Pushing the Boundaries of Slag Operability: Processing of High-MgO Nickel Concentrates with the Ausmelt® TSL Process

J.Wood[1], J.Coveney[2], S.Creedy[3], D.Grimsey[4] and A.Rich[5]

1. Manager Technology, Metso Australia, Melbourne, VIC, 3175. jacob.wood@metso.com
2. Principal Process Engineer, Metso Australia, Melbourne, VIC, 3175. james.coveney@metso.com
3. Customer Account Manager, Metso Australia, Melbourne, VIC, 3175. stefanie.creedy@metso.com
4. Principal Smelter Development Metallurgist, BHP, Kalgoorlie, WA, 6430. david.grimsey@bhp.com
5. Smelter Development Manager, BHP, Kalgoorlie, WA, 6430. anthony.rich2@bhp.com

Keywords: Nickel Smelting, Ausmelt TSL, Slag Chemistry, Operability

ABSTRACT

In 2021, BHP and Metso examined processing of high-MgO nickel sulphide concentrates using Metso's Ausmelt® Top-Submerged-Lance (TSL) technology. Testwork was conducted in Metso's pilot testwork facility in Dandenong, Australia to explore operability of the SiO_2-FeO-MgO-CaO-NiO slag system across a wide range of compositions, temperatures and bath oxygen potentials. Pilot-scale testing aimed to define slag 'operability limits', representing the lowest bath temperature at which stable process and equipment operation could be maintained. This work was supported by FactSage^{TM} thermodynamic modelling, slag viscosity measurements, physical characterisation of quenched slag samples performed by the University of Queensland and benchmarking of commercial-scale TSL nickel smelting operations.

A wide range of slag compositions were examined, with Fe/SiO_2 ratios varying from 0.4 - 1.1, CaO content from 0.8 - 7.0 wt. % and MgO content from 6 - 19 wt. %. Slag SiO_2/MgO ratio, wt. % CaO and matte grade were found to have the greatest impacts on identified operability limits.

Operability limits were found to be influenced by both the solids content in slag and viscosity of the remaining liquid slag phase, with the relative contribution of these parameters heavily influenced by the slag composition. In the majority of trials, limits were defined by a theoretical solids content of 40 - 50%, however in trials with a low Fe/SiO_2 ratio and/or low wt. % CaO, limits were characterised by a much lower solids content due to the increased effect of the liquid slag viscosity in determining the behaviour of these slags.

The testwork highlighted inherent flexibility of the Ausmelt® TSL process to operate across a wide slag range of slag compositions and recover from process disturbances without an interruption to feeding. The trials also demonstrated the possibility for Ausmelt® TSL technology to process concentrates with an Fe/MgO ratio as low as 1.4, which has important implications to the commercial-scale processing of high MgO feeds. Arsenic rejection across the trials was very good, with only 30% of arsenic in the feed inputs reporting to the matte phase. Such high levels of arsenic removal provide the Ausmelt® TSL process with a notable advantage over alternative smelting technologies.

INTRODUCTION

Metso's Ausmelt® TSL process has achieved widespread acceptance as a leading smelting technology for the treatment of copper, nickel, lead, tin and zinc bearing feeds (Wood, Hoang and Hughes, 2017). Core to the technology is a vertically suspended lance operated with its tip submerged in the slag layer of the molten bath (Figure 1). Oxygen enriched air and fuel are injected via the lance resulting in significant bath mixing and agitation with consequently high rates of energy and mass transfer. The Ausmelt® TSL process is used at more than fifty (50) non-ferrous metals production facilities globally.

The Ausmelt® TSL process has been applied at commercial scale for the treatment of nickel-bearing concentrates, matte and residues (TABLE 1). Jinchuan Nickel Mining Company (JNMC) utilises Ausmelt TSL technology to process more than 1,100,000 tonnes per year of nickel sulphide concentrates to produce a low-grade matte, which is further upgraded in downstream Peirce Smith (PS) converters (Zhou et al, 2010). Jilin Ji'en Nickel Industry Co. Ltd. (JJNI) employ a similar process flowsheet for the processing of 275,000 tonnes per year of nickel concentrates (Aspola et al, 2012).

TABLE 1 – Ausmelt® TSL Nickel References

Customer	Location	Start-up	Feed	Capacity (t/y)
Jilin Ji'en Nickel (JJNI)	China	2009	Concentrates	275,000
Jinchuan Nickel (JNMC)	China	2008	Concentrates	1,100,000
Anglo American Platinum	South Africa	2002	Matte	213,000
Bindura Nickel	Zimbabwe	1995	Residues	10,000
Rio Tinto Zimbabwe	Zimbabwe	1992	Residues	7,700

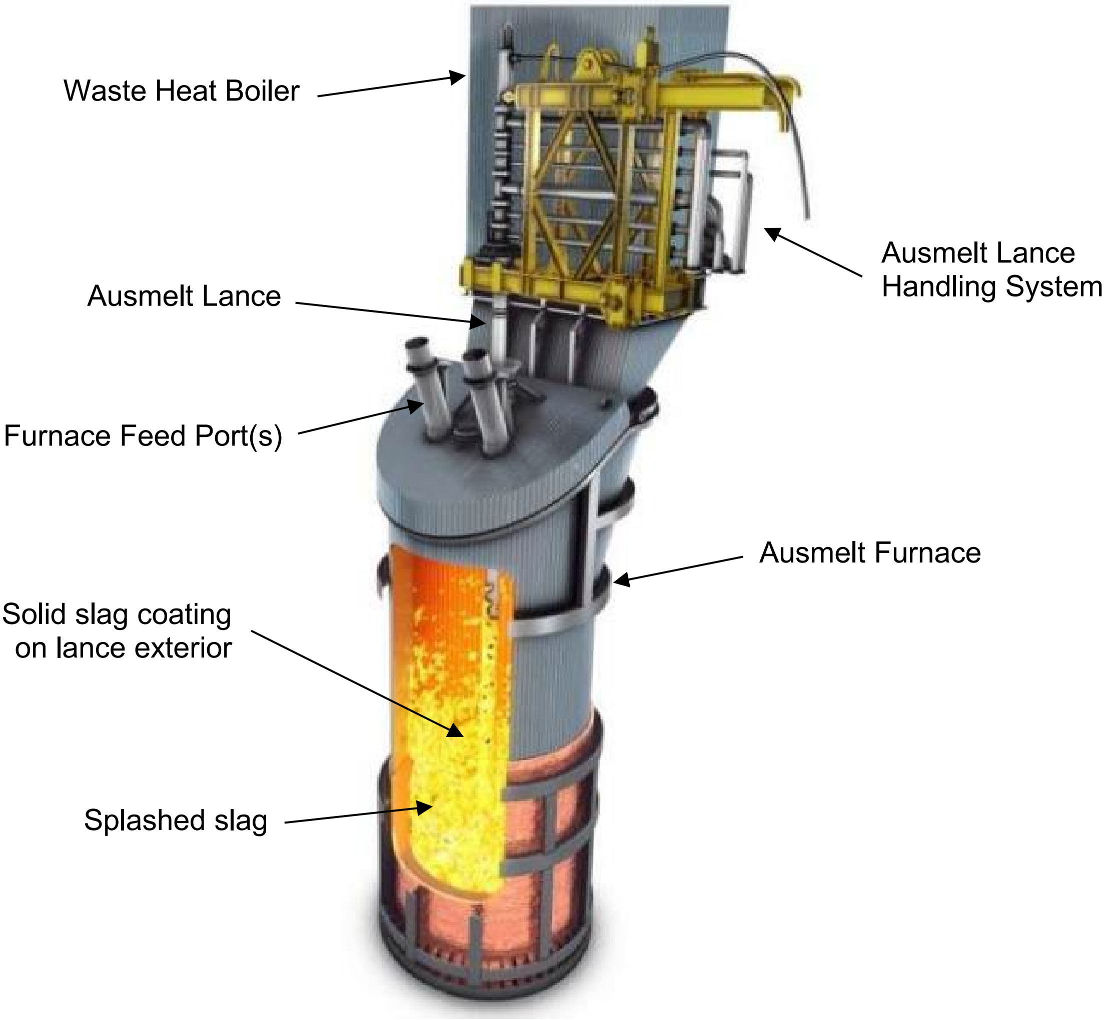

FIG 1 – Ausmelt® TSL Process Schematic

Anglo American Platinum have installed two (2) Ausmelt TSL converting furnaces to upgrade approximately 210,000 tonnes per year of low-grade electric furnace matte via a continuous converting process (Hundemark et al, 2011). The resultant composition of the high-grade matte from the TSL process is critical to recovery of contained platinum and palladium.

As with other bath smelting processes, the Ausmelt process relies on regulation of the slag fluidity to ensure effective mass and energy transfer (Wood and Hughes, 2016), straightforward transfer of molten products to downstream handling/refining operations and to minimise the propensity for bath foaming. The process typically aims to achieve operation at the lowest possible temperature through a combination of slag compositional and bath temperature control. Silica, limestone and in some cases hematite flux addition as part of the overall furnace charge is used to regulate the slag composition whilst bath temperatures are controlled by adjusting lance fuel and/or oxygen flowrates.

Unlike some other smelting technologies, the Ausmelt TSL process is capable of operating at temperatures well below the slag liquidus, with elevated concentrations of solids in slag. The highly turbulent nature of the Ausmelt TSL process means solid particles remain suspended, without settling out to form a layer of build-up on the furnace hearth.

TESTWORK

In 2021, BHP and Metso conducted fifteen (15) individual trials in Metso's pilot scale testwork facility in Dandenong, Australia to examine the processing of high-MgO nickel concentrates using Ausmelt TSL technology. The testwork examined operability of the SiO_2-FeO-MgO-CaO-NiO slag system across a wide range of compositions, temperatures and bath oxygen potentials and aimed to define slag 'operability limits', representing the lowest bath temperature at which stable process and equipment operation could be maintained.

Materials and Equipment

The following materials were used in the testwork:

- Leinster nickel sulphide concentrate
- Mt Keith nickel sulphide concentrate
- Magnesia powder
- Silica-revert flux mixture.
- Limestone flux

The feedrates of Leinster concentrate, Mt Keith concentrate, and magnesia powder were varied during the testwork to achieve a specific Fe/MgO ratio in feed blend for each trial. Magnesia powder was used to simulate processing of high-MgO concentrates, to achieve a target MgO concentration in slag. A mixture of silica and crushed revert from BHP's Kalgoorlie Nickel Smelter was introduced to achieve the target Fe/SiO_2 ratio, with limestone flux also added in the majority of trials to achieve a target wt. % CaO in slag. Concentrates and fluxes were dispensed individually and combined with a small quantity of water in a screw mixer to minimise material carryover with the process offgas. The combined feed charge was then directed to the furnace roof with an inclined conveyor. FIG 2 depicts the arrangement of equipment used for concentrate and flux handling in the testwork.

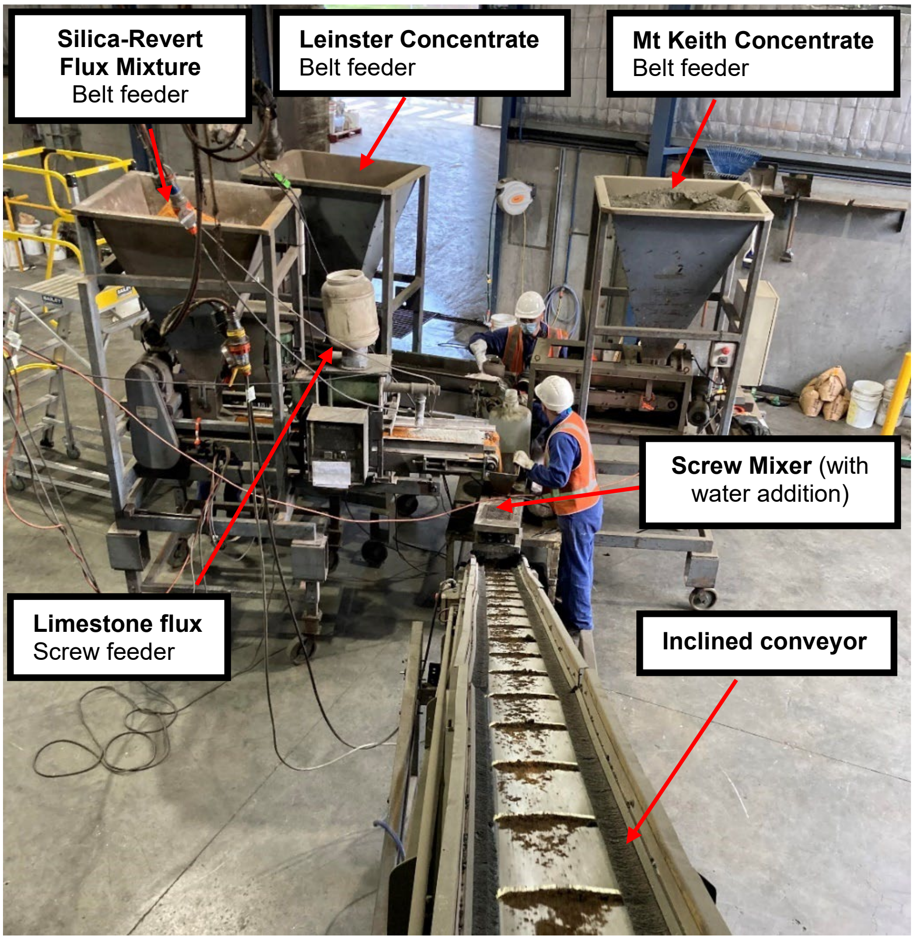

FIG 2 – Feed System Arrangement

The testwork employed a refractory-lined furnace with internal dimensions of 1900mm height and 500mm diameter. The furnace roof contained four (4) openings; the gas offtake, lance port, feed port and sampling/inspection port. The furnace was lined with magnesia-chrome refractories. A single water-cooled, copper taphole block with graphite inserts was employed in the trials. The taphole had two (2) openings, one at the hearth level and another at a height of 200mm. FIG 3 presents furnace equipment used in the testwork.

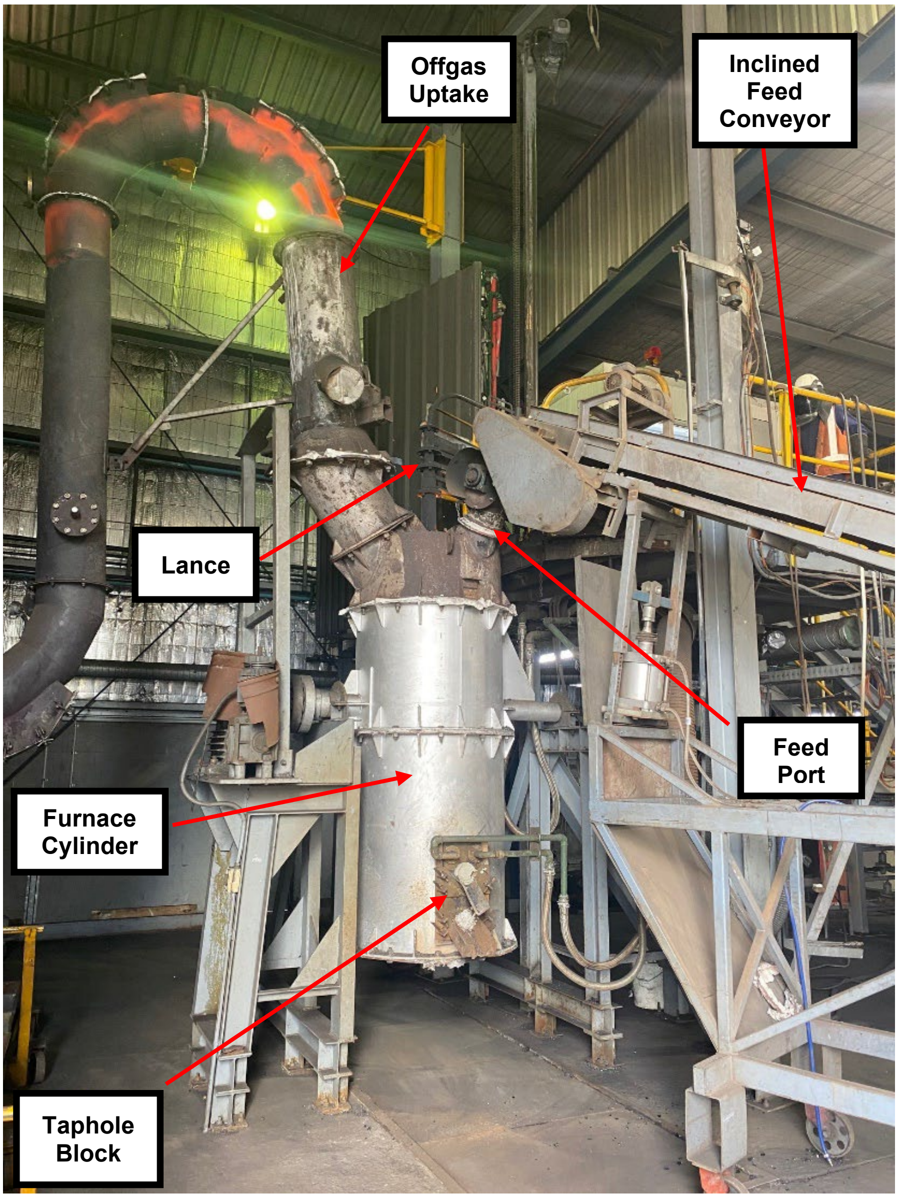

FIG 3 – Furnace Arrangement

Natural gas was used as a fuel in all trials. Flowrates of natural gas and oxygen, delivered via the Ausmelt lance were adjusted to achieve the desired bath temperature and to maintain a relatively consistent lance injection volume between the trials.

Matte and slag were tapped into sand-lined moulds (FIG 4) from both the top and bottom tapholes. The tapholes were opened using oxygen tapping rods and closed (when required) using fireclay. In instances where a mixture of slag and matte were tapped, these phases were subsequently separated once the mould contents had solidified and cooled sufficiently.

FIG 4 – Molten Product Handling

Process offgas was directed to downstream cooling, de-dusting and cleaning operations, prior to discharge to the atmosphere. Two (2) induced draught fans provided suction to maintain the furnace under constant negative pressure.

Objectives

The primary objective of the testwork was to define 'operability limits' across a wide range of slag compositions and matte grades. The 'operability limit' represented the lowest bath temperature for which stable process and furnace operation could be maintained. In particular, the testwork examined links between these identified operability limits and the following process parameters:

- Feed Fe/MgO ratio
- Slag Fe/SiO_2 ratio
- Slag MgO/SiO_2 ratio
- Slag wt. % CaO
- Slag wt. % MgO
- Matte wt. % Fe

Four (4) main indicators were used to determine when an operability limit had been reached, namely:

- Difficulties tapping slag and/or matte.
- Formation of build-up ('mush') on the furnace hearth.
- Rapid and excessive accretion formation around the furnace roof ports and/or offtake.
- 'Foamy' bath condition due to injected gases being unable to disengage from the slag bath.

Methodology

Prior to commencing each trial, FactSage$^{\text{TM}}$ software was used to calculate the slag liquidus temperature, based on target slag and matte compositions for the trial, with this information used to enable exploration of process operability limits in a controlled manner as follows:

1. Commence operation with a bath temperature at or slightly above the slag liquidus.
2. Confirm slag composition and matte grade are stable and within the target range.
3. Progressively reduce the bath temperature (measured via immersion thermocouple and confirmed with optical pyrometer during tapping) until the operability limit for a particular set of conditions has been identified.
4. Collect quenched (water-granulated) slag samples during tapping and/or via the furnace roof inspection port at the identified operability limit.
5. Increase the bath temperature slightly and maintain stable operation at or slightly above the identified operability limit for as long as possible.

Quenched slag samples taken during the testwork were subsequently analysed by the University of Queensland (UQ) using an Electron Probe Micro-Analyser (EPMA) to visually determine the slag solids content for operability limits identified in each trial (FIG 5). This work was supported by results from FactSage$^{\text{TM}}$ thermodynamic modelling, which was used to calculate the expected solids content in slag at a particular set of operating conditions (slag composition, matte grade and bath temperature).

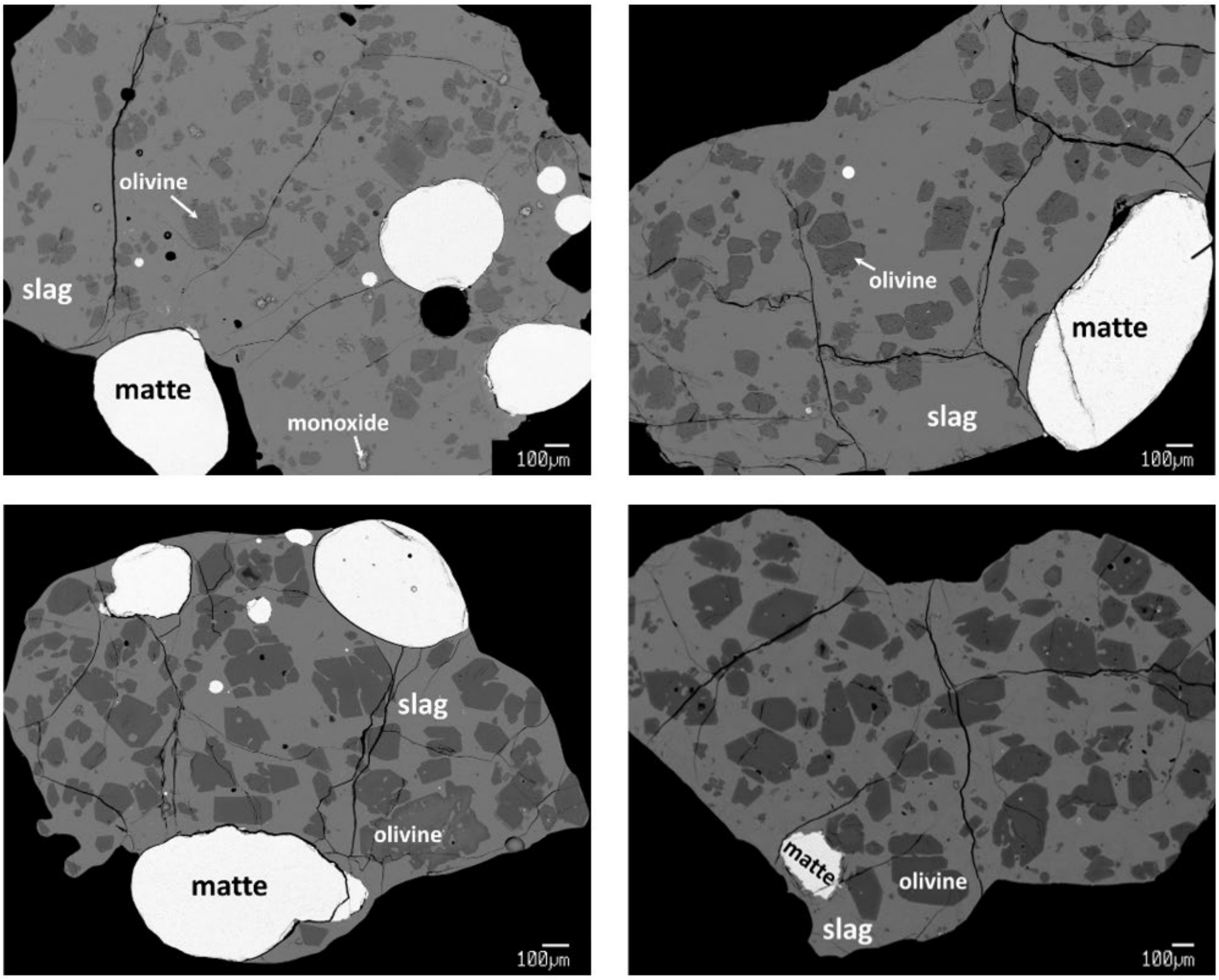

FIG 5 – Quenched Slag Analysis with EPMA

Operating Conditions

A wide range of slag compositions and matte grades were examined in the testwork (TABLE 2). This presented challenges in directly comparing operability limits for each trial, particularly given the combined effects of multiple parameters in determining the limit for a particular set of conditions. An isothermal phase diagram generated with FactSage™ is also shown in FIG 6, with the slag compositional range investigated in the testwork presented by the shaded area of the figure. The $p(O_2)$ chosen for this diagram is typical for slag in equilibrium with matte containing 15 wt. % Fe at a temperature of 1300°C.

TABLE 2 – Testwork Operating Conditions

Parameter	Minimum	Maximum
Feed Fe/MgO	1.4	3.0
Matte wt. % Fe	2.2	32.1
Slag SiO_2/MgO	1.6	5.6
Slag Fe/SiO_2	0.4	1.3
Slag wt. % CaO	0.6	8.4

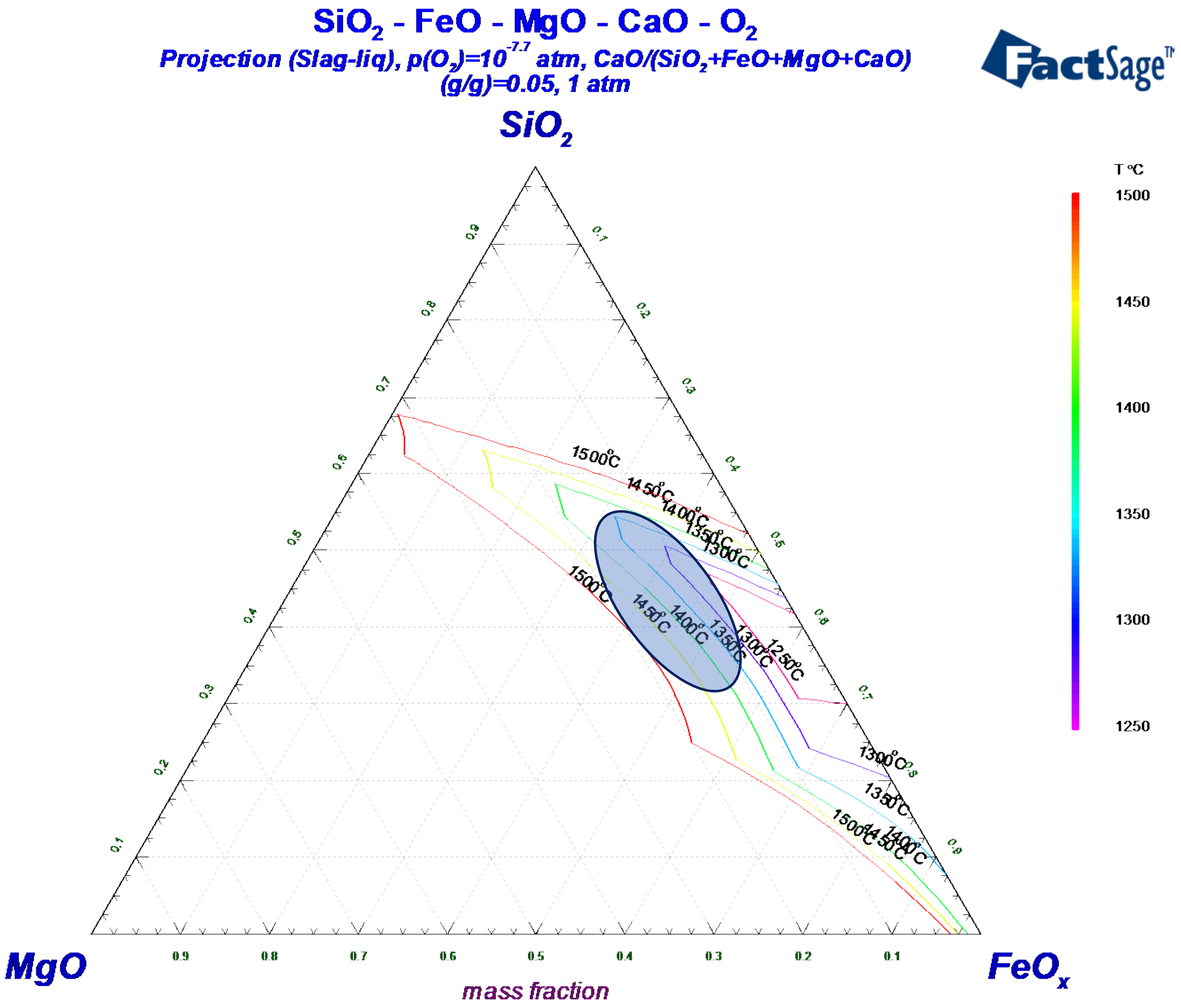

FIG 6 – Isothermal Phase Diagram

Results and Discussion

Operability limits were successfully identified in ten (10) of the trials. Prior to the testwork, it was hypothesised that the slag solids content would be the dominant parameter influencing the operability limit for a particular set of conditions. Results from the testwork indicated however, that limits were defined by both the slag solids fraction and viscosity of the remaining liquid slag phase, with the relative contribution of these parameters heavily influenced by the slag composition. Operability limits were found to be largely dictated by the slag SiO_2/MgO ratio, bath oxygen potential (matte wt. % Fe) and slag wt. % CaO (FIG 7), with minimal impact from the slag Fe/SiO_2 ratio. The effects of these parameters are discussed in more detail in the following sections.

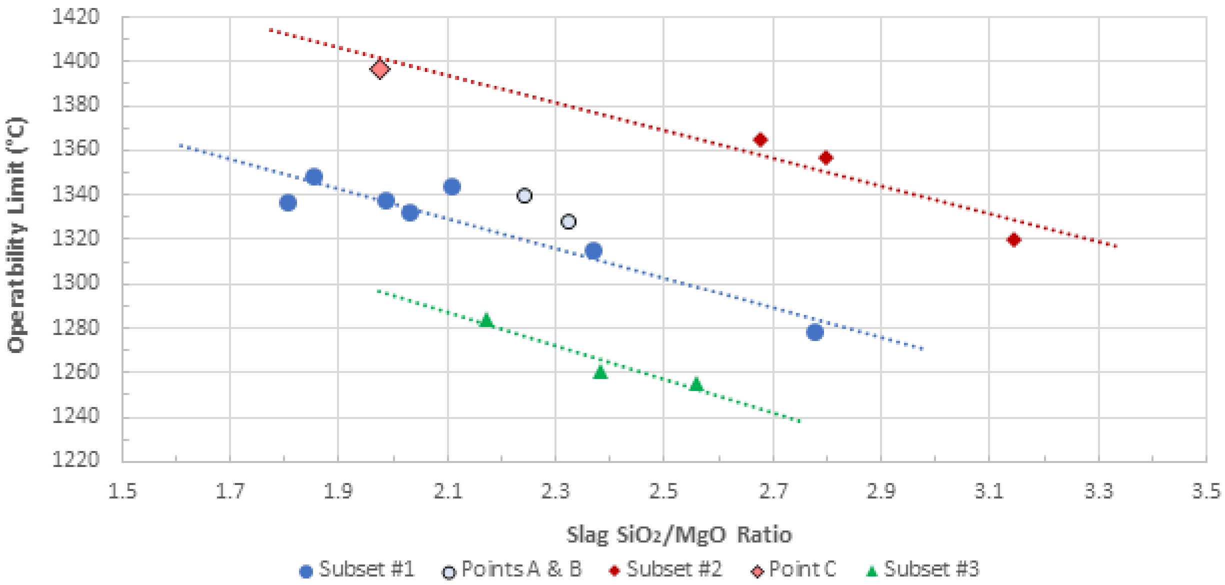

FIG 7 – Operability Limit Correlation with Slag SiO2/MgO Ratio, % CaO and Matte % Fe

TABLE 3 – Data Subset Operating Conditions

Data Subset	Slag wt. % CaO	Slag Fe/SiO_2	Matte wt. %Fe
● Subset #1	Mid (5 – 8 wt. %)	Mid (0.8 – 1.1)	Mid (8 – 13 wt. %)
○ Points A & B	Mid (6 – 7 wt. %)	Low (0.5 – 0.6)	Low (5 wt. %)
◆ Subset #2	Low (1 wt. %)	Low (0.5)	Mid (9 – 13 wt. %)
◇ Point C	Low (2 wt. %)	Mid (0.9)	Mid (8 wt. %)
▲ Subset #3	Mid (5 – 7 wt. %)	Mid (0.8 – 1.0)	High (25 – 28 wt. %)

Slag SiO_2/MgO Ratio

Operability limits were strongly influenced by the slag SiO_2/MgO ratio, evidenced by the consistent slope of data sets in FIG 7. Modelling in FactSage^{TM} confirmed the strong effect of SiO_2/MgO ratio on the slag liquidus temperature and hence, solids fraction in slag but also suggested minimal impact of slag SiO_2/MgO ratio on the liquid slag viscosity (FIG 8).

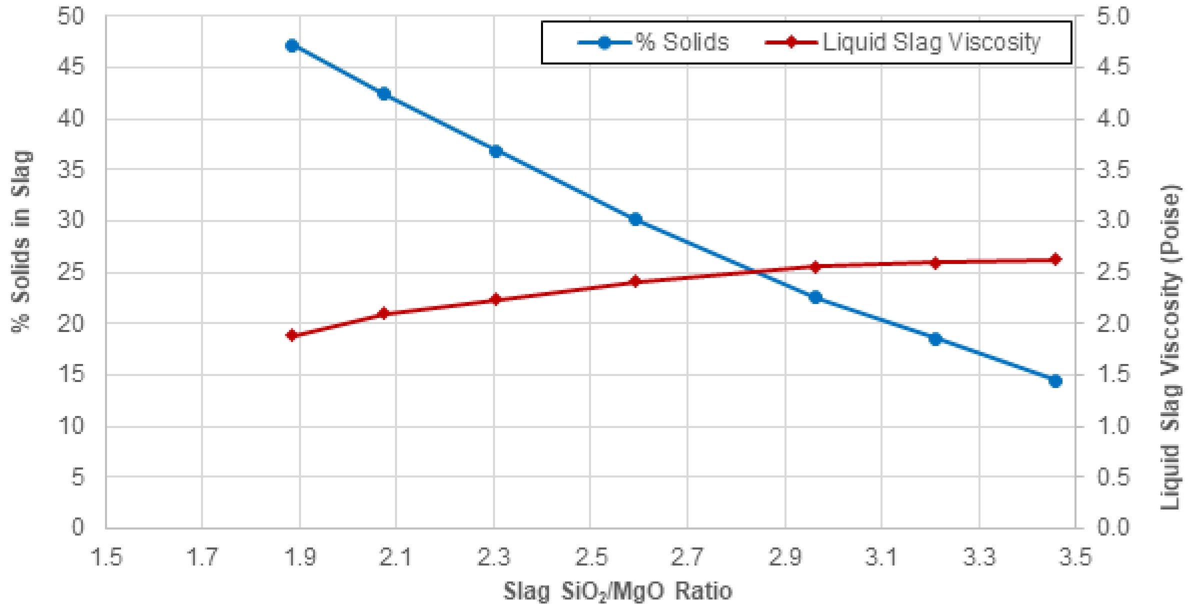

FIG 8 – Slag % Solids and Viscosity Correlation with SiO_2/MgO Ratio (calculated with FactSage™ at 1320°C, 5 wt. % CaO and 15 wt. % Fe in matte)

Slag % CaO

Decreasing slag wt. % CaO necessitated operation at higher temperatures across the range of slag compositions examined in the testwork. This finding is supported by results from Factsage™ modelling, which indicated not only an increased solids content at low wt. % CaO (particularly at low SiO_2/MgO ratio) but also a significant increase in liquid slag viscosity (FIG 10). Consequently, it was reasoned that operability limits for data Subset #2 and Point C, were dictated by both the slag solids concentration and liquid slag viscosity.

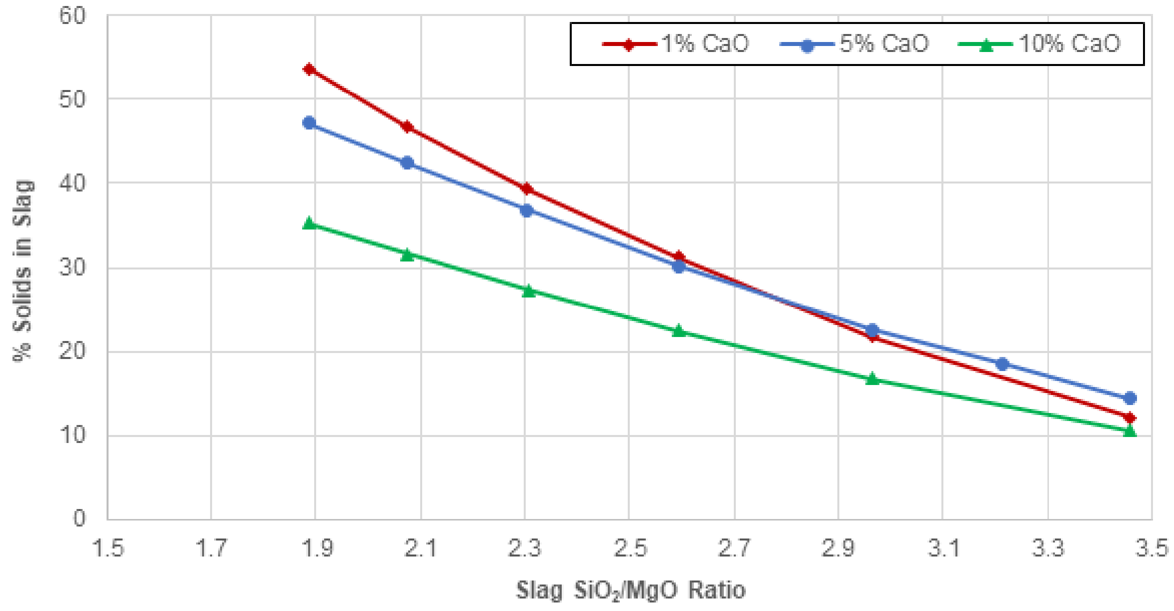

FIG 9 – Slag % Solids Correlation with SiO_2/MgO Ratio at variable wt. % CaO (calculated with FactSage™ at 1320°C and 15 wt. % Fe in matte)

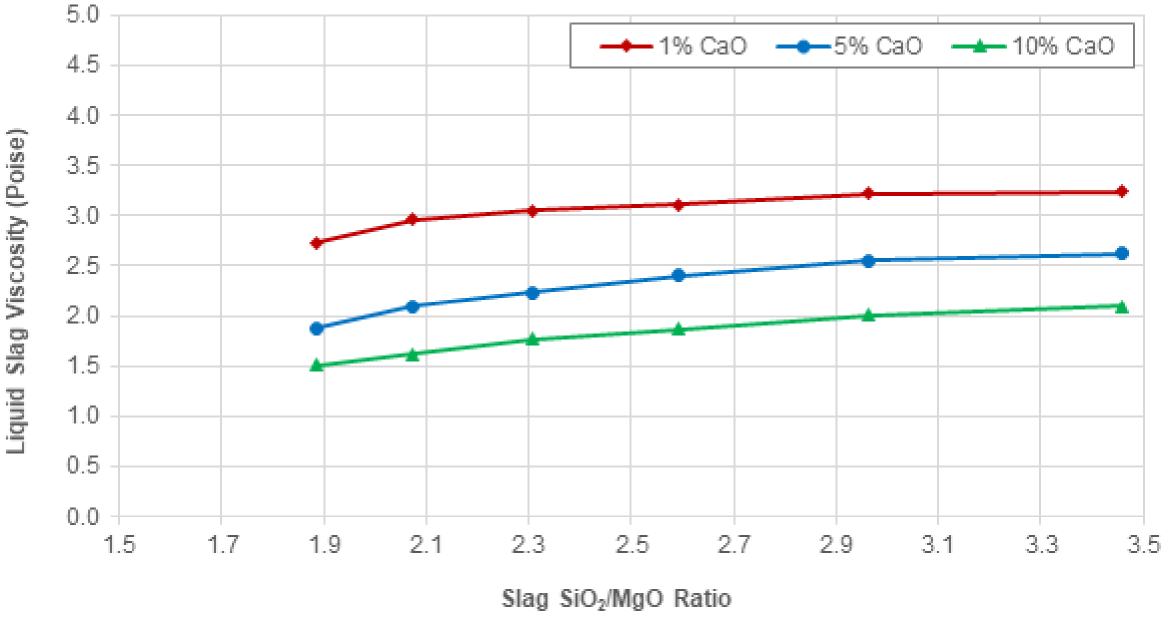

FIG 10 – Slag Viscosity Correlation with SiO_2/MgO Ratio at variable wt. % CaO (calculated with FactSage^{TM} at 1320°C and 15 wt. % Fe in matte)

Matte %Fe

Increasing wt. % Fe in matte (i.e. decreasing matte grade) enabled operation at lower temperatures across the range of matte grades examined in the testwork. Modelling in FactSage^{TM} indicated a significantly higher slag solids content with decreasing wt. % Fe in matte, particularly at high SiO_2/MgO ratio (FIG 12), due to displacement of MgO by NiO within the olivine structure and consequently, an increasing quantity of MgO reporting to the liquid slag phase. FactSage^{TM} modelling also suggested minimal effect of matte grade on the liquid slag viscosity (FIG 12), operability limits for data Subset #3, were almost entirely dictated by the slag solids content.

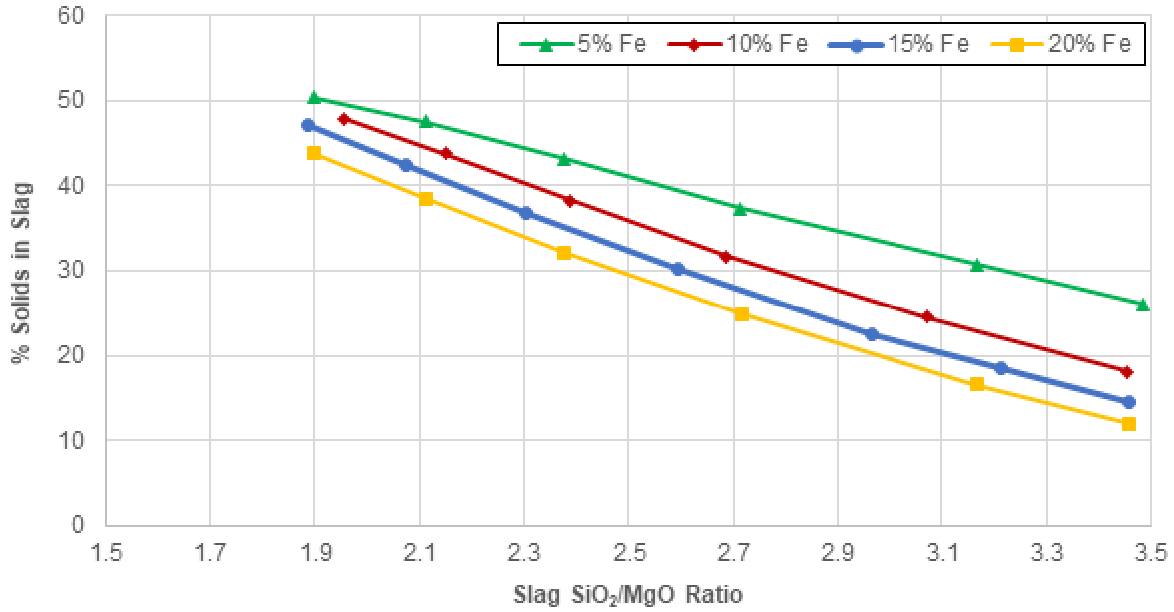

FIG 11 – Slag % Solids Correlation with SiO_2/MgO Ratio at variable wt. % Fe in Matte (calculated with FactSage^{TM} at 1320°C, $Fe/SiO_2 = 0.8$ and 5 wt. % CaO in slag)

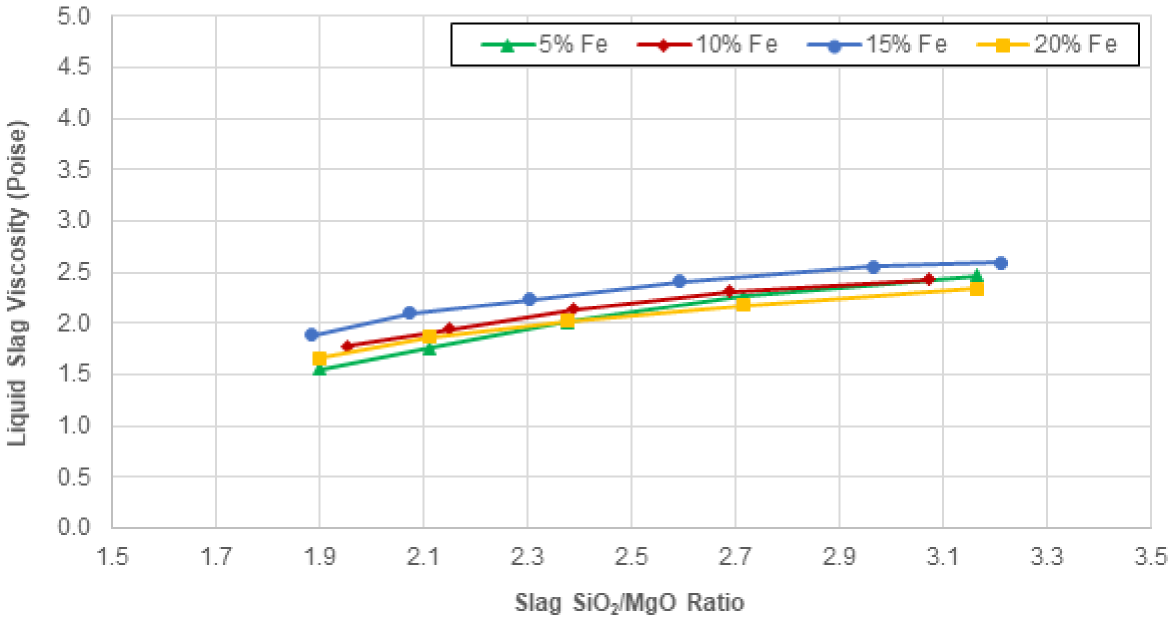

FIG 12 – Slag Viscosity Correlation with SiO_2/MgO Ratio at variable wt. % Fe in Matte (calculated with FactSage^{TM} at 1320°C, Fe/SiO_2 = 0.8 and 5 wt. % CaO in slag)

Slag Fe/SiO_2 Ratio

Variability in slag Fe/SiO_2 ratio was found to have minimal impact on identified operability limits across the range of slag compositions examined in the testwork. Whilst limits at low Fe/SiO_2 ratio were typically higher, this was rationalised by variability in matte grade (Points A and B) and wt. % CaO (Point C). Modelling in FactSage^{TM} indicated limited influence of Fe/SiO_2 ratio on the slag solids concentration, except at elevated Fe/SiO_2 ratios (FIG 14). Of greater significance, however, is the significant increase in liquid slag viscosity predicted at low Fe/SiO_2 ratio (FIG 14), which is likely to have impacted findings from the testwork.

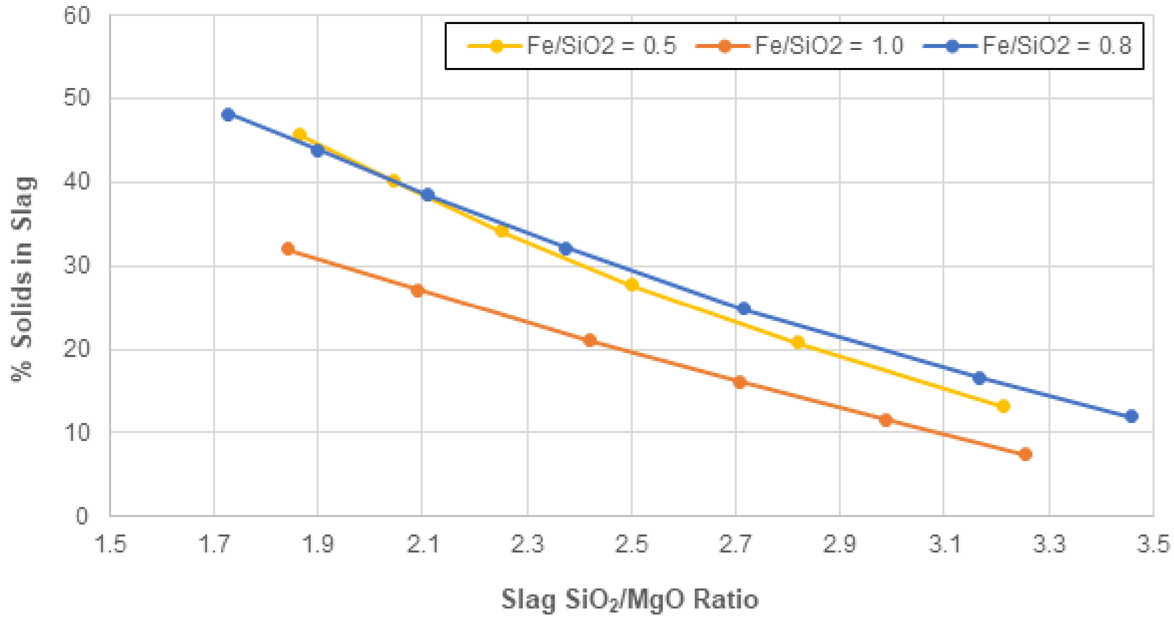

FIG 13 – Slag % Solids Correlation with SiO_2/MgO Ratio at variable Fe/SiO_2 Ratio (calculated with FactSage^{TM} at 1320°C, 20 wt. % Fe in matte and 5 wt. % CaO in slag)

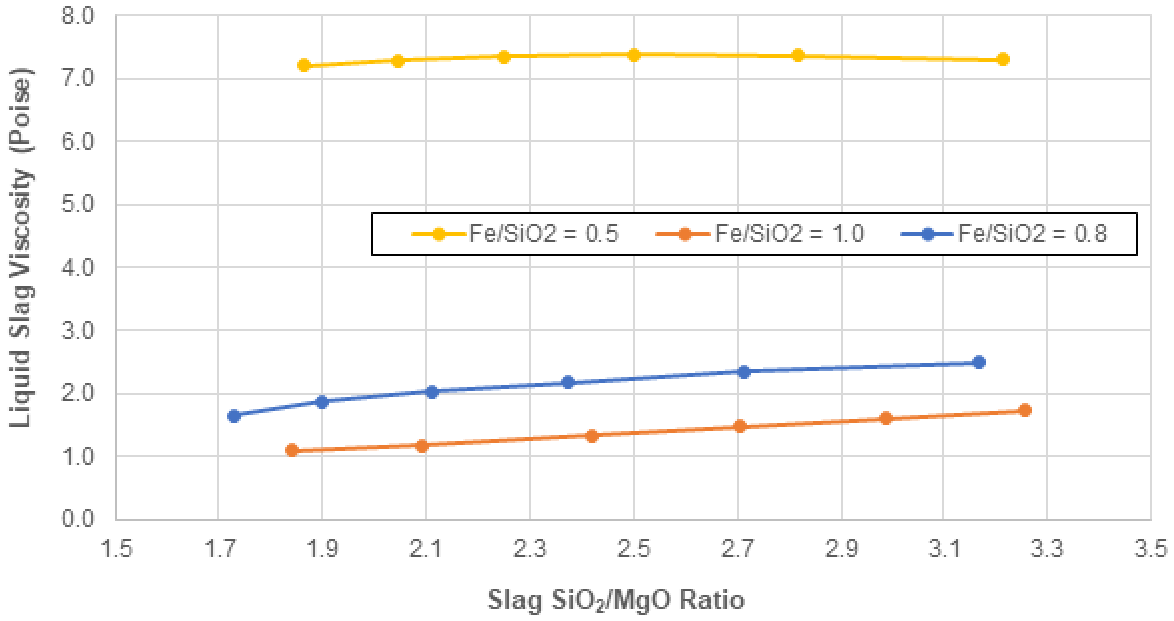

FIG 14 – Slag Viscosity Correlation with SiO_2/MgO Ratio at variable Fe/SiO_2 Ratio (calculated with FactSage^{TM} at 1320°C, 20 wt. % Fe in matte and 5 wt. % CaO in slag)

Slag EPMA Analysis

Quenched slag samples taken throughout the testwork were analysed by the University of Queensland (UQ) to visually determine the solids concentration in slag at the operability limit(s) identified in each trial. Slag samples were for the most part, characterised by a visual solids content in slag of 15 – 30%. FactSage^{TM} was also used to determine the theoretical slag solids content for each operability limit, which suggested a much higher solids fraction than observed via EPMA (FIG 15). The reasons for discrepancies between these two (2) datasets were not clear and as this was not a primary objective of the testwork, this was not investigated further.

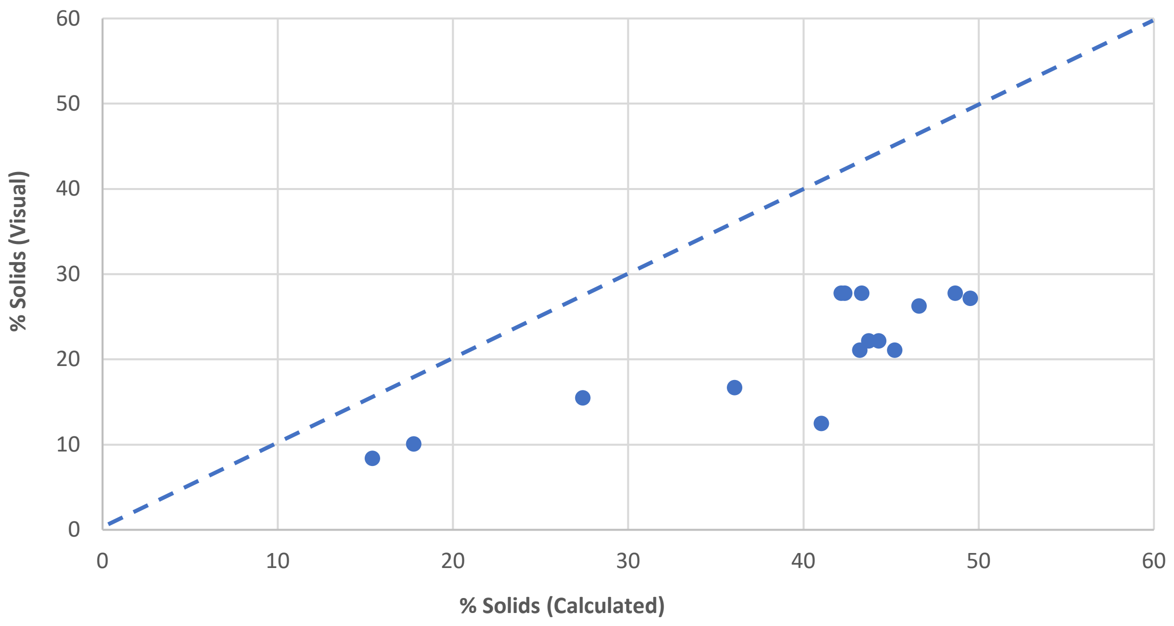

FIG 15 – Correlation in Slag Solids Content

Operability Limit Definition

Operability limits were for the most part, characterised by a slag solids content of 40 - 50% and liquid slag viscosity of 1 - 3 Poise (as determined with FactSage^{TM}), with the exception of data Subset #2 (low % CaO and Fe/SiO_2 ratio) which was had only 15 - 30% solids and viscosity of 6 - 7 Poise.

These results indicated the relative contribution of solids content and liquid slag viscosity in defining the operability limit for a particular set of conditions, varied with slag composition. FIG 16 presents the relationship between % solids and liquid slag viscosity (determined with FactSage^{TM}) for operability limits identified in the testwork. A suggested range of conditions, for which stable operation could be achieved is also illustrated by the shaded region in the figure, noting that further testwork would be required to expand the understanding of permissible operating conditions, particularly at low Fe/SiO_2 ratio.

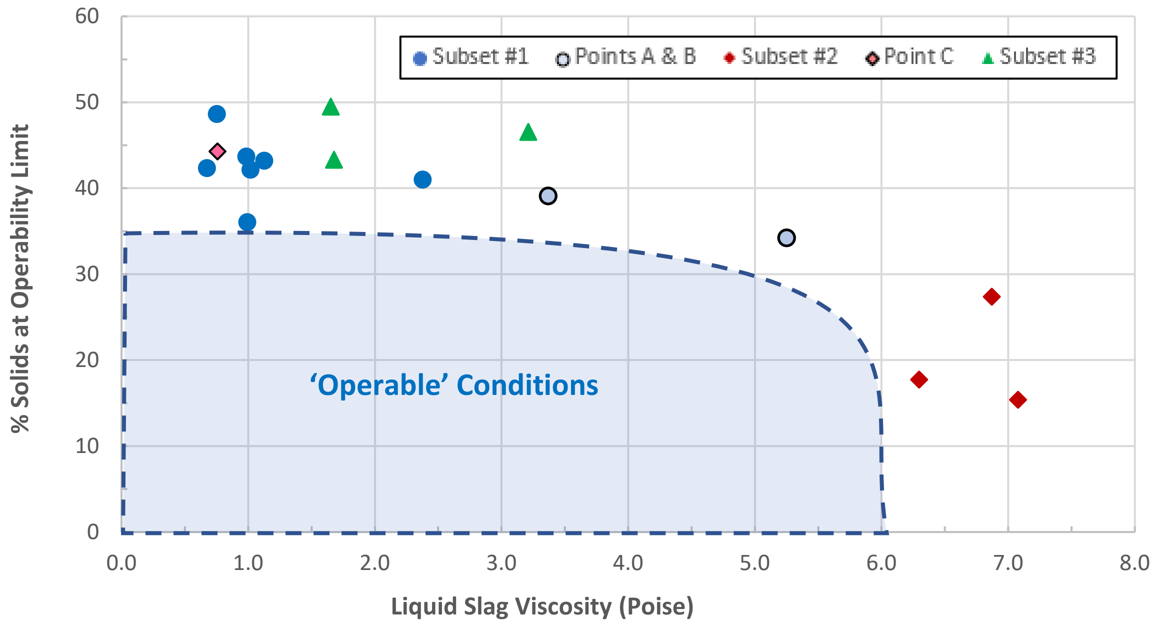

FIG 16 – Operability Limit Variation with % Solids and Liquid Slag Viscosity

TABLE 4 – Data Subset Operating Conditions

Data Subset	Slag wt. % CaO	Slag Fe/SiO_2	Matte wt. %Fe
● Mid (5 – 8 wt. %)	Mid (0.8 – 1.1)	Mid (8 – 13 wt. %)	Mid (8 – 13%)
○ Mid (6 – 7 wt. %)	Low (0.5 – 0.6)	Low (5 wt. %)	Low (5%)
◆ Low (1 wt. %)	Low (0.5)	Mid (9 – 13 wt. %)	Mid (9 – 13%)
◇ Low (2 wt. %)	Mid (0.9)	Mid (8 wt. %)	Mid (8%)
▲ Mid (5 – 7 wt. %)	Mid (0.8 – 1.0)	High (25 – 28 wt. %)	High (25 – 28%)

COMMERCIAL SCALE OPERATIONS

Results from the testwork indicated the Ausmelt TSL nickel smelting process can operate with 30 - 40% solids in slag (determined with FactSage^{TM}) across a wide range of conditions and particularly at low matte grades (> 20 wt. % Fe). This is supported by data from commercial-scale, Ausmelt TSL nickel smelters operated by JJNI (Si et al, 2017) and JNMC (January 2021, personal communication), for which FactSage^{TM} predicts a slag solids content in the range from 25 - 35%.

The ability to operate with a significant solids content in slag, provides enormous operational and economic benefits. In addition to a reduction in process oxygen and fuel consumptions by roughly 10% and 20% respectively, refractory wear rates are greatly reduced at lower temperatures, ensuring an extended furnace campaign life and thus reduced expenditure on refractory lining demolition and installation activities. The possibility of operating well below the slag liquidus also provides enhanced flexibility to handle short and long-term variability in feed material compositions and easily recover from periods of bath temperature instability.

Operability limits in the testwork manifested primarily as difficulties tapping molten slag and to a lesser extent, accretion build-up around the furnace roof ports and offtake. Owing to the design and sizing of the pilot-scale furnace employed in the trials, these issues were somewhat exaggerated, meaning operation at lower temperatures may be possible on a commercial scale. The combination of an intensely-cooled copper taphole block and small taphole openings, resulted in material freezing without regular 'working' of the taphole to keep slag flowing. These issues are readily mitigated on a commercial scale with appropriate furnace design (large taphole openings, short taphole length and multiple tapholes). For reference, JNMC utilize three (3) slag tapholes with openings of 80mm (January 2021, personal communication), with one or more tapholes in use more or less continuously (FIG 17). Similarly, the Ausmelt TSL converter operated by Anglo Platinum in South Africa, utilizes slag taphole inserts with an opening size of 75mm (Hoosen, Schione and Ramblyana, 2018).

FIG 17 – Commercial Scale Taphole Configuration

To a lesser extent, accretion build-up around the furnace roof ports and offtake also dictated operability limits observed in the trials. This is a persistent issue in the pilot-scale furnace due to both the relatively small freeboard height and significant air-ingress. On a commercial scale these issues are addressed with appropriate furnace design (sufficient freeboard height, tight sealing of ports and provision for freeboard burners to deliver localized heat input for melting of accretions).

CONCLUSIONS

Testwork conducted in Metso's pilot testwork facility in Dandenong, Australia confirmed the possibility of treating high high-MgO, nickel sulphide concentrates using Ausmelt TSL technology. The testwork examined behaviour of the SiO_2-FeO-MgO-CaO-NiO slag system across a wide range of conditions with the goal of determining the lowest bath temperature at which stable process and equipment operation could be maintained. Slag SiO_2/MgO ratio, wt. % CaO and matte grade found to have the greatest impacts on identified operability limits.

Contrary to initial thinking, results from the testwork indicated operability limits were not solely determined by the slag solids content, with the liquid slag viscosity also playing a role, particularly at low wt. % CaO and Fe/SiO_2 ratio.

The testwork highlighted inherent flexibility of the Ausmelt TSL process to operate across a large slag compositional range and recover from process disturbances an interruption to feed introduction. Results from the trials indicated the Ausmelt process is capable of operating with a high concentration of suspended solids in slag, without negative impacts to slag fluidity. The testwork also demonstrated the possibility for Ausmelt TSL technology to process concentrates with an Fe/MgO ratio as low as 1.4, which has important implications to the commercial-scale processing of high-MgO content feeds.

REFERENCES

Aspola, L, Matusewicz, R, Haavanlammi, K and Hughes, S, 2012. Outotec Smelting Solutions for the PGM Industry, in *Proceedings Platinum 2012*, pp 235–250 (The Southern African Institute of Mining and Metallurgy).

Hoosen, A, Schione, M and Ramblyana, I, 2018. Improvements to the Anglo Converting Process (ACP) Tap-Block Management, in *Proceedings from Furnace Tapping 2018*, pp 49 – 56 (The Southern African Institute of Mining and Metallurgy).

Hundermark, R, Mncwango, S, de Villiers, L, and Nelson, L, 2011. The smelting operations of Anglo American's Platinum Business: An Update, in *Proceedings Southern African Pyrometallurgy 2011*, pp 295–307 (The Southern African Institute of Mining and Metallurgy).

Si, J, Zhao, Y, Wang C and Geng, J, 2017. A Brief Analysis of the Method of Reducing the Nickel Content of Slag in Nickel Smelting Production, *China Nonferrous Metallurgy,* August 2017 Issue 4, pp 36–39.

Wood, J, Hoang, J and Hughes, S, 2017. Energy Efficiency of the Outotec® Ausmelt Process for Primary Copper Smelting, *JOM*, 69(6):1013–1020.

Wood, J, and Hughes, S, 2016. Future Development Opportunities for the Outotec® Ausmelt Process in *Proceedings 9th International Copper Conference 2016*, pp 361–372 (The Mining and Materials Processing Institute of Japan).

Zhou, M, Wan, A, Li, G, Baldock, R and Li, H, 2010. Industrial Operation of JAE Nickel Smelting Technology at Jinchuan Nickel Smelter, in *Supplemental Proceedings: Volume 1: Materials Processing and Properties 2010*, pp 525–534 (The Minerals, Metals & Materials Society).