Influence of Additives on Cokemaking from a Semi-soft Coking Coal during Microwave Heating

Gerrit COETZER1)* and Mathys ROSSOUW2)

1) Metallurgy, R&D, Exxaro Resources, 21 Roger Dyason Road, Pretoria, 0002 South Africa. E-mail: gerrit.coetzer@exxaro.com
2) Delphius Commercial and Industrial Technologies, Unit B5 Prospect Close 43 Regency Drive Route 21 Corporate Park Irene, Pretoria, 0157 South Africa. E-mail: trossouw@delphius.co.za

(Received on June 28, 2011; accepted on October 26, 2011)

Coke was produced from a Waterberg semi-soft coking coal using microwave heating and selected microwave susceptors. Waterberg semi-soft coking coal is poorly susceptible to microwave heating, especially below 500°C, and therefore requires microwave susceptors. Susceptors were selected from ferroalloy fines and their respective ores.

Various batch experiments were performed on compressed discs utilizing a resonant microwave cavity at a constant 915 MHz frequency to heat a batch of about 5 to 7 kg of the semi-soft coking coal (sscc) to obtain coke. Materials were characterized using Inductive Coupled Plasma (ICP) analysis and coke strength tests.

Dielectric property results showed that chrome and manganese ores, as well as their respective high carbon ferrochrome and ferromanganese alloys, are suitable microwave susceptors to enable rapid coke formation during microwave heating. Coke formation was completed within 2 to 3 hours up to 1100°C compared to 21 hours for a commercial plant since microwave heating reduces the “cold centre” in a coke oven. Obtained coke strengths were slightly lower than for a commercial coke but still of a high quality. It was also shown that the admixture of chrome ore resulted in its partial reduction which will be advantageous to the ferrochrome industry since this method allows for recycling of fines without additional pelletisation. The results also showed that microwave energy has the potential to be employed during commercial coke formation, either on its own or as a hybrid technology.

KEY WORDS: microwave; coke; semi-soft coal; ferroalloys; dielectric properties; strength tests.

1. Introduction

Conventional coke making processes require selecting an appropriate mixture of hard and soft coking coals to obtain coke of desired properties. A drawback of these conventional processes is that hard coking coal is always needed as part of the coking coal mixture, which has a cost implication. However, for industries that rely on market coke or coke breeze, coke properties similar to metallurgical coke are not required. A coke making method which does not require hard coking coal will be advantageous. Coke obtained by such a method can be used as a reductant for instance as required by the ferro alloy industry.

Coking coals are the coals which, when heated in the absence of air, first melt, go into a plastic state, swell or contract and then recrystallize to produce a solid coherent mass called coke. Following this initial process, the semi-coke is typically carbonised at a temperature around 900°C–1100°C to reach a desired degree of devolatilisation to produce coke of desired mechanical and thermo-chemical properties. During carbonisation in the absence of air, coking coals undergo a transformation into a plastic state at around 350°C–450°C, swell or contract and then re-solidify at around 500°C–550°C to give semi-coke and then coke. During this process, much of the hydrogen, oxygen, nitrogen, and sulphur are released as volatile by-products, leaving behind a poorly crystalline and porous carbon product. For producing coke of good quality, coals should have a certain degree of maturity as indicated by the reflectance of vitrinite of at least about 1.0, good rheological properties, and a wide range of fluidity and low concentrations of inerts.

Enhancement of the coke making process can be accomplished through electromagnetic heating and especially through microwave heating. Microwave heating operates on heating polar or polarisable molecules on a molecular level through rotation of these dipoles. The resistance to these induced motions causes losses and attenuates the electric field due to inertial, elastic, and frictional forces. As a result of losses, volumetric heating occurs. The microwave heating characteristics of materials are described by their dielectric properties.

Dielectric properties of the susceptor materials are invaluable information regarding the potential application of such materials in a microwave heating environment. Dielectric constant and loss factor measurements of materials can be determined in order to establish if a selected material can be heated through microwaves at a pre-selected frequency and temperature. The dielectric constant is the property of a
material that determines the relative speed that an electrical signal will travel in that material as well as the electric field intensity distribution. The lower the dielectric constant, the easier the signal will pass through that material and vice versa. The dielectric constant of a material depends on the intrinsic property, temperature and moisture of the material as well as the microwave frequency applied.

The dielectric loss factor gives the microwave energy that can be dissipated or absorbed in a given material. Materials with high values will absorb energy at a faster rate than materials with lower loss factors. Materials with loss factors between 0.01 and 5 are, in general, considered as good candidates for microwave heating. Materials possessing high loss factors of $>5$ may lead to thin surface heating of only a few millimeter. Materials with low loss factors that vary significantly with temperature during processing will often lead to hot spots and thermal runaway. In addition, the relative heating rates depend not only on the dielectric properties, but also on the specific heat and densities of the materials.

The penetration depth is another important dielectric property and is defined as the depth at which the incident microwave power is reduced by one-half from its value at the surface and this is inversely proportional to the frequency. It is important that the energy penetrates as deeply as possible into materials since this also dictates the dimensions of the samples to be utilized on a large scale. Therefore, for optimum microwave energy coupling, a moderate value of dielectric constant, to enable adequate penetration, should be combined with high values of loss factor to convert microwave energy into thermal energy.

Various researchers have reported on utilizing susceptors to enhance certain metallurgical reactions during microwave heating. Substances such as CuO, V$_2$O$_5$, WO$_3$, Fe$_2$O$_3$ and even metallurgical coke were utilized by Monsef-Mirzai and co-workers as microwave susceptors. Other substances included for example different chars. Various workers have introduced chromite and manganese ore fines into coke composites in order to enhance the coke strength and density as well as to produce desired intermediate or end metallic products.

Various investigators have utilized microwave heating to enhance the coke making process, such as a microwave hybrid system described by Wagener et al. and Du Broff et al., addition of additives, such as metal oxides, to enhance microwave heating, reaction rate investigations of microwave pyrolysis of coal in a char bed, a method for the manufacture of metallurgical blast furnace coke from a mixture of heavy coking coal and non- or weakly coking coal by means of rapid microwave heating rate (25 kW, $30^\circ$C/minute), and more recently coke making from a high volatile bituminous coal within 10 minutes. Shudai and co-workers have found that rapid heating through microwaves improves various characteristics, such as the degree of fluidity, the expansion rate, the caking index and the amount of melting. Also of note is the work performed by Mourão and co-workers where microwave heating was utilized for carbothermic reduction of iron ores. Worner demonstrated the reduction of metal oxides (iron, manganese, titanium, chromium, zinc and tin) by means of microwave charring of coal.

One of the major problems of coal heating with microwaves is that coal is transparent to microwave heating due to its low dielectric loss factor. This necessitates the addition of a microwave susceptor material, such as coke or char or metal oxides to enhance the heating of the coal. The addition of a proportion of the susceptor enhances both the heating rate in a microwave field, due to a very rapid energy transfer into the material being heated, and also the rate of reduction of the susceptor for the case where the susceptor is a metal oxide. Other advantages of microwave heating are that the susceptor particles would heat simultaneously, thus reducing heat transfer problems, and rapid dissipation of energy and the high energy densities capable in small volumes allows equipment to be significantly smaller in physical size than conventional systems.

The aim of this study was to determine dielectric properties of granular Waterberg semi-soft coking coal (sscc) as well as fines from ferro-alloys and their ores, followed by investigating coke formation from admixtures.

## 2. Experimental

### 2.1. Materials Utilized

Table 1 gives the proximate and ultimate analysis as well as bulk density of a typical Waterberg sscc coal utilized in this study. Table 2 presents the chemical analysis of a typical chrome ore from Rustenburg (South Africa) and a typical Manganese ore from Northern Cape (South Africa) utilized in this study. Table 2 also shows the chemical analysis for typical high carbon ferrochrome (HCFeCr) and high carbon ferromanganese (HCFeMn) alloys (both produced in South Africa) utilized in this study.

### 2.2. Dielectric Property Measurement

The dielectric properties (dielectric constant and loss factor) of the samples were measured using the cavity perturbation method. A Hewlett Packard 8753A Vector Automatic Network Analyser (300 kHz–3 GHz) was used to measure the transmission coefficient of the perturbation cavity as a function of frequency (915 MHz) and the determination of the frequency shift introduced by the presence of the sample. The cavity resonated at the TM$_{000}$ mode. Figure 1 shows a diagrammatic layout.

Each small manually compressed sample ($\sim 1000 \mu$m

### Table 1. Analysis of a typical Waterberg sscc sample.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (air-dried), %</td>
<td>2.9</td>
</tr>
<tr>
<td>Ash (dry basis), %</td>
<td>8.9</td>
</tr>
<tr>
<td>Volatile matter (dry basis), %</td>
<td>36.9</td>
</tr>
<tr>
<td>Fixed carbon (calculation) (air-dried), %</td>
<td>54.8</td>
</tr>
<tr>
<td>Total sulphur (dry basis), %</td>
<td>0.93</td>
</tr>
<tr>
<td>Carbon (dry basis), %</td>
<td>76.29</td>
</tr>
<tr>
<td>Hydrogen (dry basis), %</td>
<td>4.85</td>
</tr>
<tr>
<td>Nitrogen (dry basis), %</td>
<td>1.43</td>
</tr>
<tr>
<td>Oxygen (dry basis), %</td>
<td>7.60</td>
</tr>
<tr>
<td>Calorific value, MJ/kg</td>
<td>31.50</td>
</tr>
<tr>
<td>Bulk density @ 10% moisture, kg/m$^3$</td>
<td>650</td>
</tr>
</tbody>
</table>
powdered coal, –212 μm ferrochrome, ferromanganese and manganese ore, and –90 μm chrome ore) was placed in a 5 mm ID quartz tube, occupying a 0.05 m long section of the tube with a sample volume of 0.98 cm³, and the microwave properties measured in a dielectric constant measurement fixture. The samples were not dried prior to commencement of the measurements. The dielectric property measurement chamber has a height of 0.035 m. Samples thus extended beyond the top and bottom of the sample chamber to minimise fringing fields inside the measurement cavity. Samples were not dried prior to dielectric analyses. A conventional high temperature furnace operating up to 1200 °C was used to heat the sample in the quartz tube to the required temperature. The sample was then rapidly lowered into the microwave test fixture for the dielectric properties’ measurement. Cooling curves were prepared beforehand, to take into account the drop in sample temperature during the measurement. A ramp and soak heating profile was used, with the temperature increased to the next value over a period of 30 minutes, with a 30 minutes soak at that temperature before the measurement was taken. The dielectric properties of the mixture samples were measured between 25 and 1000 °C at 50 °C intervals up to 200 °C, followed by about 100 °C intervals. A slow nitrogen purge was bled through the quartz tube to displace any oxygen present and to prevent oxidation of samples at high temperatures. All analyses were repeated in duplicate.

2.3. Samples Prepared for Coking Tests
An admixture of about 5 to 7 kg of Waterberg sscc coal (–1000 μm, containing 10% moisture) (Table 1) and selected metal-containing fines (<212 μm) were thoroughly mixed in a homogenizing Gramec paddle mixer for 1 minute. An adequate amount of the admixture (~3 kg) was transferred into a cylindrical mould, with a 0.192 m diameter, and this was compacted at a maximum pressure of 10.2 MPa to obtain square green strength blocks with a thickness of about 0.1 m. Green strengths were only of such a degree that the blocks could be handled with ease without disintegration of the integrity of the blocks. Bulk densities of the blocks reported between 1150 kg/m³ and 1330 kg/m³, depending on the susceptor and quantities thereof utilized. The compacted particles ensured good contact between coal particles and metal-containing fines.

2.4. Microwave Equipment
Three compressed blocks of a selected mixture were transferred to an alumina-silicate (mullite) refractory reactor area (0.2 m ID, 0.3 m high, 0.1 m thick sides) fitted with a gas-tight lid and off-gas burner. The reactor was fixed into a square shaped industrial microwave oven with dimensions of 0.4 mx0.4 mx0.4 m. The refractories and admixture were irradiated from the 4 diagonal sides at a horizontal level in such a way that the microwave power was balanced between the four sides during the process with manual coupling tuners at each waveguide entrance into the reactor (see Fig. 2). Four K-type ungrounded thermocouples were pushed 0.05 m deep inside pre-drilled holes (0.05 m apart from each other) into the top compressed block. One thermocouple was utilized for controlling the microwave energy during the coking process. Nitrogen gas was purged through the sides of the waveguides into the reactor to prevent accumulation.

![Diagrammatic representation of the dielectric measuring system](Fig. 1)

![Layout of microwave coking reactor](Fig. 2)
of flammable volatiles in the waveguides.

2.5. Coking Tests

In the coking reactor, the admixture was purged with nitrogen gas and heated using microwave irradiation. Nitrogen purging was terminated when the admixture reached a temperature of about 250°C when the admixture started to devolatilize. Microwave heating was performed in a conventional fashion, e.g. using microwaves at 915 MHz (wavelength 0.33 m) in a resonance microwave applicator without any external heating. A maximum of 16 kW forward effective power, i.e. 4 kW per waveguide, was introduced into the reactor cavity. Coke reactor gas was driven off and combusted. The coal was allowed to devolatilize and form coke for a relatively short period, e.g. from 2 to 3 hours for temperatures between 1 000°C and 1 150°C. After terminating the microwave energy, the formed coke was again purged with nitrogen, to prevent combustion and formation of ash, until the sample cooled down to below 500°C. The coke was allowed to cool down for another 12 hours before it was removed from the reactor. Each test started at ambient temperature.

2.6. Strength Tests

2.6.1. Rotating Drum

All formed coke, moisture content below 3%, was stabilized in a ½ micum rotating drum (1 m diameter, 0.5 m wide, fitted with 2 lifters (0.05 m height)) running for 30 seconds. The sample was screened for 2 minutes and the +20 mm fractions were again tumbled for 100 revolutions, i.e. 4 minutes. The resultant material was again screened for 2 minutes to remove fines.

2.6.2. I-drum

The material generated from the ½ micum drum was screened and crushed to generate particles ranging from +19 mm to –22.4 mm. Samples of 250 g, containing less than 3% moisture, were transferred to an I-drum (0.71 m length, 0.13 m inner diameter) and it was rotated for 10 minutes at 22 rpm. The samples were removed and screened for 2 minutes in order to determine the fraction of particles below 10 mm. In order to qualify the repeatability of results, 10 evaluative tests were performed on the commercial coke sample. A confidence level above 95% was obtained. For this study, each sample was repeated in triplicate.

3. Results and Discussion

3.1. Dielectric Properties

Figures 3 to 8 present dielectric properties obtained for various materials as a function of temperature up to about 1150°C.

The dielectric constant for a Waterberg sscc sample (Fig. 3) changed slightly during heating below 500°C, but it significantly increased at temperatures above 500°C. Similar results were noted for a Donbas coal[23] over a similar temperature range. The increased phenomenon coincides with an increase in electrical conductivity[24-26] and is in turn associated with an increase in carbon content due to devolatilization. However, this is not coinciding with the plasticization and re-solidification temperature range as found, in general, for this coal since the Gieseler softening and re-solidification temperatures are lower, i.e. 412°C and 441°C, respectively. Structural changes in the formed semi-coke and coke may have determined the characteristics of the dielectric constant of the coke during its formation. The decrease in value at 867°C may be ascribed to the final coke structural formation. This value fairly coincides with the
The dielectric constant of a typical commercially formed coke as shown in Fig. 4. The dielectric loss factor for the Waterberg sccc sample shows the same tendency as found for the dielectric constants. This tendency was also found for the Donbas coal by Slobodskoi and Sklyar. 23)

Penetration depth of microwaves as determined at 915 MHz into the Waterberg coal is also shown in Fig. 3. The penetration depth increased up to 2.77 m from room temperature to 200°C, but it dropped off sharply above 390°C to only 0.05 m. The former high penetration depth value indicates that this coal will not absorb microwaves efficiently enough at low temperatures since the microwaves will pass straight through the samples without being heated or poorly heated by microwaves. It also indicates that, in order to heat up Waterberg coal with microwaves above 390°C, a microwave susceptor needs to be added in order to enhance the microwave heating thereof.

A commercial Chinese coke was also investigated in order to compare its dielectric properties with those of Waterberg sccc coal since this coal is also utilized for coke formation. The commercial coke showed high dielectric constants and loss factors over the temperature range investigated (Fig. 4). The dielectric constants and loss factors increased for the typical commercial coke between 150°C and 320°C. This coincides with a decrease in penetration depth to very low values of only 0.005 m. Above 400°C, the dielectric constants and dielectric loss factors levelled-off, whereas the penetration depth increased with increasing temperature up to 0.022 m at 1074°C. Therefore, this coke can be utilized as a microwave susceptor throughout the temperature range under consideration. This would also explain the enhanced microwave susceptibility of a formed coke at increasing temperatures.

It follows from Fig. 5 that the dielectric constants increased with temperature for chromite ore. Church et al. 27) reported a dielectric constant of 11.22 for chromite at a frequency of 915 MHz and at 25°C, whereas this study obtained a value of 4 for the South African ore. The higher value might be due to either a compositional difference or the sample was more compressed by Church et al. 27) than in this study. The dielectric loss factor varied over the temperature range investigated. The penetration depth decreased significantly from a high 3.33 m at ambient temperature and decreased to 0.7 m at 409°C, whereupon it levelled-off between 0.054 m and 0.133 m with increased temperature. The exceptionally high penetration depth over the temperature range under consideration indicates that microwaves will probably only pass straight through this material at temperatures below about 400°C without enhancing the heating thereof. However, chromite will enhance microwave heating of an admixture with Waterberg sccc sample above 400°C based on the abovementioned penetration values, making it a suitable microwave susceptor.

Figure 6 gives the dielectric properties obtained for the manganese carbonate ore under consideration. The dielectric constants and loss factors increased both with temperature. Similar trends were also obtained by Amankwah and Pickles 28) for different manganese carbonate ores. However, the values obtained by these latter authors are significantly lower than those obtained during this study. The penetration depth increased from ambient temperature to 100°C to 0.689 m and then decreased gradually down to 0.016 m at 1148°C. This material is also suitable as a microwave susceptor especially at temperatures above 300°C.

The dielectric constants of HCFeCr (6.8% C) increased significantly from ambient temperature to 150°C, i.e. from 16.97 to 256 (Fig. 7) and then levelled-off. The dielectric loss factor increased from 0.634 to 9.194 from ambient temperature to 100°C. The latter value is quite high and surface
skin heating may occur, but the corresponding minimum penetration depth is 0.63 m, indicating that surface heating should not be expected. The penetration depth varied significantly over the temperature range with a maximum value of 0.655 m at 670°C. The overall high penetration depth values may indicate that this material will retard microwave heating since the penetration depths are too high and microwaves would rather pass through the material without enhancing microwave heating above 300°C.

It follows from Fig. 8 that the dielectric constants of HCFeMn 6.7% C increased significantly from ambient temperature up to 560 at 510°C, whereupon it levelled-off. The high loss factor at 401°C, i.e. 64.46, indicates again the possibility of a surface skin heating effect, but the penetration depth at this point was determined to be only 0.016 m. The penetration depth varied also considerably over the temperature range. The penetration depths of the ferromanganese are, in general, lower than those obtained for ferrochrome, nonetheless ferromanganese should also be a good microwave susceptor above 51°C.

3.2. Microwave Modelling

The microwave heating equipment used for this work employs the Industrial, Scientific and Medical (ISM) frequency of 915 MHz. Since the dielectric properties of the materials vary substantially over the temperature range of
interest, a microwave reactor configuration was needed that would allow uniform heating of the product over this temperature range, to ensure good product quality. A microwave reactor configuration was selected that also minimises localised overheating of the product in front of the microwave feed ports and is similar to the type of configuration that would be used on a large scale, continuous coking system. Figures 9 and 10 show the microwave electric field distribution in the product bed inside the reactor for both cold (ambient temperature) and hot (1 100°C) sscc, respectively, as determined with Ansoft High Frequency Structure Simulator (HFSS) software. Red coloured regions correspond to a high electric field strength, since power dissipation is proportional to electric field squared, and regions of high power dissipation. Blue coloured regions indicate low electric field strength. At ambient temperature the low dielectric constant and low dielectric losses of sscc resulted in a single standing wave peak near the centre of the reactor. At elevated temperatures the high dielectric constant and low dielectric losses of sscc resulted in multiple standing waves in the product bed, with 3 heating zones distributed through the bed. Heat conduction transferred heat from the zones of high power dissipation to the remainder of the product.

3.3. Microwave Heating Curves

Microwave heating curves for various susceptor admixtures are shown in Fig. 11.

Moisture is mostly removed during the first half hour of microwave heating and the process proceeded quite slowly. Most of the admixtures heated gradually up to 1 000°C to 1 200°C with 10% HCFeCr, 20% HCFeMn and 40% Mn ore the exceptions. These latter admixtures showed temperature runaways with 10% HCFeCr more pronounced between 400°C and 800°C within 5.4 minutes. According to Cha and co-workers,11) thermal runaway is observed when material temperatures reach a certain temperature and its loss factor is sharply raised. The increase of loss factor leads to increase of power dissipation and also increase the material temperature. It was found in this study that the loss factor of HCFeCr was nearly unaffected by temperature between 400°C to 800°C, i.e. decreasing from 2.78 to 1.30. However, these values are still quite high, indicating that microwave energy dissipation should be good and therefore enhancing thermal runaway. Furthermore, the power penetration depth increased significantly over this temperature range. A similar tendency, although less pronounced, was observed for HCFeMn which has a high loss factor in the 200 to 400°C temperature range, i.e. 50–64. It is not clear why a thermal runaway was observed for 40% Mn ore between 200 and 450°C and not for lower quantities.

In a coking process, thermal runaway can be advantageous since this may accelerate the coking process and reduce microwave energy consumption. However, such runaway may also interfere with the coking formation process and damage refractory linings in the reactor. Referring to Fig. 12, no evidence was found that the thermal runaway interfered with the strength of the formed coke in the presence of 10% HCFeCr. It is not known what the affect will be on the reactivity of such a coke and thus should be investigated in future.

Table 3 summarises the chemical analysis and yields of obtained coke composites.

Carbon contents of the formed coke, as well as their reactivities, will dictate up to what extent admixtures can be tolerated in various applications. Future studies will be conducted to determine this aspect. Coke yields were in the order of 61% to 68%, as expected for the high volatile Waterberg sscc material.

3.4. Strength Tests

Figure 12 presents the I-drum strength test results obtained for the various admixtures with specific reference to the –10 mm size fractions as a basis. Most of the coke strength results reported in the 8 to 12% region and are slightly lower (higher fractions below 10 mm) than the 6% obtained for the commercial coke. This clearly indicates the high potential of rapid coke formation by means of microwave heating despite the addition of susceptors. The strengths seemed to be nearly unaffected with the presence of different amounts of chrome ore, whereas they decreased linearly with increased manganese ore. Both 20% additions of HCFeCr and HCFeMn resulted in relatively low strengths. According to Loison et al.,29) infusible substances

![Fig. 11. Microwave heating curves.](image1)

![Fig. 12. I-drum strength test results obtained for various coke formed admixtures.](image2)
The obvious goal is to add as high as possible amount of ore or ferroalloy to coking coal in order to either recycle fines or to obtain a partially reduced composite without changing the coke or reductant properties adversely. According to Fukuda and Yanagikawa, the maximum chromite ore addition to coal in order to produce a suitable strength coke is less than 45%. The results obtained in this study fall within the criteria as set forth by these investigators and confirmed the potential of utilizing these susceptors during microwave coke formation.

### 3.5. Partial Reduction

Since the coke formation process was rapid and baking thereof limited to only one to two hours and the processes terminated at temperatures below 1200°C, it can only be expected that chromite reduction be limited. According to Fukuda and Yanagikawa, the reduction percentage of chromite depends on the length of time that the maximum temperature is maintained above 1200°C for at least 5 hours. From a microwave application point of view, this can be achieved in practice but the microwave heating curves (Fig. 11) were levelling off above 1000°C to 1100°C, indicating that the advantage of rapid microwave heating started to falter. In the latter case, gas or electrical heating might be substituting microwave heating at these temperatures or otherwise a hybrid system might also be applicable. However, it could be that long baking times are unnecessary since microwave heating changes the heating mechanism which might also affect the crystallization process and coke formation. Nevertheless, economics as well as suitable refractories will dictate the viability of a suitable heating regime.

Theoretical calculations, using Factsage (commercially available software and database), indicated that chromite ore will be partially reduced at 1000°C to 1100°C in a coking coal environment as set out above to form Fe metal, Cr2O3, and Fe and Cr carbides. This partially reduced material may form in a short period as illustrated above. The SEM micrograph (Fig. 13) shows a reaction zoning effect obtained around a Fe chromite particle embedded in a coke matrix. This zoning effect was due to Fe migration during partial reduction of the chromite where about 8% Fe was removed from the chromite particle, leading to a Cr enrichment of about 4%. The micrograph also shows the precipitation of the formed Fe metal in the middle of the particle with the following composition: 89 wt% Fe, 5.4 wt% Cr, 1 wt% C, 0.8 wt% Mg, 0.6 wt% O, and 0.5% Al. Fe metal also was precipitated around the edges of the particle as a Fe sulphide (most probably pyrrhotite). The presence of Fe metal dictates then that the formed coke should be dry quenched and not quenched with water since the latter would result in the oxidation of the Fe particles. The sulphur originated from the coal feed material as well as some sulphides associated with the chromite ore.

### Table 3. Chemical analysis and yield of coke products.

<table>
<thead>
<tr>
<th>Coke product</th>
<th>SiO2 (%)</th>
<th>Al2O3 (%)</th>
<th>CaO (%)</th>
<th>MgO (%)</th>
<th>Fe(tot) (%)</th>
<th>Fe2O3 (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Cr (%)</th>
<th>Cr2O3 (%)</th>
<th>MnO (%)</th>
<th>C (%)</th>
<th>Product yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% chromite</td>
<td>8.45</td>
<td>9.40</td>
<td>0.37</td>
<td>3.79</td>
<td>5.38</td>
<td>7.69</td>
<td>0.005</td>
<td>0.64</td>
<td>7.19</td>
<td>10.5</td>
<td>0.50</td>
<td>59.6</td>
<td>66.8</td>
</tr>
<tr>
<td>30% chromite</td>
<td>7.14</td>
<td>11.0</td>
<td>0.43</td>
<td>5.20</td>
<td>6.27</td>
<td>8.97</td>
<td>0.007</td>
<td>0.57</td>
<td>10.6</td>
<td>15.5</td>
<td>0.56</td>
<td>51.1</td>
<td>67.9</td>
</tr>
<tr>
<td>10% HCFeCr</td>
<td>9.91</td>
<td>7.66</td>
<td>0.23</td>
<td>2.88</td>
<td>3.52</td>
<td>5.03</td>
<td>0.008</td>
<td>0.73</td>
<td>4.15</td>
<td>6.07</td>
<td>0.24</td>
<td>67.2</td>
<td>63.9</td>
</tr>
<tr>
<td>20% HCFeCr</td>
<td>9.11</td>
<td>7.44</td>
<td>0.47</td>
<td>2.18</td>
<td>3.99</td>
<td>5.71</td>
<td>0.009</td>
<td>0.69</td>
<td>5.29</td>
<td>7.73</td>
<td>0.15</td>
<td>65.2</td>
<td>64.8</td>
</tr>
<tr>
<td>20% MnO</td>
<td>9.97</td>
<td>3.39</td>
<td>3.91</td>
<td>1.47</td>
<td>2.34</td>
<td>3.35</td>
<td>0.006</td>
<td>1.16</td>
<td>0.03</td>
<td>0.045</td>
<td>13.6</td>
<td>65.4</td>
<td>61.2</td>
</tr>
<tr>
<td>30% MnO</td>
<td>9.61</td>
<td>3.20</td>
<td>4.32</td>
<td>2.00</td>
<td>2.87</td>
<td>4.10</td>
<td>0.004</td>
<td>1.15</td>
<td>0.10</td>
<td>0.15</td>
<td>20.7</td>
<td>57.0</td>
<td>61.8</td>
</tr>
<tr>
<td>40% MnO</td>
<td>8.91</td>
<td>2.60</td>
<td>5.89</td>
<td>2.03</td>
<td>2.53</td>
<td>3.62</td>
<td>0.001</td>
<td>0.88</td>
<td>0.09</td>
<td>0.13</td>
<td>26.7</td>
<td>51.6</td>
<td>68.8</td>
</tr>
<tr>
<td>20% HCFMn</td>
<td>9.66</td>
<td>3.11</td>
<td>4.59</td>
<td>1.60</td>
<td>2.33</td>
<td>3.33</td>
<td>0.004</td>
<td>1.12</td>
<td>0.17</td>
<td>0.25</td>
<td>18.9</td>
<td>57.7</td>
<td>62.5</td>
</tr>
</tbody>
</table>

Fig. 13. SEM micrograph of a Fe chromite particle embedded in a coke matrix.
chrome or manganese metallurgical industry. Fine particle susceptors included in the coal matrix, prior to coking, induced partial reduction of admixed ores. Furthermore, as the fines material is used as a microwave susceptor and a seeding precursor for coke formation, recycling of coke or metal fines can be eliminated or reduced. The study also showed that microwave coking has the potential to significantly reduce coking time compared to conventional coking processes and obtainable coke strengths might be suitable for the metallurgical industry.

Acknowledgements
The authors express their sincere thanks to Exxaro Resources for permission to publish this paper. The authors also thank Mr M Dlamini for the strength tests and Dr T Wallmach for the SEM micrograph.

REFERENCES
7) A. C. Metaxas and R. J. Meredith: Industrial Microwave Heating, Peter Peregrinus, United Kingdom, (1988), 357.
24) S. G. Aranov and Y. B. Tyutyanukov: The Engineer’s Digest, 17 (1956), 133.