen Steelmaking
Q-BOP	Quick Basic Oxygen Process (Bottom blowing)
SBQ	Special Billet Quality
GRG	Generalized Reduce Gradient
VAI	Voest-Alpine Industry

Although nature commences with reason and ends in experience, it is necessary for us to do the opposite that is to commence with experience and from this to proceed to investigate the reason.

Leonardo Da Vinci