Chapter 5: Conclusions & recommendations

In chapter 4 the results from the test program were presented, discussed and interpreted. In this chapter the study is concluded and recommendations made regarding implementation and future studies. I start this chapter by summarizing the main findings of the study. Then these findings are linked to literature and theory. Gaps, anomalies and deviations in the data are discussed. The chapter is concluded with recommendations for future studies. The order of discussions is:

5.1 Summary of main findings
5.2 Results linked to literature and theory
5.3 Gaps, anomalies and deviations in data
5.4 Recommendations

5.1 Summary of main findings

During preparation of the LSR sample from a crude ilmenite concentrate 90 per cent of the chromite and 29 per cent of the ilmenite in the crude ilmenite reported to the LSR fraction. The ilmenite content of LSR at 84.6 per cent was lower than that of crude ilmenite at 90.8 per cent, reflecting a higher content of non-ilmenite related minerals in the LSR (15.4 per cent vs. 9.2 per cent). The chromite content of LSR at 1.1 per cent was double that of crude ilmenite at 0.4 per cent resulting in a Cr_2O_3 content of LSR at 0.56 per cent vs. 0.21 per cent in crude ilmenite. I came to the conclusion that it would be more difficult to decrease the Cr_2O_3 content of the LSR to less than 0.1 per cent, than for crude ilmenite, given the higher Cr_2O_3 content in LSR as well as the lower TiO_2 available for dilution of the Cr_2O_3.

With the Fe_2O_3: FeO mass ratios of both the crude ilmenite and the LSR being less than 1-1.57 (0.44 and 0.74 respectively), I assumed that oxidative roasting will enhance the magnetic susceptibility of the ilmenite in both types of material. No amount of roasting and/or magnetic separation would decrease the content of MgO, MnO and V_2O_5 in the final ilmenite product though, because these components are in solid solution in the ilmenite. If the magnetic susceptibility of only the ilmenite in crude ilmenite or LSR could be increased, the content of CaO, SiO_2 and Al_2O_3 in the final ilmenite product could be decreased by magnetic separation.

When roasting LSR the rate of oxidation – as measured by the rate of increase in magnetic susceptibility - is controlled by temperature rather than the oxygen content of the oxidizing gas atmosphere. As for crude ilmenite an ideal, single roasting condition does not exist for LSR and the appropriate roasting conditions for crude ilmenite are also appropriate to LSR. The study indicated that when roasting LSR two control strategies could be followed: a high temperature (800°C), short retention time (5 to10 minutes) strategy or low temperature (750°C), long retention time (10 to 40 minutes) strategy. When exceeding the maximum retention time limits the magnetic susceptibility of the both the crude ilmenite and the LSR decreased. This decrease was attributed to over-roasting as described by Nell and Den Hoed (1997).

Separability curves for crude ilmenite and LSR samples roasted at 800°C for 10 minutes in air indicated that roasting increased the magnetic susceptibility of both the ilmenite in the concentrate as well as the chromite. In the roasted crude ilmenite sufficient ilmenite was available to dilute the chromite present to less than 0.1 per cent Cr_2O_3. (It is worth recalling that the Cr_2O_3 content of LSR was much higher than crude ilmenite: 0.6 per cent compared with 0.2 per cent). In LSR insufficient ilmenite was present to dilute the chromite present to less than 0.1 per cent Cr_2O_3. Separability curves for crude ilmenite and LSR samples roasted at 750°C for 20 minutes in air indicated that roasting increased the magnetic susceptibility of both the ilmenite in the concentrate as well as the chromite. In both the roasted crude ilmenite and the LSR sufficient ilmenite was available to dilute the chromite present to less than 0.1 per cent Cr_2O_3. Therefore the quality and recovery of ilmenite was a function of the rate of enhancement of magnetic susceptibility of ilmenite relative to that of chromite. These results show that it is possible to produce an ilmenite product suitable for ilmenite smelting by subjecting LSR to roasting and subsequent magnetic separation, under the roasting conditions published for crude ilmenite by Nell and Den Hoed (1997) or Bergeron and Prest (1974).

The chromite in the LSR was of the magnesiochromite spinel series. The chromite in the UG1 sample was also of the magnesiochromite spinel series and very close in composition to that of the chromite in LSR – this being the reason for the selection of UG1 chromite for this study. The mass ratio of Fe_2O_3:FeO in the chromite from the LSR was 0.5 whilst in the UG 1 chromite it was 0.64. I therefore assumed that should roasting have an impact on the magnetic susceptibility of the UG1 chromite the impact on the chromite in LSR would be more significant that that of the UG1 chromite. When subjecting the UG1 chromite to varying roasting conditions the results indicated that the hypothesis that the magnetic susceptibility of chromite remains constant during magnetizing roasting of an ilmenite concentrate under the oxidising conditions, was not true. Roasting did increase the magnetic susceptibility of the UG1 chromite and iron rich exsolutions was observed on the roasted UG 1 chromite particle surface. I then postulated that these iron rich exsolutions is the cause of the increase in magnetic susceptibility observed in UG 1 chromite.

5.2 Results linked to literature and theory

The crude ilmenite used in this study had a composition similar to that of the crude ilmenite described by Nell and Den Hoed (1997). At 90.8 per cent the ilmenite content of the crude ilmenite was similar to the 90.0 per cent reported by Nell and Den Hoed (1997). The Cr_2O_3 content of the crude ilmenite used in this study (0.21 per cent) was less than the typical values quoted by Nell and Den Hoed (0.3 per cent). No published data was available on the composition of LSR. The Fe_2O_3: FeO ratios of both the crude ilmenite and the LSR, 0.44 and 0.74 respectively, were less than 1-1.57. According to Walpole (1991) this ratio would have been the Fe_2O_3: FeO ratio at which the magnetic susceptibility of ilmenite would be at a maximum. It was therefore concluded that to increase this ratio from 0.44-0.77 to 1-1.57 the ilmenite in both the LSR and the crude ilmenite had to be oxidized.

Beukes and Van Niekerk (1999) did not propose roasting conditions for LSR. This study indicates that for beneficiation purposes LSR could be roasted under some of the conditions used for the roasting of crude ilmenite, but that the roasting conditions should be chosen with care. This study confirms observations made by previous investigators on the effect of the roasting atmosphere, temperature range and retention time ranges on the magnetic susceptibility of crude ilmenite (Nell and Den Hoed 1997; Bergeron and Prest 1974). Nell and Den Hoed reported a five– to six fold increase in magnetic susceptibility of crude ilmenite at 750°C in about 30 minutes. Similar results were observed for crude ilmenite roasted at 750°C from 5 to 40 minutes and for LSR from 10 to 40 minutes. At 800°C the results of this study differed from that of Nell and Den Hoed (1997), though. For 30 minutes at 800°C Nell and Den Hoed (1997) reported their optimum increase in magnetic susceptibility, while the results of this investigation indicate that much shorter reaction times (less than 10 minutes) are required at 800°C for both LSR and crude ilmenite. Nell and Den Hoed (1997) stated that the risk of over roasting at 800°C was high and less so at 750°C. This was also observed in this study.

Nell and Den Hoed (1997) reported a 90 per cent recovery when separating material at about 500 x 10^{-6} cm^3/g for crude ilmenite roasted at 750°C for 30 minutes. The results of this study indicate the same recovery (90 per cent) for crude ilmenite but with separation at lower magnetic field strengths (about 400 x 10^{-6} cm^3cc/g). The recovery for LSR is less, at 65 per cent, for separation at 400 x 10^{-6} cm^3/g, which was expected, given that LSR contained so much more gangue and material other than ilmenite. Nell and Den Hoed (1997) stated that roasting did not increase the magnetic susceptibility of other minerals present in their crude ilmenite concentrate. They stated that there was a tendency for Fe-containing spinels (including chromium) to become less magnetized during roasting under oxidizing conditions. The results in this study indicated that roasting under oxidizing conditions could increase as well as decrease the magnetic susceptibility of chromite in both the crude ilmenite and the LSR concentrate. The rate at which the increase in magnetic susceptibility took place was different for the ilmenite and the chromite – more so at 800°C than at 750°C. At 750°C the risk of over-roasting of ilmenite is lower than at 800°C and the prospect of separation of ilmenite from chromite higher.

5.3 Gaps, anomalies and deviations in the data

One might ask the question: How would the results from a small sample of crude ilmenite or LSR prepared on laboratory scale equipment compare to the variation in composition observed in a full scale operation?

Another question that arose was: How would the results from this laboratory scale, batch process investigation compare to that of a full scale continuous process plant where retention time distributions and temperature gradients in the roasting reactor are realities that have to be dealt with?

Utilizing one type of natural chromite, UG1 chromite, to represent another type of natural chromite, chromite in the unroasted LSR, is risky. The first prize would have been to separate chromite from the LSR to utilize in the study. Practical problems render such an approach unfeasible (the chromite content of LSR, expressed as mass percentage of Cr_2O_3, is only 0.6 per cent).

5.4 Recommendations

1. When characterizing the feed material used for these types of experiments the following analysis methods were most useful:
   - XRF analysis
   - Reflected light microscopy
   - Micro-analysis
   - Particle counting
   - QEM-SEM and QEM-scan
   - Malvern particle size analysis
   - Magnetic susceptibility measurements
2. The following analyses should be used or interpreted with caution:
   - Titration (Fe^{2+}/Fe^{3+} analysis)
3. The following analyses were not useful:
   - XRD
4. Further analyses that would have been useful but were not conducted were:
   - Fe^{2+}/Fe^{3+} content of the unaltered and altered ilmenite in the crude ilmenite and the LSR before and after roasting as well as that of the chromite before and after roasting.
5. The study indicated that when roasting LSR two process control strategies could be followed: a high temperature (800°C), short retention time (5-10 minutes) OR low temperature (750°C), long retention time (10-40 minutes). Care should be taken not to over- or under roast the crude ilmenite or LSR. The process control strategies for crude ilmenite could be similar. From a roaster reactor perspective the same reactor could be used to roast both LSR and crude ilmenite, i.e. the roaster for Process #1 and Process #3 described by Beukes and Van Niekerk could be the same reactor. The plants for Process #1 vs. Process #3 would differ in materials handling and magnetic separation equipment.
6. Determining the impact of different roasting conditions on the rate at which the magnetic susceptibility of chromite increases relative to the rate at which the magnetic susceptibility of ilmenite increases would be useful from an operating perspective. The ideal roasting conditions would be where the magnetic susceptibility of the ilmenite increases at a high rate - where the risk of over-roasting could still be managed - while that of the chromite increase at a very low rate. The process should be terminated at the optimum point for separation.
7. To determine how representative the fractionation test results would be of other roasting and magnetic separation methods, the procedure would have to be repeated on the feed material used for the other methods and the results compared to that of the methods. This would provide a basis for comparison of various test results.
8. When roasting LSR under the tested conditions (kinetic control), more than one control strategy could be followed:
   - High temperature, short retention time i.e. at 800°C for 5-10 minutes. The risk of over oxidation was high and the retention time of material in a reactor should be closely controlled. Equipment suitable for this process would be a batch reactor or a plug flow reactor (PFR) with a very good control system (Levenspiel 1999).
   - Lower temperature, longer retention time i.e. at 750°C for 10-40 minutes or even more. Although the maximum increase in magnetic susceptibility was not reached, a larger range of retention times in the reactor would result in very similar increases in magnetic susceptibility. This strategy was therefore very suitable for a reactor where material has a retention time distribution, i.e. a continuous stirred tank reactor (CSTR) (Levenspiel 1999).
9. As a control strategy on LSR roasting the low temperature (750°C), long retention time (10-40 minutes) approach would be recommended, especially when roasting in a reactor that would have a wide retention time distribution. The retention time distribution of a reactor could be determined

by introducing a tracer material with the feed and sample the product at regular intervals with subsequent analysis of the tracer content in the product. The impact of changes in the feed rate and subsequent increase in hold-up on the retention time distribution of the reactor should be determined as well.

10. These tests indicated that because LSR had much higher chromite contents than crude ilmenite and much less ilmenite to dilute it with, it would be very important to enhance the magnetic susceptibility of all of the ilmenite carefully and to enhance the magnetic properties of any of the chromite as little as possible. It seems that the rate of enhancement of the magnetic susceptibility of chromite is considerably lower than that of ilmenite at lower temperatures.
11. It would be interesting to compare the results of this study to high chromite containing ilmenite concentrates from deposits elsewhere in the world.
12. A study should be conducted on the proposed mechanism for the increase in magnetic susceptibility of the UG1 chromite by subjecting both the UG 1 chromite and the LSR chromite to longer residence ties (i.e. 60, 120 and 180 minutes at 750°C in air). Characterisation of both the roasted and unroasted particles should include SEM optical analysis and EDX and WDS chemical analyses.
13. Could these results be extrapolated to include the behaviour of chromite and ilmenite when roasting the high susceptibility rejects (HSR)?

<u>In short</u>: In chapter 5 the study was concluded and recommendations were made regarding implementation and future studies.