

MECHANISM OF FORMATION OF FOAMING SLAGS
IN ELECTRIC ARC FURNACES

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Synopsis: The intention of the present work was to study the influence of slag composition, slag temperature, saturation degree of the slag, methods for gas production and coal/coke quality on slag foaming in EAF meltshops. The investigation was performed in pilot plant and industrial scale. A model of the slag foaming mechanism is described based on the experimental results. The temperature and the saturation degree of slag and especially the quality of the reducing agent were found to be the most important factors.

Key words: Steelmaking, EAF, Slag foaming

1. Introduction

All modern EAF meltshops producing low alloy steel grades are using slag foaming practice today and the introduction of this technique has reduced the specific consumption of electric energy considerably. Lance injection of coal (coke) powder and oxygen is the most common method for slag foaming practice.

The foaming mechanism is, however, not clearly understood despite intensive studies of the subject in the recent years.

According to Ameling [1], foaming could occur or not occur with the same basicity, and there was no good explanation to this.

In order to have a better understanding of the mechanism of formation of slag foaming, experiments on pilot scale were carried out at MEFOS and on industrial scale at several Nordic steelworks. Parameters such as slag composition, slag temperature, saturation degree of the slag, method for gas production and coal (coke) quality were studied in this work. For the evaluation of the slag properties a model developed at KTH was used [2].

2. Experimental procedure

Experiments were carried out under various conditions in a 12 tonne electric arc furnace at MEFOS with a bath surface area of 4.2 m². For each experiment 8 tonnes of scrap and 850 kg synthetic slag were melted. The steel temperature varied from 1580°C to 1650°C. Variation of foam height with time was recorded by a video camera. The gas production and the decarburization process were controlled on-line by MEFARC, a process control system for EAF developed by MEFOS.

3. Experimental results

Injection of Different Mixtures

Results of experiments with different injection mixtures are summarized in Figure 1. As indicated, there is an evident relation between the CO gas production rate and the foam height. No significant difference of foaming effect was observed for injection of the different mixtures to the slag. However, the effect of FeO-content in the slag on foaming is significant. For slags with a FeO-content less than 10 percent, the foam stability, i.e. the slope of the lines in Figure 1, was found to be 8.2 min·cm/kg as compared to 19.5 min·cm/kg for slags with more than 10 percent FeO.

For slags with a FeO-content lower than 10 percent, the activity of FeO is low and hence a low production rate of CO gas was obtained, which will decrease the foam stability.

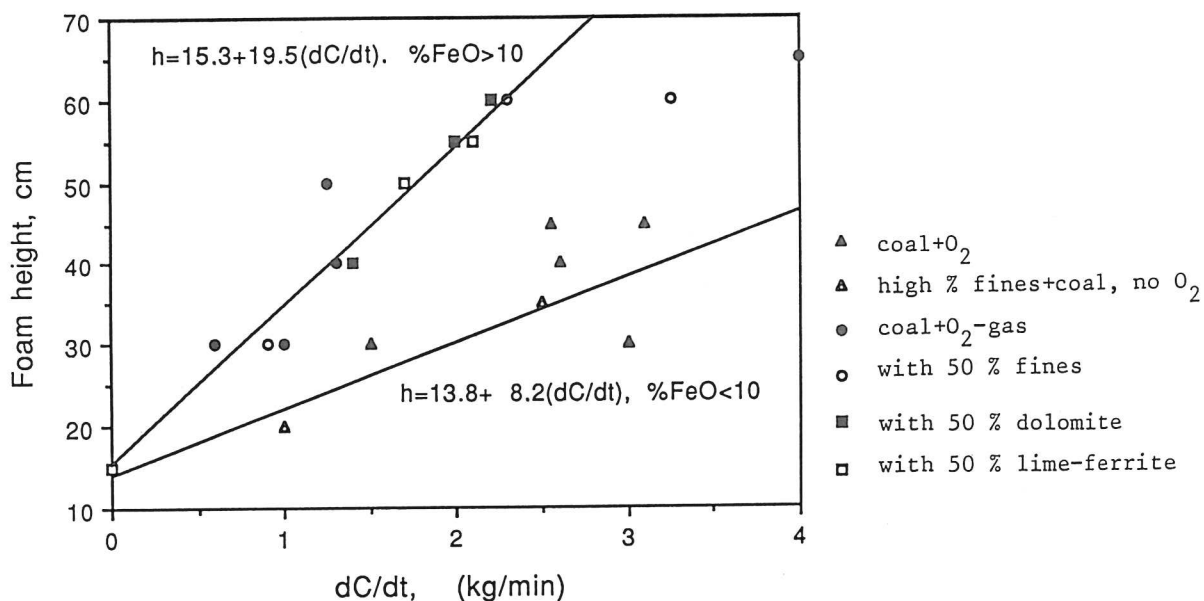


Fig.1 Foam height as a function of gas production (dC/dt) furnace area 4.2 m²

Gas Production, Slag Composition and Temperature

Effect of slag compositions, methods for gas production and slag temperatures on slag foaming are shown in Table 1. A linear relation between the foam height and the gas production is obtained. As shown, injection of oxygen alone gives bad slag foaming despite a good gas generation. This is, however, easily explained by the temperature increase due to the exothermic reactions $\text{Fe} + 1/2\text{O}_2(\text{g}) = \text{FeO}$ and $\text{C} + 1/2\text{O}_2(\text{g}) = \text{CO}(\text{g})$ which decreases the viscosity of the slag.

It was also shown that higher saturation degree of the slag and lower slag temperature proved a better foaming. The foam stability in the equation is between 8 and 12.5 for foaming with only oxygen injection as compared to 20-30 min·cm/kg for the others with injection of oxygen and coal.

Quality of Injected Coal/Coke

Effect of quality of injected coal/coke is given in Table 2. As shown, powdered graphite and petroleum coke had the most positive effect on slag foaming.

Compared to powdered graphite, petroleum coke has a much better long-term effect on slag foaming. The gas production by FeO reduction is much more smooth and steady. This implies a more stable slag foam. With its high reactivity, petroleum coke is able to cool the EAF slag to a low temperature and at the same time maintain the reaction rate. FeO reduction by powdered graphite is also fast, even at low temperatures. The graphite was, however, quickly consumed and consequently the slag foam collapsed immediately after injection. Both ash and volatile matters in the highly volatile coal appear to retard the reaction between FeO and carbon.

Table 1 Effect of slag composition and temperature on slag foaming in the pilot plant experiments

Injectants	FeO	CaO	SiO ₂	MgOsat	Temperature °C		Foam height
					steel	slag	
O ₂	13	49	6		1595	1620	$\Delta h = 15 + 12.5 \cdot dC/dt$
O ₂	15	45	7	2.8	1650		$\Delta h = 15 + 8 \cdot dC/dt$
O ₂ + coal	21	45	6	2.4	1580	<1300	$\Delta h = 15 + 20 \cdot dC/dt$
O ₂ + coal	17	46	11	2.9	1585	1400	$\Delta h = 15 + 33 \cdot dC/dt$
O ₂ + coal	18	46	11	2.1	1650	1420	$\Delta h = 15 + 24 \cdot dC/dt$
O ₂ + coal + lime	14	48	12	4.9	1650	1390	$\Delta h = 15 + 14 \cdot dC/dt$

Table 2 Foaming with different reducing agents. Results from pilot plant experiments.

Experiments	Reducing agents	The lowest measured temperature in slag, °C	Relation foam height and gas production
1	Powdered graphite	1360	$h = 15 + 18 \cdot dC/dt$
2	Coke fines	1690	$h = 15 + 7 \cdot dC/dt$
3	Brown coal coke	1500	$h = 15 + 10 \cdot dC/dt$
4	Petroleum coke	1380 low temp. high temp.	$h = 15 + 27 \cdot dC/dt$
5	Highly volatile coal	1540	$h = 15 + 8 \cdot dC/dt$

Industrial Trials

Figure 2, based on observations in a Nordic meltshop confirms the validity of the linear relationship between foam height and gas production, and the influence of slag composition.

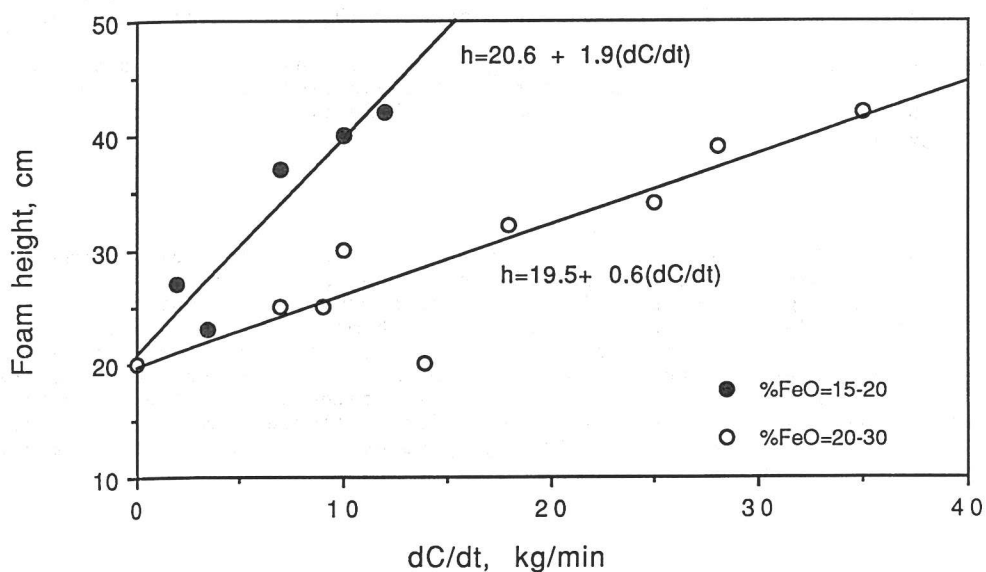


Fig. 2 Foam height as a function of dC/dt. Data from one Nordic meltshop. Furnace area 24 m².

4. Discussion

As shown in the previous section, the relation between the slag foam height and the gas production (dC/dt) can be expressed as follows:

$$h = h_0 + KdC/dt \text{ (cm)} \quad (1)$$

where

h	foam height (cm)
h_0	initial foam height (cm)
dC/dt	gas production in terms of the rate of carbon removal (kg/min)
K	foam stability (min · cm/kg)

Gas production

Gas production is one of the most essential factors on the slag foaming according to equation (1). In slag foaming practice, the CO-gas is generally produced by the two chemical reactions:



and



i.e. the CO production is proportional to $-d(\% FeO)/dt$.

According to Ozawa et al. [3], the FeO-reduction rate can be expressed as follows.

$$-\frac{d(\% FeO)}{dt} = K' [(\% FeO) - (\% FeO)_{eq}] \quad (4)$$

K' is called capacity coefficient and is a function of physical parameters such as viscosity, temperature, contact area, reactivity of the reducing agents etc. [3].

Sugata et al. [4] described the FeO-reduction rate as a function of activation energy Q , interface area A , temperature T and FeO-activity a_{FeO} .

$$\dot{n}_{FeO} = A \cdot K'' \cdot \exp(-Q/RT) \cdot a_{FeO} \quad (5)$$

Equations (4) and (5) indicate that the FeO content or a_{FeO} is an important factor for gas generation. Therefore, it is reasonable to state that the gas production is mainly controlled by the following factors:

- injection rate and quality of solid carbon
- activity or concentration of FeO in the slag
- injection rate of oxygen gas
- temperature

Effects of viscosity of the slag

Figure 3 shows the relation between the foam stability and the relative effective viscosity ($\eta_e/\eta \cdot 100$) of the slag calculated assuming the slag temperature to be equal to that of the steel bath. Despite the different conditions prevailing during the experiments, Figure 3 shows clearly that the foam stability increases with the relative effective viscosity.

$$K = -46 + 0.68 \cdot (\eta_e/\eta \cdot 100) \quad (6)$$

in which η_e can be expressed by the following equation [5].

$$\eta_e = \eta(1 - 1.35\theta)^{-5/2} \quad (7)$$

where

η	viscosity of molten slag
η_e	effective viscosity of the slag
θ	fraction of precipitated solid phases calculated according to ref. [2].

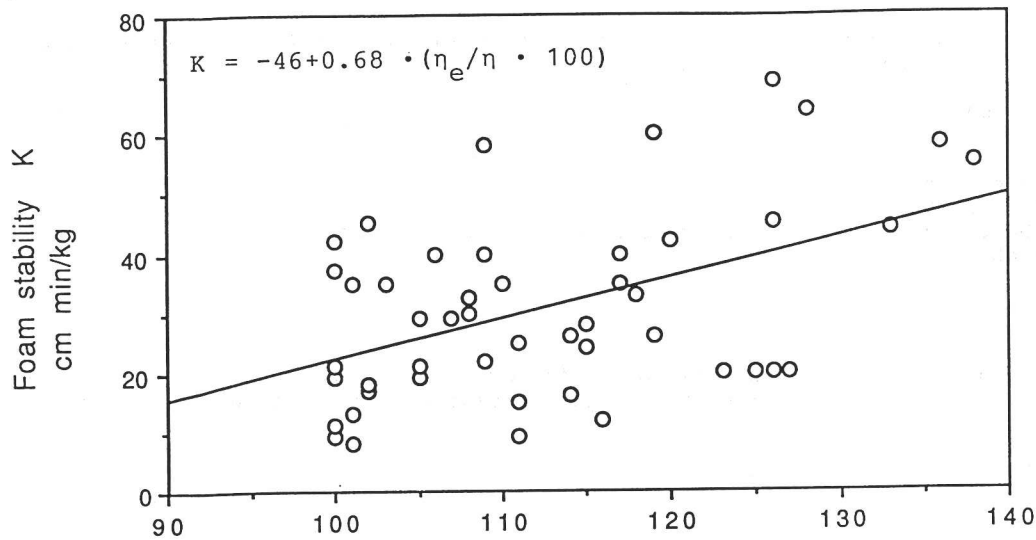


Fig. 3 Foam stability versus relative effective viscosity of slag

The foam stability is thus a function of:

- viscosity of the slag
- fraction of precipitated solid phases

Both factors mentioned above vary with temperature and slag composition.

The effect of the suspended second phase, solid particles of CaO, Ca₂SiO₄ and MgO on slag foaming was confirmed by the work of Ito and Fruehan [6, 7].

5. Conclusions

Mechanism for the formation of slag foaming - a model

On the basis of the obtained experimental results, a model for the formation of slag foam is suggested as illustrated in Figure 4 with the following explanations:

- 1) High viscosity of slag + adequate gas production = good slag foaming, $h = h_0 + KdC/dt$.
- 2) High viscosity can be obtained by the endothermic reaction $FeO+C=Fe+CO(g)$ in combination with a suitable slag composition. Accordingly, the slag temperature will be maintained at a low level resulting in precipitation of solid particles. The solid particles provide a high effective slag viscosity giving a high value of K.
- 3) The reaction $FeO+C=Fe+CO(g)$ also provides the necessary amount of gas for the slag foaming in a high viscosity slag.

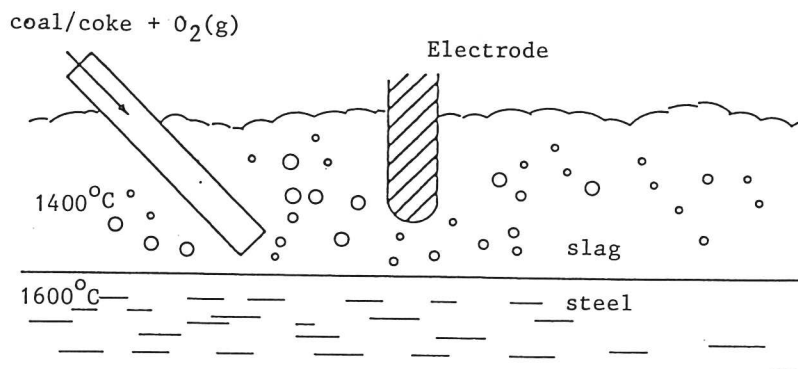


Fig. 4 Illustration of slag foaming in EAF practice

Thus, an important factor for a good slag foaming practice is to provide the necessary conditions for the highly endothermic reaction between FeO and coal/coke to proceed continuously, thereby increasing the effective viscosity through precipitation of stabilizing solid particles.

The slag composition should be selected so as to give a suitable fraction of solid particles [8].

6. References

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