Reductive matte smelting of UG2 concentrate using Al, FeSi, and SiC reductants

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INTRODUCTION

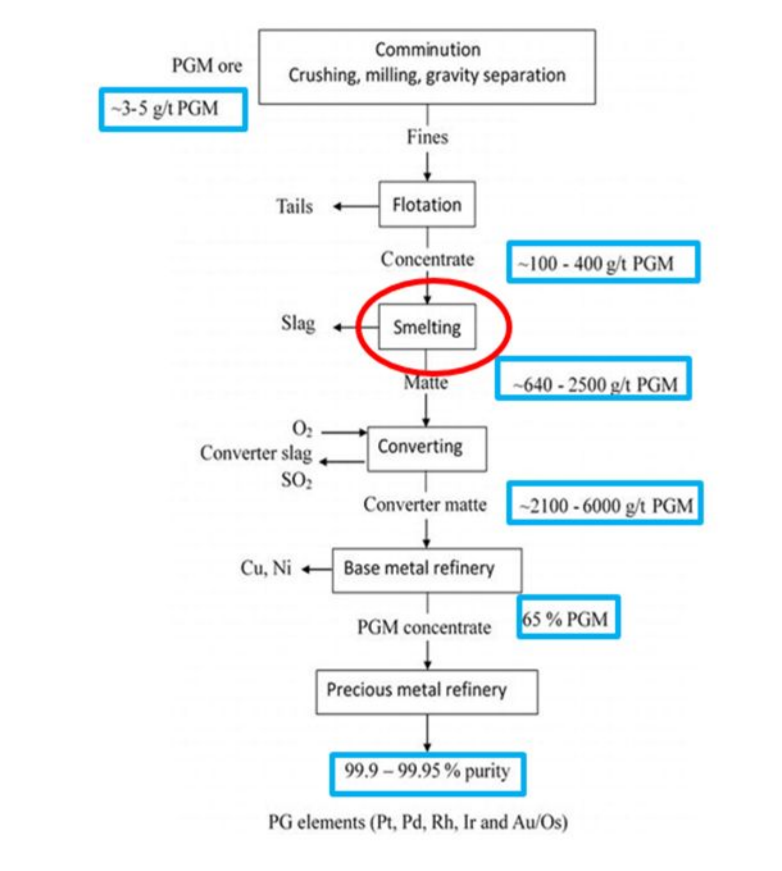
- Bushveld Complex (BC) – largest source of PGMs with over 80% global reserves

- PGMs+Au are mainly mined from the three reefs in the BC
  - Merensky reef - historical and current source, higher PGMs' and base metals' (BMs) contents
  - Upper Group 2 (UG2) - chromite-rich reef, higher PGMs' contents, lower BMs and S contents
  - Platreef - lower PGM content, but higher BMs' contents

- Merensky ore has been processed over the year
  as the primary source of PGMs+Au

INTRODUCTION

- Processing flowsheet for Merensky ore



INTRODUCTION

- The imminent depletion of Merensky ore has shifted the focus of PGM smelter to UG2 ore
  - UG2 differs mineralogically from Merensky: higher chromite content, lower S content

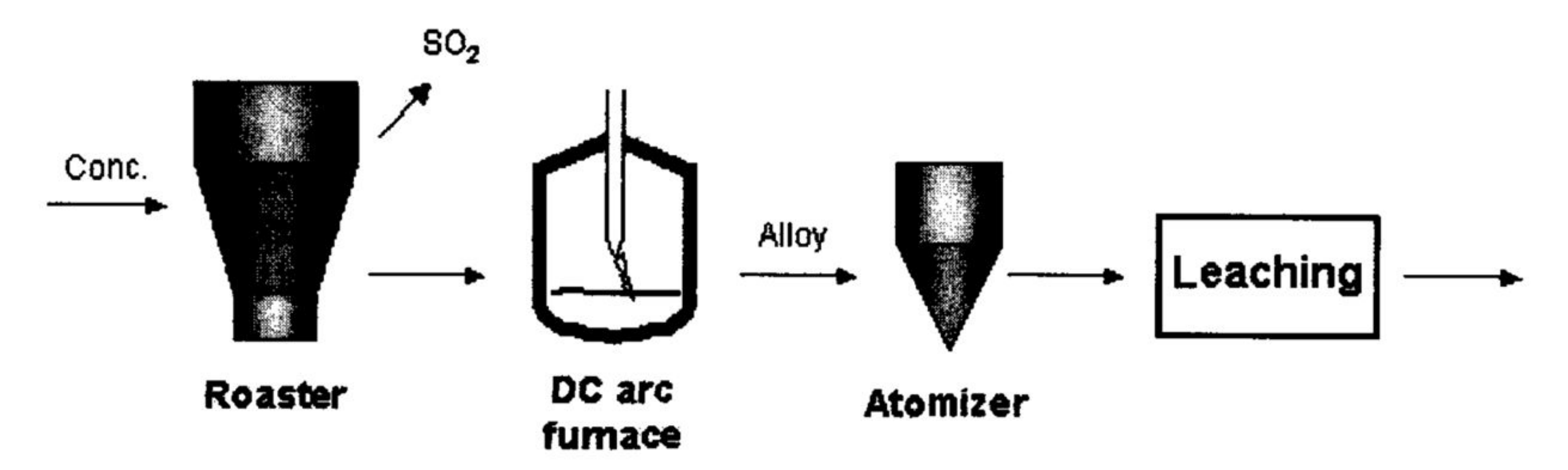
- This shift introduced new smelting challenges, which include the spinel formation and lower PGM matte falls

- The spinel challenges include:-
  - Poor separation of the matte and slag – compromised PGM recoveries
  - Build up on the furnace refractories, resulting in the reduction in furnace working volume and lifespan

- Solution for addressing high chromite ores:-
  - Chromite control via flotation, include the use of the innovative Jameson flotation technique
  - Direct hydrometallurgical approaches (e.g. Kell process)
  - Blending of UG2 and Merensky to dilute chrome content and increase S, and thus the matte fall
  - Mintek's ConRoast process

INTRODUCTION

- ConRoast process
  - Dead roasting of the UG2 concentrate in a DC arc furnace
  - Produces Fe-rich alloy containing PGMs and Cr tolerant slag
  - Can process 100% UG2 concentrate, with high contents of Cr_2O_3



INTRODUCTION

- Jones and Geldenhuys (2011) explored the feasibility of using the current installed furnace capacity while dealing with high chromite and low S contents, by investigating carbothermic matte smelting – increases matte-alloy fall and improves solubility of chromium in the slag

- Pros of reductive matte smelting
  - Good process – when the process is well designed
  - Chromium management – Cr solubility in the slag, thus reducing the formation of the problematic spinel
  - Lower S emissions – environmental benefit
  - Can be adaptable for feed material with low S and high Cr_2O_3, such as the UG2

- Cons of reductive matte smelting
  - Risk of furnace failure when having both matte and alloy present
  - Operational and control complexity – since operating under reducing conditions and possibly mixed matte/ alloy phases, controlling the process (slag chemistry, metal phase separation, matte/ alloy composition) is more challenging
  - Carbon footprint

OBJECTIVE OF THIS STUDY

- Investigate alternative reductants for reductive matte smelting: Al, FeSi, and SiC

- Mini objective
  - To conduct thermochemical simulations on the UG2 concentrate at varying Al, FeSi, and SiC reductants to investigate the smelting conditions (recipe, temperature)

  - To confirm the technical feasibility of using reductants such as Al, FeSi, and SiC as in reductive matte smelting for PGMs through crucible tests

  - To verify slag phase compositions, with a view to assessing the formation of the chrome-spinel

PROCEDURES

- Raw materials
  - UG2 concentrate

Chemical composition of the raw material (mass %)

Al_2O_3	CaO	Co	$FeCr_2O_4$	$CuFeS_2$	FeS_2	Fe_3O_4	MgO	MnO	NiS	SiO_2	TiO_2	C	PGMs+Au (ppm)
4.66	2.50	<0.05	4.02	2.69	2.80	9.46	22.45	0.14	2.94	45.60	0.31	0.28	550.53

  - Al/FeSi/ SiC reductants

Chemical composition of the reductants (mass %)

Reductant	Al	Fe	Mn	Si	C
Al	99.31	0.25		0.44	
FeSi	0.32	15.40	0.13	85.70	0.03
SiC				70.05	29.95

- Products analysed by
  - ICP-OES – determination of Al, Ca, Co, Cr, Cu, Fe, Mg, Mn, Ni and Si,
  - LECO – determination of C and S
  - Fire Assay (6E) coupled with ICP-OES – determination of PGMs and Au
  - XRD and EPMA – determination of chemical phases in the slags

PROCEDURES

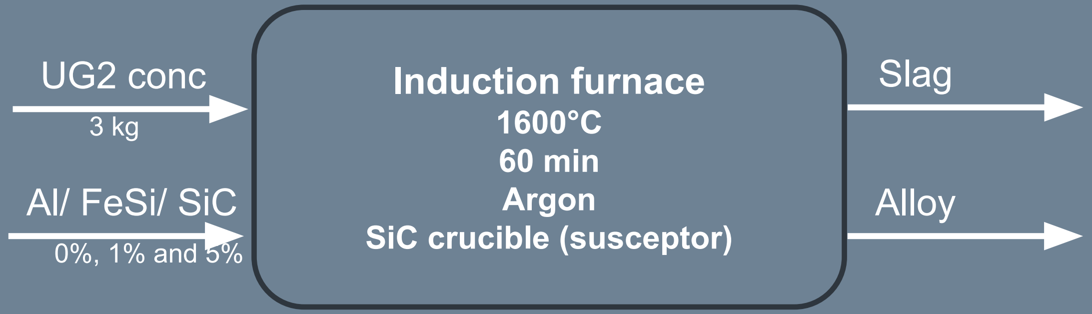
Thermochemical simulations:-

- Conducted using FactSage 8.3 software
- Databases used included –
  - FactPS (pure substances)
  - FToxid (oxide phases)
  - FTsulf (sulphide phases)
  - SGTE (alloys)
- Simulation conditions were:-
  - Smelting temperature of 1600°C
  - Varying Al/ FeSi/ SiC reductants from 0% - 20%

- Slag solution database does not typically include PGMs, thus the calculated deportment of PGMs between the product phases was anticipated to be distorted.
- Simulations were anticipated to provide results that will assist in determining the stability of chrome spinel and also guide the experimental work.

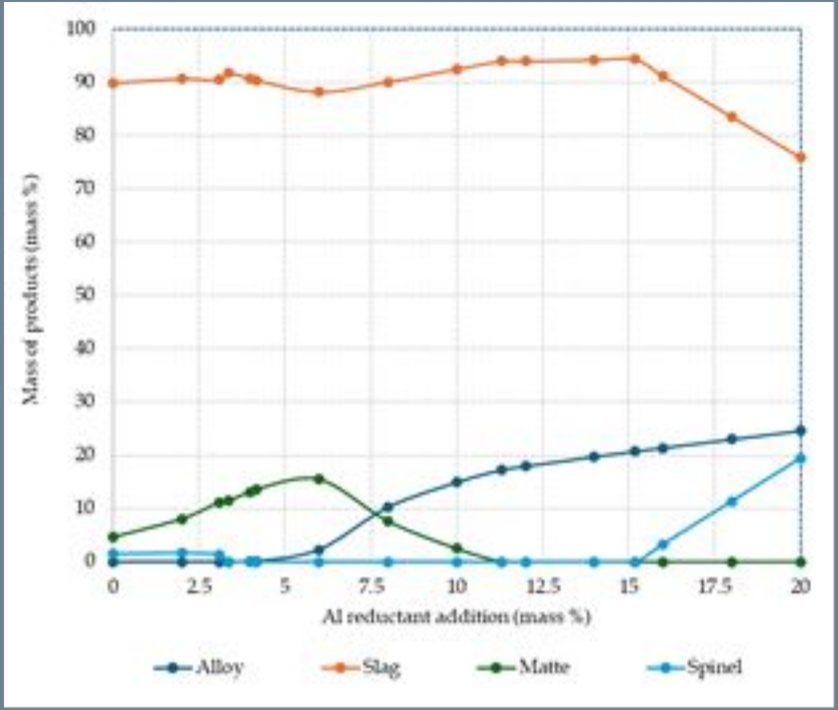
PROCEDURES

- Empirical testwork (based on simulation results)



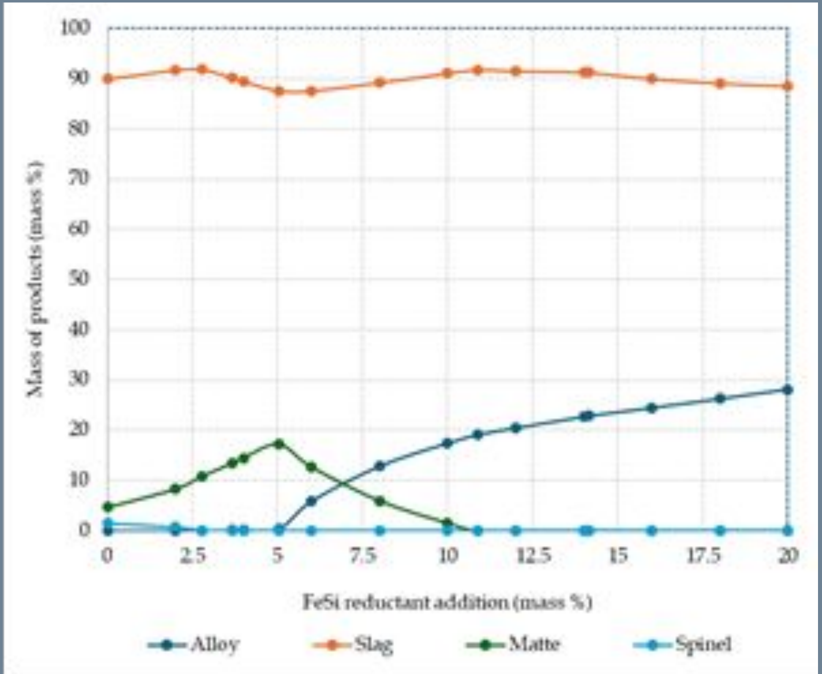
RESULTS AND DISCUSSION

- Thermochemical simulation results
  - UG2 with Al reductant



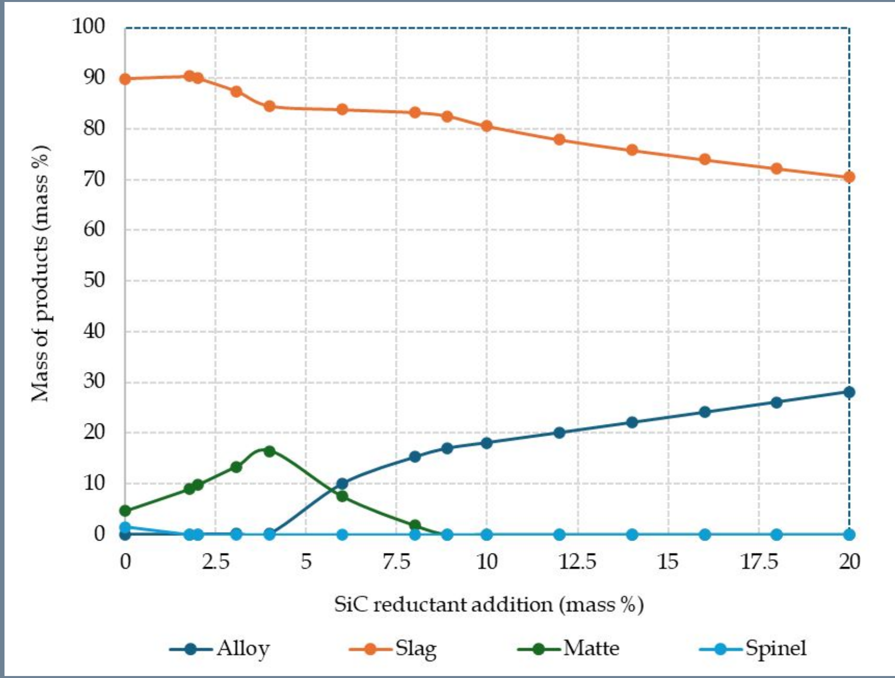
RESULTS AND DISCUSSION

- UG2 with FeSi reductant



RESULTS AND DISCUSSION

- UG2 with SiC reductant



RESULTS AND DISCUSSION

- Empirical smelting testwork
  - Baseline test (Test 1) – no matte could be collected, but alloy - SiC susceptor crucible was more reductive than initially anticipated – over reduction already
  - No matte was collected during the smelting tests, although simulation results showed the presence of matte between 0% and 5% reductant additions
  - Slag mass determined by different, thus, if matte formed it was attributed to slag (not visible)

Bench scale smelting product masses

	Product masses, %		
Test	Alloy	Slag	Loss
1	**3.94**	**90.71**	**5.34**
2	**4.51**	93.19	2.30
3	**5.36**	90.43	4.20
4	**3.92**	87.84	8.24
5	**7.54**	90.66	1.80
6	**5.77**	93.26	0.98
7	**6.58**	87.99	5.42

RESULTS AND DISCUSSION

- Chemical compositions of the slags
  - PGMs+Au contents in the slags were generally high
  - No specific trend observed due to separation challenges

Test	Al_2O_3	CaO	Cr_2O_3	FeO	MgO	MnO	SiO_2	TiO_2	**PGMs+Au (ppm)**
1	7.06	2.75	1.11	2.75	24.80	0.13	56.40	0.33	**71.30**
2	8.43	2.72	1.15	5.35	24.20	0.13	54.60	0.32	**23.86**
3	15.70	2.80	0.95	1.39	24.40	0.12	53.30	0.33	**23.59**
4	6.99	2.59	0.96	2.21	24.90	0.13	54.40	0.33	**71.60**
5	6.97	2.73	0.92	2.76	24.70	0.14	56.30	0.37	**91.78**
6	9.21	2.78	0.75	1.74	33.70	0.14	44.80	0.43	**42.64**
7	11.40	3.00	0.80	1.79	25.20	0.18	54.40	0.53	**45.16**

RESULTS AND DISCUSSION

- Chemical compositions of the alloys
  - Fe-rich alloys containing the PGMs (BMs)
  - S contents in the alloys were <1%
  - No conclusive results regarding the effect of different reductants
  - PGMs and Au concentrated in the alloys

Test	Co	Cr	Cu	Ni	Si	Fe	S	PGMs+Au (ppm)
1	0.36	6.04	3.47	12.10	10.15	64.85	0.91	4165
2	0.37	6.65	3.99	12.50	7.84	62.30	0.91	4407
3	0.39	4.70	3.24	13.40	10.20	64.70	0.75	4022
4	0.32	7.79	3.89	11.00	10.60	63.00	0.56	3180
5	0.31	8.33	4.45	10.50	13.70	61.20	0.44	3357
6	0.35	8.63	4.13	10.73	9.64	65.42	0.43	2327
7	0.29	9.53	4.82	10.15	12.00	61.35	0.30	2225

RESULTS AND DISCUSSION

- PGMs+Au recoveries to alloy
  - Recoveries were generally low and inconclusive about the effect of different reductants
  - Product separation challenges – non-accountability for the matte stream (slag analysis results)
  - Conclusive in that reductive matte smelting of UG2 using Al, FeSi, and SiC resulted in PGMs +Au reporting to the alloy due to overreduction - not the targeted matte.

$$\text{Recovery 2} = \left(1 - \frac{\text{mass of PGMs + Au in slag}}{\text{mass of PGMs + Au in feed}}\right) \text{ x } 100$$

Test	Recovery (%)
1	**88.6**
2	**94.8**
3	**96.4**
4	**88.5**
5	**87.4**
6	**93.3**
7	**93.0**

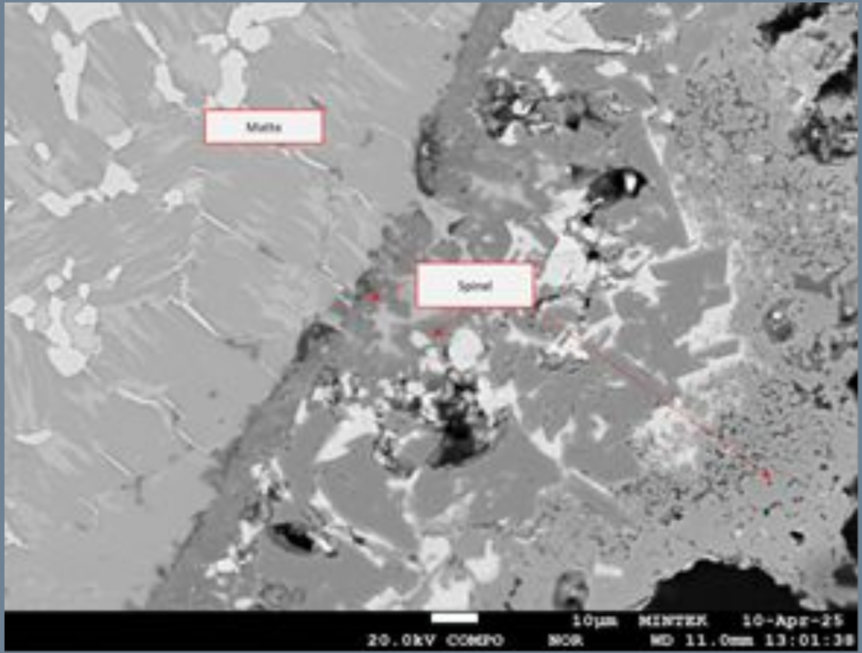
RESULTS AND DISCUSSION

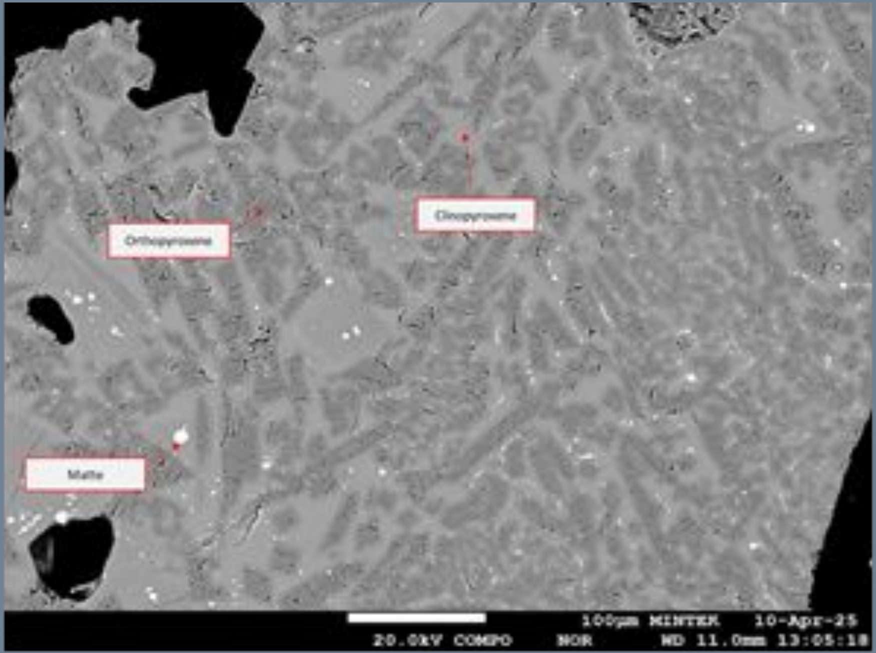
- Mineralogical characterization of furnace slags
  - Slags with 0% and 1% reductant additions generally had major pyroxene phases
  - Tests with higher reductant additions of 5% had pyroxene and olivine as major phases
  - The FeSi and SiC reductants at 5% additions had additional phases which included periclase, iron silicon, and quartz

Phase	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Clinopyroxene	*****	*****		*****	*****		***
Orthopyroxene	***	****	***	****	***	***	****
Olivine			*****			*****	****
Periclase					**		
Iron silicon					*		*
Quartz							*
***** predominant, **** major, *** intermediate, ** minor, *trace							

RESULTS AND DISCUSSION

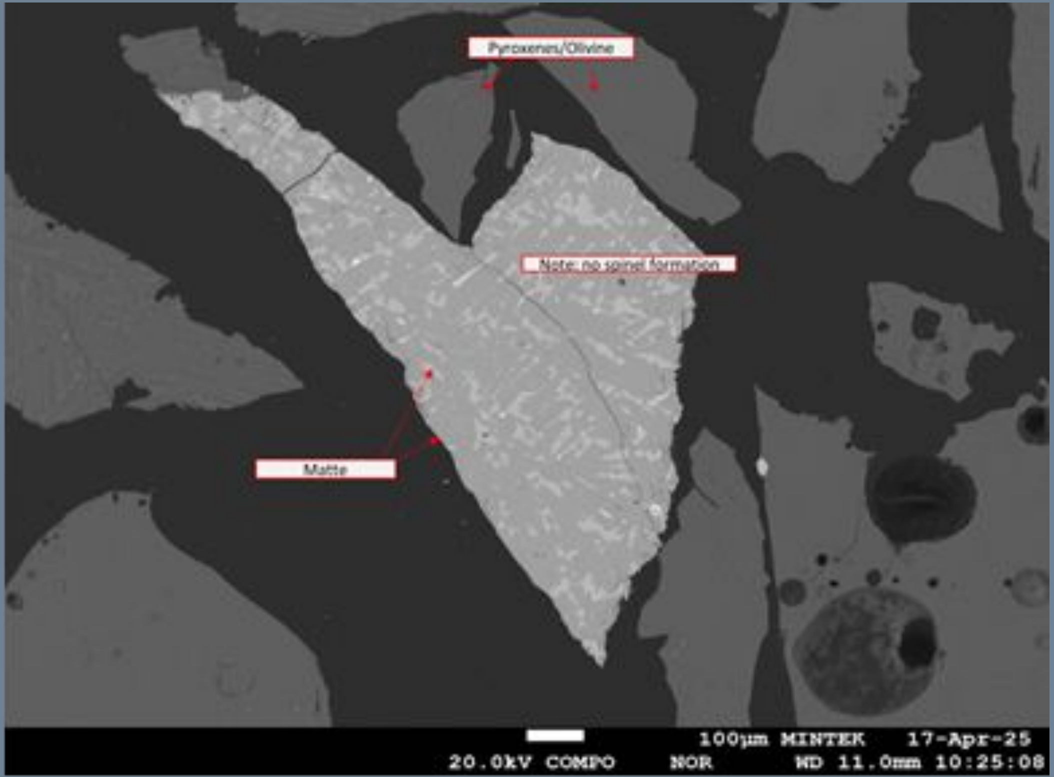
- General appearance of the phases formed when no reductant, Al, and Fesi reductants were used





RESULTS AND DISCUSSION

- General appearance of the slag when SiC was used as a reductant



CONCLUSIONS

- Thermochemical simulation results showed that these reductants can be used for matte smelting
- Experimental results showed that due to overreduction by SiC susceptor, the results on the use of these reductants for reductive matte smelting were inconclusive
- The matte was entrained in the slag, and the separation of the slag and matte was challenging
- Melt properties were affected because of over-reduction

RECOMMENDATIONS

- To use a bigger furnace where crucible containment will not a problem, arc furnace.

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