

NICKEL, COPPER AND COBALT COALESCENCE IN COPPER CLIFF CONVERTER SLAG

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Abstract

The aim of this investigation is to assess the effect of various additives on coalescence of nickel, copper and cobalt from slags generated during nickel extraction. The analyzed fluxes were silica and lime while examined reductants were pig iron, ferrosilicon and copper-silicon compound. Slag was settled at the different holding temperatures for various times in conditions that simulated the industrial environment. The newly formed matte and slag were characterized by their chemical composition and morphology. Silica flux generated higher partition coefficients for nickel and copper than the addition of lime. Additives used as reducing agents had higher valuable metal recovery rates and corresponding partition coefficients than fluxes. Microstructural studies showed that slag formed after adding reductants consisted of primarily fayalite, with some minute traces of magnetite as the secondary phase. Addition of 5 wt% of pig iron, ferrosilicon and copper-silicon alloys favored the formation of a metallized matte which increased Cu, Ni and Co recoveries. Addition of copper-silicon alloys with low silicon content was efficient in copper recovery but coalescence of the other metals was low. Slag treated with the ferrosilicon facilitated the highest cobalt recovery while copper-silicon alloys with silicon content above 10 wt% resulted in high coalescence of nickel and copper, 87 % and 72 % respectively.

Keywords: Matte, converter slag, settling, coalescence, nickel

1. Introduction

Vale's the Copper Cliff smelter is one of the largest in the world and extracts nickel, copper, cobalt and precious metals from a concentrate that is approximately equal parts nickel and copper and a nickel-to-cobalt ratio of about 30. Sudbury basin deposits are gaining more interest since nickel and copper containing minerals are accompanied with minor amounts of silver, gold and platinum group metals [1-2]. Vale's Copper Cliff operation extracts nickel from a combination of pentlandite ((Fe,Ni)₉S₈) and variable amounts of chalcopyrite (CuFeS₂), pyrrhotite (Fe₇S₈) and/or pyrite (FeS₂) and violarite (Ni₂FeS₄) [3-5]. Similarly to other pyrometallurgical extraction processes [6], it is technically difficult to produce high-grade nickel concentrate without loss of nickel due to the intergrowth of the various sulphide minerals and the presence of dissolved nickel in the pyrrhotite crystal lattice. Therefore, a bulk concentrate of about 20 wt% CuNiCo is treated in two stages; flash smelting and converting [7-8].

During flash smelting, a 20 wt% CuNiCo concentrate is fed in to an INCO flash furnace and is blown with oxygen burners located on opposite end walls of the vessel. Silica is added as a flux to ensure

immiscibility of nickel sulphide rich matte and iron oxide based slag. Once the target matte level is reached the matte is tapped and sent to converters. A segment of Vale's Copper Cliff Smelter flowsheet is given in Figure 1.

The matte generated during flash smelting is a homogeneous mixture of nickel, copper, cobalt, iron and sulphur. Removal of the remaining iron and sulphur is accomplished by the use of Peirce-Smith converters. Charging of the converter occurs when matte is poured into the vessel through an opening in the top. The molten matte is blown with oxygen-enriched air Sulphur to remove the remaining iron and sulphur in the following generalized reaction:



The iron oxide forms a slag phase that floats above the newly formed matte phase of low iron content (0.5 wt%-2.5 wt%). Due to high oxygen pressure and the lower temperature required to eliminate residual iron from the matte, a large amount of matte remains entrained in the slag phase. Since the output of a converter is nearly directly proportional to the amount of oxygen blown through the charge, oxygen enrichment is a natural choice for use in converter practices. The oxygen enrichment not only increases

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the conversion rate but also allows for addition of cold charge, which allows for the recovery of nickel and cobalt from various solids formed in the smelter. This cold charge prevents temperature rise that would erode the refractory lining of the converter [10]. A typical chemical composition and operational parameters of smelting process is summarized in Table 1.

This study follows an experimental process developed by Wolf and Utigard [12] for converter slag settling. The effect of various industrial and prospective reductants and/or flux additions on coalescence of valuable metals entrained in converter slag is investigated and compared with settling tests with no reductant/flux addition. The matte recovery rate for different additions is reported. The matte and slag produced during the tests are characterized with optical and scanning electron microscopy to determine the composition and phases present. Finally, X-ray diffraction is used to analyze selected slags to determine the compounds present in the slag.

1.1 Factors affecting metals loss during smelting and converting

For slags formed during the smelting or converting steps, the amount of metal loss is

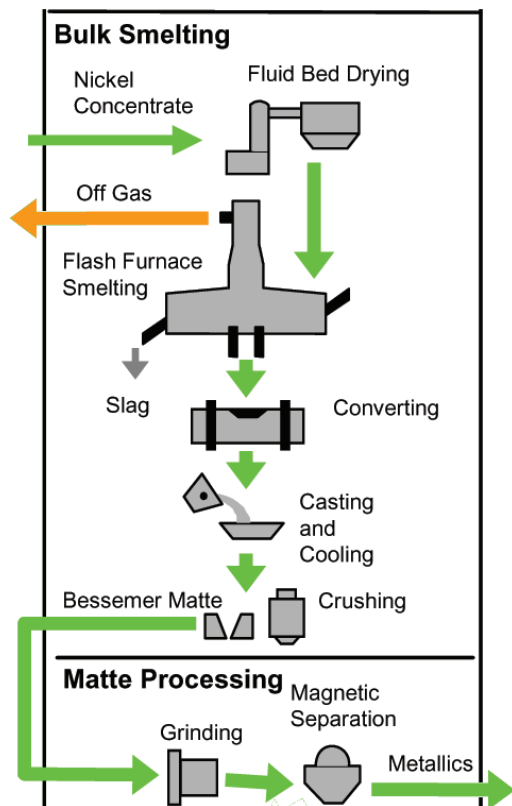


Figure 1. Bulk smelting segment of Vale's Copper Cliff Smelter Flowsheet [9].

Table 1. A typical matte and slag chemical compositions and operational parameters for Copper Cliff smelting process [11].

Smelting		Converting	
(INCO Flash Furnace)		(Peirce-Smith Converter)	
Matte (t/d)		Bessemer Matte	
NiCuCo (%)	47.5	NiCuCo (%)	77.3
Ni/Cu wt. Ratio	0.91	Ni/Cu wt. Ratio	0.82
Ni/Co wt. Ratio	34.6	Ni/Co wt. Ratio	78.9
Fe (%)	24.4	Fe (%)	0.52
S (%)	25.9	S (%)	21-22
Matte Tapping Temperature (°C)	1210	Pouring Temperature (°C)	1020
Slag (t/d)		Slag	
SiO ₂ (%)	36.4	SiO ₂ (%)	26
Total Fe (%)	43	Total Fe (%)	51
FeO(%)	44.2	FeO(%)	44.2
Fe ₃ O ₄ (%)	12	Fe ₃ O ₄ (%)	23
MgO (%)	1		
Slag Skimming Temperature (°C)	1280	Skimming Temperature (°C)	1225
(Ni%)Matte/(Ni%)Slag	50		
(Cu%)Matte/(Cu%)Slag	53		
(Co%)Matte/(Co%)Slag	3.2		

proportional to the matte grade, i.e. as the matte grade increases the amount of metal lost also increases. These metal losses are either dissolved as oxides or are present as physically entrapped matte prills. Dissolved metal losses are related to sulphide and oxygen activities and the matte grade. During flash smelting, a combination of a low matte grade and low oxygen potential causes the dominant metal losses to be sulphides [8]. During converting, the matte grade is high with increased activities of nickel and copper sulphides and decreasing activity of FeS. The first cause of the matte losses is the increased sulphide activity that drives the system to form more metal oxides that further dissolve into the slag according to general chemical reaction:



Another cause for the matte losses occur when the matte particles are carried up by the gaseous bubbles that form during this converting process [13]. Presence of gas bubbles at the matte-slag interface is an important factor affecting matte's settling rate due to the limited residence time that causes matte droplets to not settle through the slag layer.

A third significant cause for the matte losses are

low temperature zones in the converter bath. The solubility of matte decreases with temperature and this leads to the precipitation of matte particles from the slag [14].

Considering the large amount of slag produced during nickel smelting, a significant fraction of nickel, copper and cobalt are contained in slags. In pyrometallurgical 'slag cleaning' two concurring phenomenon contribute in to coalescence and subsequent valuable metals recovering from slag, namely physical settling of matte particles and chemical reduction of dissolved metals. The primary reducing agents used in this process are coke, coal, pig iron or other carbon-containing materials as well as ferrosilicon. The reductant addition will reduce metal oxides into either metallic or sulphide forms, while at the same time reduce solid magnetite to liquid FeO which decreases slag viscosity and improves settling rate [15]. It is also common practice to add sulphide concentrate, pyrrhotite or pyrite to the process. This addition of sulphur will favor the transformation of nickel, copper and cobalt oxides into sulphides and at the same time will lower the melting temperature of the matte to less than 1300 °C from the 1400 °C of the nickel iron alloys [8-9, 16].

2. Experimental

Converter slag samples from Vale are periodically received in approximately one kilogram batches. 400 g samples were taken from the respective batch. Each of the slag samples were poured into a cylindrical alumina crucible (17 cm high x 3.8 cm inner diameter) and placed inside a 30 cm × 40 cm × 36 cm chamber of the Lindberg 12500 W electric furnace and heated to the set temperature. Flux and reductant additions, ranging from 1 wt% to 20 wt%, were measured out and then combined with the correct amount of converter slag while maintaining the 400-gram of total weight. Once the slag and additives were combined, the ingredients were mixed vigorously and loaded into the furnace. Silica and lime were chosen as fluxes while reductants were chosen based on a previous work reported by Wolf and Mitrašinović [17] where various factors were taken in consideration, such as density, melting temperature relative to converter slag, ability to reduce molten FeO to molten metallic iron, availability and cost. Major components of converter slag are FeO and SiO₂ that are forming a fayalite type slag (2FeO–SiO₂) with a melting temperature close to its congruent point and therefore operational temperature could be further reduced below 1200°C. The pseudo-binary system of the FeO–SiO₂ system is given in Figure 2. Flux and reductant additions together were also tested to observe how their combination would affect metal recovery. A summary of all tests is shown in Table 2.

After settling tests were complete the settled matte was separated from the slag. The separation was achieved by first, chipping away the alumina crucible with a chisel and hammer, second the matte and slag phases were separated by a combination of hammering and wedging the interface apart with a flathead screwdriver. Once the matte and slag phases were disjoined, samples of each phase were sent to Vale Technical Services Limited (VTSL) for chemical assaying.

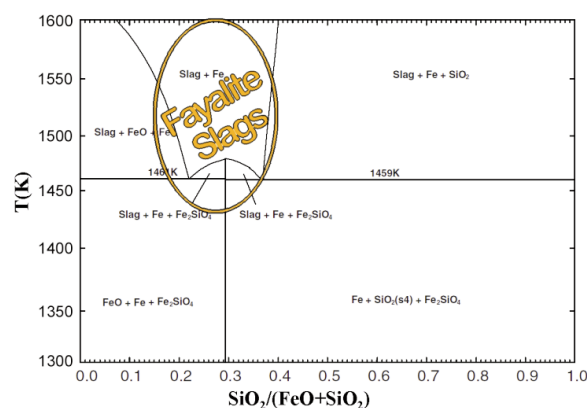


Figure 2. Pseudo-binary phase diagram of the slag depicted as FeO–SiO₂ system [18].

3. Results

Copper Cliff slag comprises of magnetite embedded in fayalite matrix. While the slag's microstructure is consistent physical appearance vary from smooth surface to some very porous particles. Residues of converter matte that are found in slag vary in size from 1mm round shape to very fine 5 µm thick elongated matte prills. Figure 3 shows a micrograph of the matte and slag after one hour treatment at 1300oC without additive addition. The matte consist of Cu-S phase (Fig.3, region 2) embedded in Ni-S matrix (Fig. 3, region 1). The EDS examines showed that the region 2 in Fig. 3 is Cu₂S-FeS while region 1 corresponds to Ni₃S₂-FeS phase. In previous work it was found that Lamella-like structures in matte is more pronounced for shorted settling times [20].

The amount of matte, slag and crust produced after testing and the normalized chemical assays of nickel, copper, cobalt, iron, sulphur and oxygen is given in Table 3. Settling trials (Tests 1-3, Table 3) conducted on converter slag without flux or reductant indicated satisfactory tests repeatability. Settling at 1300°C at one hour recovered about 60 % of all copper, 50 % of all nickel and about 6 % of all cobalt while keeping iron recovery at 0.3 % and sulphur recovery at about 10 %.



Table 2. Summary of conducted trials showing additive (flux or reductant) used and the total mass of the sample before melting. All settling tests were performed at 1300°C for 1 hour.

	Test #	Flux	Reductant	Notes
No additive	1	None	None	Reference samples
	2	None	None	&
	3	None	None	Repeatability tests
70wt%Cu	4	None	5wt% Cu30Si	First settling test with Cu30Si
30wt%Si	5	None	5wt% Cu30Si	Re-test for statistical accuracy
	6	3wt% SiO ₂	5wt% Cu30Si	Reductant and Fe/SiO ₂ = 2
	7	3wt% SiO ₂	5wt% Cu30Si	Re-test for statistical accuracy
90wt%Cu	8	None	5wt% Cu10Si	First settling test with Cu10Si
10wt%Si	9	3wt% SiO ₂	5wt% Cu10Si	Reductant and Fe/SiO ₂ = 2
SiO ₂	10	3wt% SiO ₂	None	Test with Fe/SiO ₂ = 2 #1
	11	7wt% SiO ₂	None	Test with Fe/SiO ₂ = 1.75
	12	12wt% SiO ₂	None	Test with Fe/SiO ₂ = 1.5
	13	3wt% SiO ₂	None	Test with Fe/SiO ₂ = 2 #2
	14	3wt% SiO ₂	None	Test with Fe/SiO ₂ = 2 #3
CaO	15	1wt% CaO	None	Lime content of 1 wt%
	16	2wt% CaO	None	Lime content of 2 wt%
	17	5wt% CaO	None	Lime content of 5 wt%
	18	20wt% CaO	None	Industrial level content added
Pig Iron	19	3wt% SiO ₂	2.5wt% Pig Iron	First pig iron test - 2.5wt%
	20	3wt% SiO ₂	5wt% Pig Iron	First pig iron test - 5wt%
	21	3wt% SiO ₂	7.5wt% Pig Iron	First pig iron test - 7.5wt%
	22	3wt% SiO ₂	5wt% Pig Iron	Re-test for statistical accuracy
	23	3wt% SiO ₂	5wt% Pig Iron	Re-test for statistical accuracy
	24	None	5wt% Pig Iron	Pig iron without excess silica
	25	None	5wt% Pig Iron	Re-test for statistical accuracy
85wt%Fe	26	None	5wt% Fe15Si	Ferrosilicon test #1
15wt%Si	27	None	5wt% Fe15Si	Ferrosilicon test #2
	28	None	5wt% Fe15Si	Ferrosilicon test #3
FeS	29	3wt% SiO ₂	5wt% FeS	
Coke	30	None	5wt% Coke	First coke test
	31	3wt% SiO ₂	5wt% Coke	Coke and Fe/SiO ₂ = 2

3.1 Effect of silica and lime fluxes

The matte yield and partition coefficients of nickel, copper, cobalt, iron and sulphur from each test is summarized in Table 4. Partition coefficients were calculated based on the matte assays obtained by VTSL. No data is available for the tests in which a chemical assay was not conducted. When comparing tests with added silica to the converter slag (Tests 10-14) to those of without flux (Tests 1-3), the recoveries and partition coefficient of nickel, copper and cobalt are higher while the iron and sulphur transition is unchanged for tests with silica addition.

It is known that additions of up to 20wt% lime to converter slag will lower the melting temperature from about 1200°C to less than 1100 °C. However, the addition of 20wt% lime resulted in no matte collection, in fact, the matte particles were simply observed to descend to the bottom portion of the crucible but as independent prills as seen in cross-section macrograph in Figure 4. It was also shown that a 5wt% addition of lime to converter slag prior to settling would lower both metal recoveries and

partition coefficients relative to settling with no additions. For this reason, no further investigation was carried out on the additions of lime to converter slag.

3.2 Carbon containing reductants

Employing pig iron as reductant (Tests 19-25) revealed two conclusions: a) tests with pig iron settles less matte than settling without additives and b) the recovery of nickel and cobalt increases while the copper and sulphur recoveries decreases. Comparing the results for pig iron (Tests 19-25) with the settling without additives (Tests 1-3) it is clear that coalescing is greater for nickel, copper and cobalt while unchanged for iron and lower for sulphur. This indicates the matte recovered from the addition of 5wt% pig iron to converter slag is of a higher grade than of matte recovered settling without additives. Furthermore, an addition of 2.5wt% pig iron settled only about half the matte than settling without additives, and hence had lower recovery while tests with 7.5wt% pig iron addition did not produce any coalescing as the matte formed metallic layers that



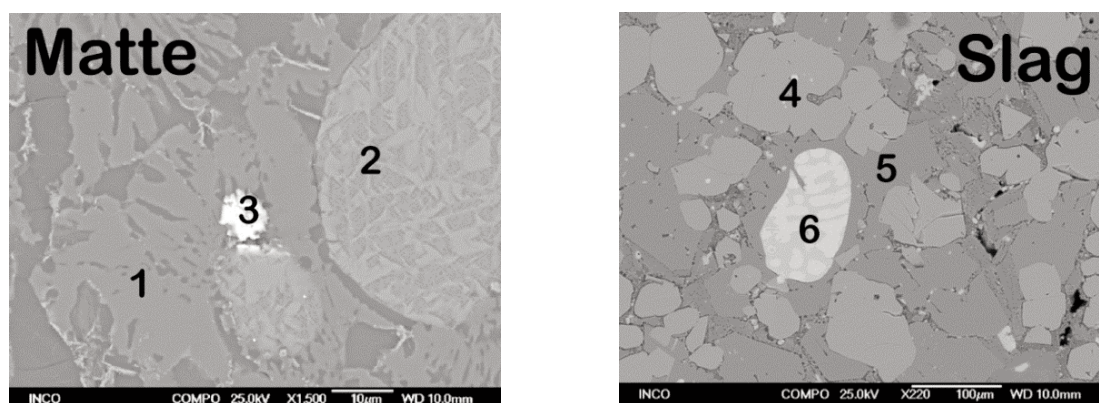


Figure 3. Characteristic components of matte and slag after one hour treatment at 1300 °C without additive addition. 1) Ni_3S_2-FeS , 2) Cu_2S-FeS , 3) Ag particle, 4) FeO , 5) $FeO-SiO_2$ and 6) entrained matte prill.

Table 3. Normalized chemical assays of copper, nickel, cobalt, iron, sulphur and oxygen for matte and slag formed after one hour treatment at 1300°C.

	Test #	Matte Assay /wt%						Slag Assay /wt%					
		Cu	Ni	Co	Fe	S	O	Cu	Ni	Co	Fe	S	O
No additive	1	33.8	25.2	0.81	13.8	21.8	3.46	1.13	1.29	0.57	54.3	1.23	28.7
	2	31.7	25.9	0.79	14.6	22.1	3.76	-	-	-	-	-	-
	3	32	25.5	0.79	14.4	22.5	3.62	-	-	-	-	-	-
70wt%Cu 30wt%Si	4	54.6	19.7	1.39	8.9	14.2	0.68	0.69	0.25	0.45	53.3	0.83	30
	5	56.9	20.2	2.09	10.7	8.9	0.55	1.34	0.32	0.42	54	1.07	28.2
	6	58	18.1	1.77	9.4	12	0.31	0.95	0.27	0.45	52.1	0.8	29.9
90wt%Cu 10wt%Si	7	58.3	20.2	1.72	7.9	10.5	0.68	1.11	0.32	0.49	52.5	0.8	29.8
	8	70.7	11.7	0.21	1.8	14.6	0.47	-	-	-	-	-	-
	9	71.6	12.7	0.18	1.7	12.7	0.71	-	-	-	-	-	-
SiO ₂	10	33.2	25.4	0.79	13.4	23	3.1	0.8	1.02	0.54	52.4	0.82	31
	11	-	-	-	-	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	-	-	-	-	-	-
	13	37.2	24.1	0.7	11.8	23.4	2.01	0.69	0.92	0.53	52.9	0.67	30.3
	14	36.9	26	0.64	11	22.5	2.1	0.8	1.07	0.53	53.4	0.56	30.8
CaO	15	-	-	-	-	-	-	-	-	-	-	-	-
	16	-	-	-	-	-	-	-	-	-	-	-	-
	17	30.9	25.3	0.96	15.4	21.9	4.05	1.68	1.82	0.54	52.6	1.56	30.3
	18	-	-	-	-	-	-	1.33	1.28	0.47	48.1	1.17	28.2
Pig Iron	19	32.7	29.3	0.97	12.1	22.1	2.3	0.56	0.51	0.48	50.6	0.77	33.6
	20	27.2	32	3.42	24.1	12.1	0.57	0.78	0.38	0.38	54.6	1.32	28.6
	21	-	-	-	-	-	-	1.19	0.2	0.25	53.7	1.6	29.2
	22	27.7	36.1	2.96	18.9	13	0.61	0.61	0.35	0.41	51.8	0.97	32.3
	23	25.5	37.7	3.65	22.3	9.9	0.42	0.53	0.16	0.39	55.2	1.11	29
	24	27	39.2	3.57	19.4	9.7	0.56	1.35	0.49	0.61	77.8	1.82	0.5
	25	23.7	41.9	4.12	21.8	7.5	0.3	0.74	0.31	0.42	57.2	1.26	27.1
85wt%Fe 15wt%Si	26	22.3	36.7	5.58	31.4	3.2	0.32	1.29	0.41	0.36	54.8	1.51	28.7
	27	21.7	35.7	5.76	32.8	2.7	0.72	0.79	0.14	0.32	55.4	1.35	28.5
	28	21.1	35.9	5.86	34.1	2.1	0.4	1.02	0.26	0.32	55.6	1.51	27.5
FeS	29	22.6	19.4	1.34	27.2	24.5	3.76	-	-	-	-	-	-
Coke	30	-	-	-	-	-	-	0.7	0.2	0.33	53.9	1.4	29.3
	31	24.6	27.6	4.19	32	10.5	0.55	0.59	0.05	0.26	52	1.45	29.9

were intertwined within the slag at the bottom portion of the crucible.

Using 5 wt% coke as reductant did not produce any matte. Instead, two distinct slag regions were found inside the crucible. The upper half of the

crucible was a hard, porous slag that contained small (< 1 mm) metallic prills. While the bottom half of the crucible was virtually identical to the slags that formed in all other tests. These two phases are presented in Figure 5.



3.3 Si alloys reductants

The addition of 5 wt% 90wt%Cu-10wt%Si maintained copper recovery in the same range as settling without additives but decreased coalescing of both nickel and cobalt significantly. Figure 6 shows an EDS analysis of matte formed during a 5 wt% 70wt%Cu-30wt%Si addition (Test4-7). The addition of 5 wt% 70wt%Cu-30wt%Si alloy increased the recoveries and partition coefficients of nickel and cobalt while at the same time lowered the sulphur recovery and kept the iron and copper recovery in the same range as settling without additives.

It is possible to increase the recoveries of nickel and cobalt while at the same time lowering copper, iron and sulphur recoveries by the addition of 5 wt% ferrosilicon to converter slag (Tests 26-28, Tables 3 and 4). Examining the high partition coefficients of nickel and cobalt and low sulphur partition coefficients indicates that ferrosilicon is an effective reducing agent. Unfortunately, the partition for copper decreases in the ferrosilicon tests and the iron partition doubles indicating lower matte grade. The upmost partition coefficients for the four examined metals elements are around 80 for copper, 80 for nickel, five for cobalt and 0.2 for iron.

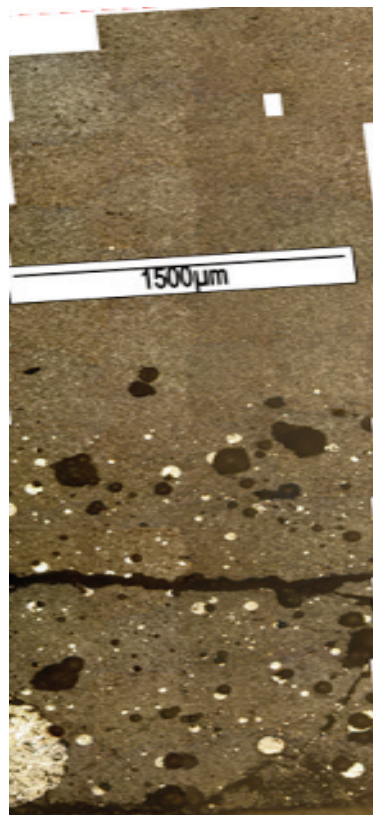


Figure 4. Cross-sectioned crucible with the converter slag sample after adding 20 wt% lime and settling at 1300 °C for one hour.

4. Discussion

Slags originated from nonferrous metals extraction processes impose a great environment attentive. In developed countries strict regulations already force large nickel and copper producers to employ separate cleaning processes for slags with high heavy metals content. Therefore, with the goal to achieve less than one percent of heavy metals in disposed slags with lower process disruptions [19] a better understanding of thermodynamic and kinetic parameters of settling process should be done and research on the development of new additives (reductants and/or fluxes) [20, 21].

A better understanding of the assimilation mechanism of new additives is key factor allowing further advancements in process efficiencies. The faster an additive can dissolve into solution, the process capacity increases and the chances for losses are lower. Therefore, the most favorable path of the additive assimilation is its melting followed by simultaneous exothermic reaction and assimilation process. Typical industrial additives are ferroc carbon alloys such as pig iron. This type of additive has a melting point above temperature of the liquid bath and does not exhibit any exothermic chemical reaction. The assimilation mechanism for ferroc carbon is defined by the formation of the solid layer of slag around the additive that subsequently has to melt and thereafter ferroc carbon



Figure 5. Upper and lower part of converter slag after addition of 5 wt% coke and treatment at 1300 °C for one hour

Table 4. Summary of all tests done showing used additive and the weight of the collected matte and slag with partition coefficients for copper, nickel, cobalt, iron and sulphur after coalescing for one hour at 1300 °C.

	Test #	Flux	Reductant	Mass (g)			Partitions				
				Matte	Slag	Crust*	Cu	Ni	Co	Fe	S
No additive	1	None	None	17.1	378.3	0	30	20	1	0.3	18
	2	None	None	15.7	373.9	0	-	-	-	-	-
	3	None	None	18.8	390.2	0	-	-	-	-	-
70wt%Cu 30wt%Si	4	None	5wt% Cu30Si	36.5	359.9	0	79	80	3	0.2	17
	5	None	5wt% Cu30Si	29.2	355.8	15.6	43	63	5	0.2	8
	6	3wt% SiO ₂	5wt% Cu30Si	28.5	355.8	16.4	61	68	4	0.2	15
	7	3wt% SiO ₂	5wt% Cu30Si	27	355	20	53	63	4	0.2	13
90wt%Cu 10wt%Si	8	None	5wt% Cu10Si	25.8	354.6	21.1	-	-	-	-	-
	9	3wt% SiO ₂	5wt% Cu10Si	23.1	364.2	17.4	-	-	-	-	-
SiO ₂	10	3wt% SiO ₂	None	21.2	378.8	0	41	25	1	0.3	28
	11	7wt% SiO ₂	None	-	-	-	-	-	-	-	-
	12	12wt% SiO ₂	None	-	-	-	-	-	-	-	-
	13	3wt% SiO ₂	None	7.8	249.2	169	54	26	1	0.2	35
	14	3wt% SiO ₂	None	7.1	305.9	94.3	46	24	1	0.2	40
CaO	15	1wt% CaO	None	16.8	381.2	0	-	-	-	-	-
	16	2wt% CaO	None	16.5	379.5	0	-	-	-	-	-
	17	5wt% CaO	None	13.4	376.6	0	18	14	2	0.3	14
	18	20wt% CaO	None	-	-	-	-	-	-	-	-
Pig Iron	19	3wt% SiO ₂	2.5wt% Pig Iron	8.8	374.5	15.7	58	58	2	0.2	29
	20	3wt% SiO ₂	5wt% Pig Iron	20.2	372.4	5.8	35	83	9	0.4	9
	21	3wt% SiO ₂	7.5wt% Pig Iron	0	391.5	6	-	-	-	-	-
	22	3wt% SiO ₂	5wt% Pig Iron	14.9	372.3	11.2	45	104	7	0.4	13
	23	3wt% SiO ₂	5wt% Pig Iron	14.7	372.3	10.9	48	242	9	0.4	9
	24	None	5wt% Pig Iron	14.3	371	12	20	79	6	0.2	5
85wt%Fe 15wt%Si	25	None	5wt% Pig Iron	14.6	375.4	8.3	32	135	10	0.4	6
	26	None	5wt% Fe15Si	16	373.9	10.8	17	89	16	0.6	2
	27	None	5wt% Fe15Si	15.1	372.8	12.9	28	256	18	0.6	2
FeS	28	None	5wt% Fe15Si	15.7	372	13.6	21	139	18	0.6	1
	29	3wt% SiO ₂	5wt% FeS	13.4	386.6	0	-	-	-	-	-
Coke	30	None	5wt% Coke	0	276.4	0.5	-	-	-	-	-
	31	3wt% SiO ₂	5wt% Coke	14.8	262.4	9.3	42	532	16	0.6	7

*Crust is the part of sample that remained attached to the crucible

dissolves into the slag. Acquired results confirmed that copper-silicon reductants significantly improved valuable metals coalescence from Copper Cliff converter slag because its melting point is below the temperature required in the extraction process and the existence of exothermic chemical reactions [22]. Hence, the assimilation mechanism of the copper-silicon additive is defined by concurrent melting and exothermic chemical reaction which further significantly ease maintaining the operating temperature inside the converter [17, 22].

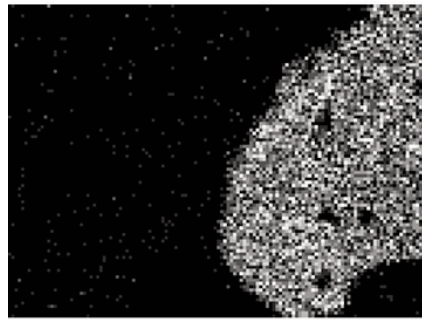
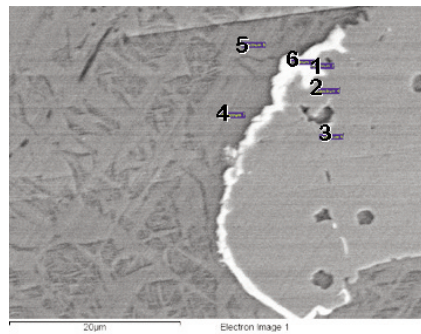
An interesting result could be obtained by adding reductants and fluxes in combination with one another where exothermic and micro exothermic effects of selected reductants can add up on the increased coalescence of nickel, copper, cobalt and other precious metals.

5. Conclusion

An investigation on the coalescence of nickel, copper and cobalt in fayalite slag was conducted in

order to understand the behaviors of these metals and how the addition of selected reductants and/or fluxes will affect the metal recovery from Copper Cliff converter slag. Silica was added to converter slag to lower the Fe/SiO₂ ratio of the slag from 2.3 to 2. Such additions were found to lower the recoveries of nickel, copper and cobalt but increase the partition coefficients of copper and nickel as compared to settling with no additions. It can be concluded that silica additions will recover a higher grade matte when compared to the matte recovered from tests with no additions. Reductants that slightly increased metal recovery were: 90 wt%Cu-10wt%Si, FeS and coke. For 90wt%Cu-10wt%Si there was an insufficient amount of silicon to reduce the converter slag, coke was too light and only reduced the upper portion of the slag. Nickel, copper and cobalt recoveries and partition coefficients were increased if 5 wt% each of pig iron, ferrosilicon (15 wt% Si) and 70wt%Cu-30wt%Si were added individually to converter slag prior to melting. Each of these three reductants favored the formation of a highly metallized matte. After comparing the nickel, copper





Ni Ka1



Co Ka1



Cu Ka1

Spectrum	Cu	Ni	Co	Mo	Pb	Fe	S	Total
1	33.4	12		35.3	16.1	3.2		100
2	30.6	53.3	3.3			12.8		100
3	38.4	47.3	3.4			10.9		100
4	80					0.8	19.2	100
5	74.3					4.6	21.1	100
6	45	7.6		36	7.6	2.6		98.7

Figure 6. X-ray mapping and normalized EDS analyses of the matte generated after addition of 70wt%Cu-30wt%Si reductant (Test 4-7)

and cobalt recoveries data it was concluded that ferrosilicon facilitated the most effective coalescence of cobalt while pig iron and ferrosilicon are equally effective in recovering nickel and 70wt%Cu-30wt%Si is the most effective for copper recovery.

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