ANDALUSITE AS SLAG CONDITIONER IN FERROCHROME PRODUCTION: A CASE STUDY IN TECHNO-ECONOMIC MODELLING

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ABSTRACT

A raw materials supplier approached the Centre for Pyrometallurgy to assess the possibility of using andalusite as flux addition to condition slags in the FeCr industry. A theoretical study on the possible benefits on a FeCr operation was done, but after careful study of the actual practical cost implications in became quite clear that it is not practical or economical to add andalusite to FeCr furnaces using South-African ores. A techno-economic framework is of the utmost importance when considering any project, of which this is an example: it provides a basis for industry partners that are not directly knowledgeable about an operation to assess the economic feasibility of changing various furnace/operational inputs. This paper evaluates the theoretical basis for adding Al_2O_3 raw materials to FeCr operations: it was found that although it makes sense to do so, the overall effect would be minimal and would actually increase production cost by some 1.2% or more, based on mass/energy balances and some economic data.

KEYWORDS: *Andalusite, slag conditioning, FeCr production, South-Africa.*

INTRODUCTION

The importance of slag basicity of FeCr recovery

Fluxes form an integral, yet small part of the raw material inputs to any submerged arc based FeCr production process. FeCr slags are inherently Al_2O_3-SiO_2-MgO based, with small amounts of CaO and CrOx [1]. The oxidation state of Cr in these slags is co- and/or trivalent, depending on the partial pressure of oxygen (which depends on process temperature), as well as the basicity of the slag itself. In a review paper by Holappa, a summary of the effect of basicity on the activity of CrO in the slag is shown (repeated here as figure 1).

The effect of basicity is an important one: the amount of CrOx lost to slag (which in turn relates to overall Cr recovery) can be carefully controlled by controlling slag basicity. The effect of temperature is slight compared to the effect of basicity; as is, in terms of Cr recovery, the effect of the partial pressure of oxygen (conditions are strongly reducing in these furnaces). Overall, the amount of Cr lost to slag decreases with increasing basicity. The problem, however, is that high basicity slags are resistant to dissolving chromite spinels, the main chrome-containing raw material in FeCr production. Mechanistically, the dissolution of chromite (M_3O_4 or rather $MO.N_2O_3$ with $M=Fe^{2+},Mg^{2+}$ and $N=Al^{3+},Cr^{3+},Fe^{3+}$) is driven by reaction with CO to reduce "Cr_2O_3" to CrOx which is subsequently dissolved in a SiO_2-based slag to react with coke to form FeCr alloy [2]. To this end, a high basicity slag inherently limits this dissolution leading to higher slag viscosity (and subsequently more metal entrapment, tapping problems and lower Cr recovery). Unaltered spinel (in usually in the form of $MgAl_2O_4$) also contributes to this problem, necessitating careful control of the input composition of raw materials.

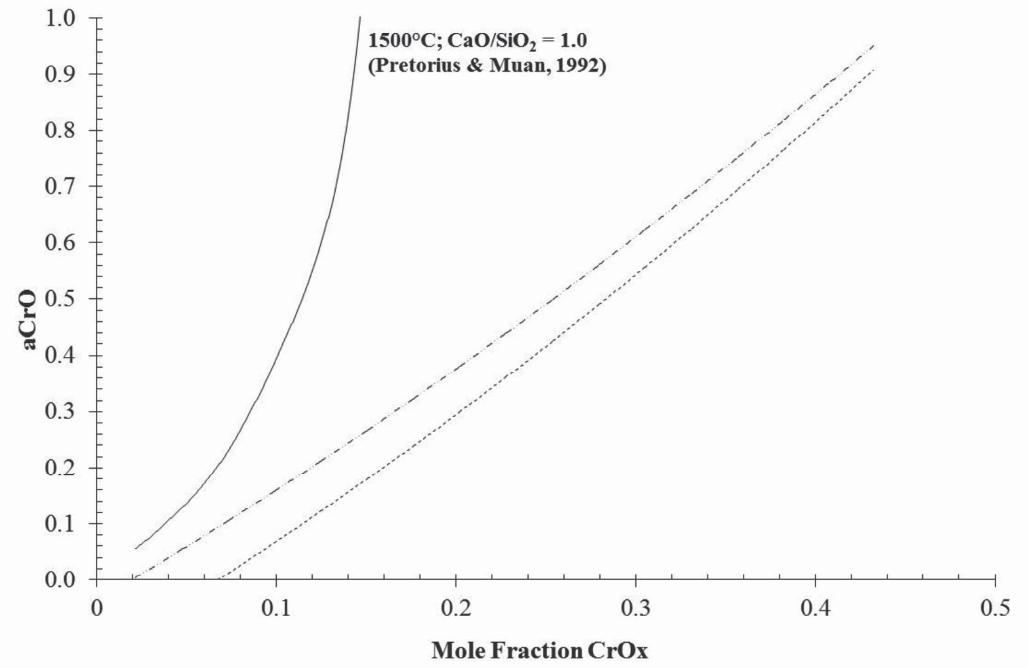

Figure 1: The activity of CrO in various FeCr slags by various authors as extracted (in part) from Holappa and Xiao [1]

The importance of Al_2O_3 in FeCr slags: effect on Cr recovery

At higher slag basicities (roughly 0.8), Al_2O_3 increases Cr recovery [1], but high amounts of MgO (present because of chromite) can react with Al_2O_3 to form $MgAl_2O_4$ spinel, which in turn is a counter-intuitive approach to increasing Cr recovery. In most cases, FeCr producers would, based on raw material composition, adjust the MgO/Al_2O_3 ratio of the actual furnace input to avoid spinel formation. In turn, basic components (MgO and CaO, which can be added to increase slag basicity) along with Cr_2O_3 are deleterious to slag viscosity and conductivity as reported by Holappa [1].

The case for andalusite as source of Al_2O_3 and SiO_2 to condition FeCr furnace slags

In typical SAF FeCr operations, quartz (SiO_2) is added as the main fluxing agent to achieve a slag conducive to the dissolution of the partially altered chrome-spinel phase in the slag/metal/coke reaction zone in the furnace. The amount of flux required is a function of the desired metal chemistry (through dissolution and subsequent reaction of CrOx with carbon in the slag melt) and liquidus temperature of the slag (to ensure tapping metal and slag is possible from the furnace). There is very little merit, in general, to add any other fluxes as ores (and concentrates) already contain or are blended to the correct chemistry to achieve slag basicity conducive to FeCr smelting.

Data from various FeCr producers was gathered to assess alignment with published data, but mostly data in open literature is quoted and used in this report, to ensure transparency and to avoid any confidentiality issues that might arise.

A baseline mass and energy balance was done for a standard operation (excluding heat losses, since this will differ for different processing routes) to show the possible effects of andalusite addition on various parameters that influence the overall cost of production of FeCr.

The slag temperature for the energy balance was taken to be 1700°C, the off-gas temperature 400°C, the metal was assumed to be at the same temperature as the slag (although it would be slightly cooler).

The approach for this calculation was to calculate the minimum energy-, reductant- and flux requirement to produce a metal and slag product of fixed composition (based on typical analyses for FeCr and slag analyses), subject to the achievable recoveries of Cr to metal for South-African ores. Metal chemistry is fundamentally a function of the ore chemistry, specifically the Cr/Fe ratio of the ore (see Cramer et al [3]), whilst slag chemistry is based mostly on the amount of Al_2O_3 in the slag. These ratios (Cr/Fe) are quite low in South-African ores and concentrates (typically around 1.6 and lower), resulting in limited Cr recovery, depending on the process route. Minor elements in the ash were ignored – focus was on SiO_2 and Al_2O_3, the main components that report to slag.

The mass/energy balance was set-up in such a way that FeCr containing 50%Cr, 40%Fe, 7%C and 3%Si is produced from an ore with the analysis with roughly 40% Cr_2O_3 and MgO/Al_2O_3 ratio of approx. 1. The carbon and silicon content might vary (be lower for MCFeCr) per product, but the calculation is done based on this chemistry to compare to most cost models published (all calculations for pricing is usually published for a 50% Cr product). The actual Cr content of FeCr produced in South Africa is not likely to exceed 53% (since it is limited by the Cr/Fe ratio in the ore/concentrate [3]). The slag chemistry was fixed with basicity (MgO/SiO_2 ratio in this case) of 1, with some FeO in the slag. It should be noted that this slag will not be fully molten at temperature. It was assumed that the andalusite product contained 60% Al_2O_3.

The base calculation calculates the minimum amount of SiO_2 required for the desired slag and metal chemistry. Subsequently, the amount of andalusite to yield the same amount of SiO_2 added as flux was calculated. The summarised results are below in table 1.

Table 1: Theoretical effect of andalusite addition on power consumption

Flux	Energy required (no losses)	Slag	Theoretical Cr recovery	Flux	Flux
	MWh/t	(t/t FeCr)	%	(t/t FeCr)	(t/t Feed)
Baseline (Quartz only)	2.65	1.49	68.73	0.08	0.03
Andalusite only	2.74	1.67	67.41	0.13	0.05

It is important to note that the energy requirement is theoretical, in practice it is higher, but the relative mass and energy change when using the different fluxes will be the same.

It can be seen that using andalusite will result in an increased amount of energy used – the principle reason for this is simply because the amount of "Al_2O_3" added will be heated and will increase the slag volume as well, requiring more energy for melting. The theoretical amount of recovery gained (note the figures are quite low for high SiO_2, low Cr/Fe ratio feeds) is almost insignificant (in actual fact, some Cr might be lost in the case of Andalusite addition, since more slag is produced). Even if a mixture of Quartz and Andalusite is used, there will be little benefit, since Al_2O_3 will be added to the mix. Many FeCr producers avoid this (since Al_2O_3 is fixed by the ore/concentrate and reductant mix and could lead to $MgAl_2O_4$ solid spinel phases in the slag phase, making tapping difficult). It should also be noted that the flux component makes up a small amount of the actual feed, making it a small component in the overall costing model.

Cost implications

Literature exists on furnace costing models for FeCr furnaces, but many producers publish estimates of their production cost. A recent study done by Biermann et al [4] reveals that the cost of the chromite ore, reductants and electricity accounts for the largest part of producing FeCr (>80%). Figures recently published recently by IFM [5], reveals the distribution of production cost.

Table 2: Production cost breakdown for a FeCr operation [5]

Production cost ZAR/lb contained Cr	Actual FY2011	Actual FY2013H1	Pro Forma* FY2012H1	Pro Forma* FY2013H1	H1 v FY11 Chg	Chg %
Ore	R1.71	R1.97	R1.72	R1.97	R0.27	15.5%
Reductants	R1.55	R1.18	R1.35	R1.19	-R0.36	-28.0%
Electricity	R1.48	R2.05	R1.49	R1.40	-R0.08	-4.7%
Operating	R0.41	R0.46	R0.45	R0.46	R0.05	11.3%
Depreciation	R0.34	R0.41	R0.38	R0.41	R0.06	16.7%
Fixed cost	R0.77	R0.42	R0.65	R0.47	-R0.30	-51.1%
ZAR/lb Cr	**R6.25**	**R6.48**	**R6.04**	**R5.90**	**-R0.35**	**-3.8%**

* Adjusted for changes in unit reductant and electricity costs from FY2011

From table 2, it can be seen that fluxes are not even explicitly shown as a cost component (it would be included in operating costs). It is likely that the costs in table 2 are based on a 50%Cr product.

More detailed figures gathered from various partners (unpublished/confidential averages for 2011), show similar trends: 22% of the cost for power (worsened in SA now by very steep electricity costs), 33% for ore, 23% for reductants and 2.3% for fluxes (the remaining 19.7% of the cost is attributed to transport, administration etc. costs). Since it costs roughly 80 – 100 USc/lb Cr to produce FeCr, the maximum effect of the fluxes is roughly 1.8-2.3 USc/lb. Since the influence of electricity costs is stronger (by roughly one order of magnitude), than that of the cost of a flux, any increase in power consumption (due to the flux) would be detrimental to the overall profitability of the process. By simply replacing, for example quartz with andalusite will increase the power requirement with 5.6% and 1.19% respectively, which means that the cost of production will increase with roughly 1.2%, relative to the cost of a quartz-only operation. Although this increase seems small, the extreme increases and expected increases in electricity costs in South Africa will exacerbate this effect. Finally, some raw material suppliers feel that FeCr producers could use andalusite as additive in, for example, pellet mixes – this, however, is counter-intuitive, since FeCr producers aim to lower SiO_2 levels in chromite sources.

CONCLUSION

Al_2O_3 additions to FeCr slags might be beneficial on a theoretical basis, but overall, the amount of Cr recovered for a South African operation assessed here will essentially remain the same (since it is limited by ore chemistry), whilst increasing power consumption in the furnace. The subsequent increase in power consumption would increase the price of production roughly 1.2%, and will be exacerbated by increasing electricity costs. Subsequently, the market for andalusite remains limited for this industry, even if used in for, example, pellets – since many producers prefer low SiO_2 containing pellets. A techno-economic approach to this type of problem proves useful and a framework is to be developed in future, in a generic manner to facilitate such types of analyses, since it cannot be ignored.

REFERENCES

[1] L. Holappa and Y. Xiao: "Slags in ferroalloys production – review of present knowledge" Journal of the South African Institute of Mining and Metallurgy, vol. 104, no. 7, pp. 429 437 (2004).
[2] P.C. Hayes: “Aspects Of SAF Smelting Of Ferrochrome”, INFACON X, 1-4 February 2004, Cape Town, South Africa.
[3] L.A. Cramer, J. Basson and L.R. Nelson: "The impact of platinum production from UG2 ore

on ferrochrome production in South Africa." Journal of the South African Institute of Mining and Metallurgy, vol. 104, no. 9, pp. 517-527 (2004).

[4] W. Biermann, R.D. Cromarty, and N.F. Dawson: "Economic modelling of a ferrochrome Furnace." Journal of the South African Institute of Mining and Metallurgy, vol. 112, no. 4, pp. 301-308 (2012).

[5] Interim Financial Results for the half year to 31 December 2012, available at www.ifml.com (Accessed April 2013).