SPECIAL REPORT

Chromite mining and ferrochrome smelting in Zimbabwe

by A. E. Roberts, T. R. C. Fernandes, R. Nzuma, B. M. C. Tsomondo, A. Lesko and A. Mutemererwa

The Zimbabwean Institute of Mining Research (IMR) covers a wide range of specialities from geology and metallurgy to mineral economics and analytical chemistry. One of its major projects during the early 1990s is a interdisciplinary programme on one of Zimbabwe's main resources the chromium ores of the Great Dyke. The project has been funded by the Swedish Agency for Research Cooperation with Develping Countries (SAREC). The following excerpts are chosen by RMR from reports published by IMR on the project.

In a series of articles Raw Materials Report will present Third World research institutes that focus on the mining industry and on mineral policies.

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Economic geology

Current research into mechanised mining on the Great Dyke

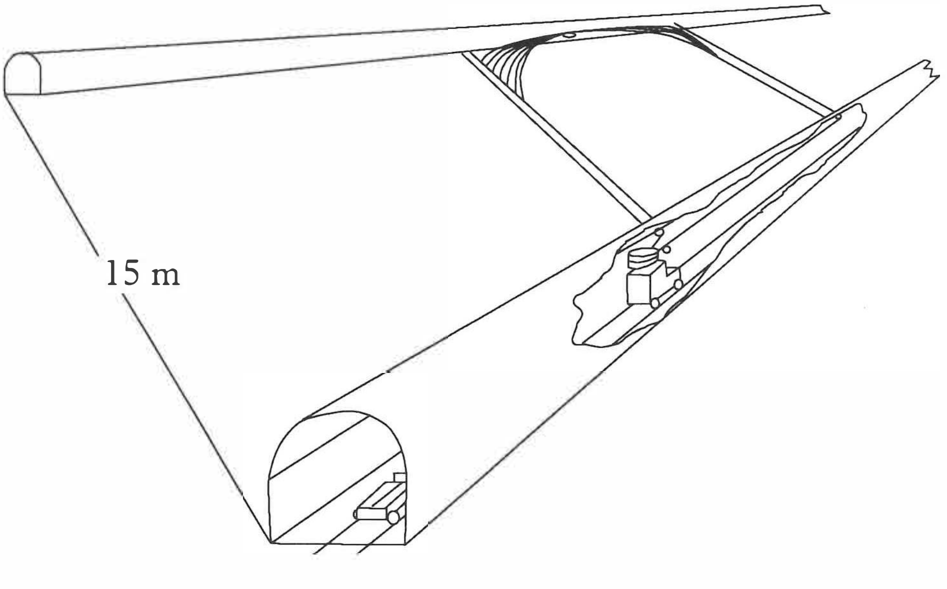
by A.E. Roberts

Gold mineralisations on the huge Witwatersrand goldfield is confined to narrow tabular orebodies or "reefs" usually only a few centimeters wide. Mining these orebodies by conventional drill and blast stoping techniques has necessitated diluting the ore with barren material from both above and below the reef while requiring men to work in stopes which are dangerously narrow.

Technology borrowed from the dimension stone cutting industry is now being transferred to the underground workplace. Blocks are sawn to a desired size by the use of a steel wire rope which is drawn across the block of stone and lubricated by a continuous stream of water in which a cutting medium is circulated. Chilled steel shot is still used for coarse cutting but for finer work carborundum or diamond grit has become the norm. Suppliers of rock cutting equipment have recently made available narrow steel wire cutting ropes fitted with cylindrical inserts surfaced with a wear resistant matrix impregnated with diamond grit.

Following the introduction of wire cutting techniques on some of the Witwatersrand gold mines in the Orange Free State of South Africa, it was decided to try this technique on the narrower chromite seams of the Great Dyke. The cutting wires currently under test at the Great Dyke Mine were developed for the hard and abrasive formations encountered on the Witwatersrand, but are able to function well in the Zimbabwean chrome mines with negligible amounts of wear. It is believed that cutting wires custom made for the soft sectile serpentinite of the Great Dyke will be more successful as an efficient method of stoping out the narrow chromite seams.

The trial stoping area on the Great Dyke Mine is located on the 8th level and has been set up between sub-levels 15 meters apart, which provides the conventional stoping back for chrome mines on



Schematic figure showing the wire cutting tecnique on trial mining chromite on the Great Dyke in Zimbabwe.

the Great Dyke. The motive power is provided by an electric winch mounted on a carriage running on the haulage tracks. The tension of the wire is maintained by winching back the carriage. A vertically mounted grooved drum drives the cutting wire by friction, and the alignment of the wire between the cut face and the drive drum is maintained by a movable series of flanged pulleys. This unit was developed in South Africa specifically for use underground on the Witwatersrand mines.

Mining is initiated from two pairs of diamond drill holes located above and below the chromite seam, with each pair about five meters apart. The cutting wire is first threaded from the lower haulage through the bottom pair of drill holes and around a centrally located pulley on the upper haulage. An abundant supply of water is required to flush away the talcose cuttings which would otherwise form a thick paste which will quickly clog the cutting wire. This water is piped under pressure down the drill holes from the upper haulage. The tension of the wires is maintained by monitoring the current required to rotate the driving drum at its operating speed and winching back the carriage.

A cutting speed of 2 to 4 meters per hour has been returned over the full face. When the cut faces have been established, the pulley in the top haulage is removed and the wire cuts down from the top along one continuous curved channel. When the cut is within two meters of breaking through into the lower haulage, the wire is withdrawn and the procedure repeated through the two upper diamond drill holes to cut the hangingwall slice. It has been found necessary to vary the angle at which the starting holes are drilled so that the final stope slice is wider at the lower haulage than at the upper. This is to prevent the liberated slice of chromite ore becoming wedged between hanging and footwall where the cuts follow an undulating surface. ■

Metallurgy

High-carbon ferrochromium upgrading

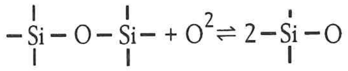
by B.M.C. Tsomondo

The process of high-carbon ferrochrome (HCFeCr) upgrading in an induction furnace through chromite ore addition is based on the principle of refining by slag-metal reactions. The carbon in the alloy reduces the chromite ore resulting in the chromium and iron contents of the alloy increasing, accompanied by a decrease in the carbon content of the alloy.

Of importance is the optimization of slag composition so as to obtain the required fluidity and chemical properties in the refining slag medium. Optimization of slag chemistry was carried out at constant power inputs so that variations in slag properties and the degree of carbon elimination could be attributed solely to changes in the slag composition parameter.

Chemical analyses of alloy and slag samples taken progressively during the tests were used in the study of the reaction kinetics of the system for various process parameters and routes. In the two-stage process incorporating slag removal, slags with a very low viscosity were obtained. The better results obtained in terms of carbon elimination are consistent with a rate controlling mechanism based on bulk transport within the slag phase. However, since there was no provision for temperature measurement, the exact rate controlling mechanism cannot be deduced with certainty.

The control of slag viscosity was based on the basic concept of the polymerisation-depolymerisation reaction:



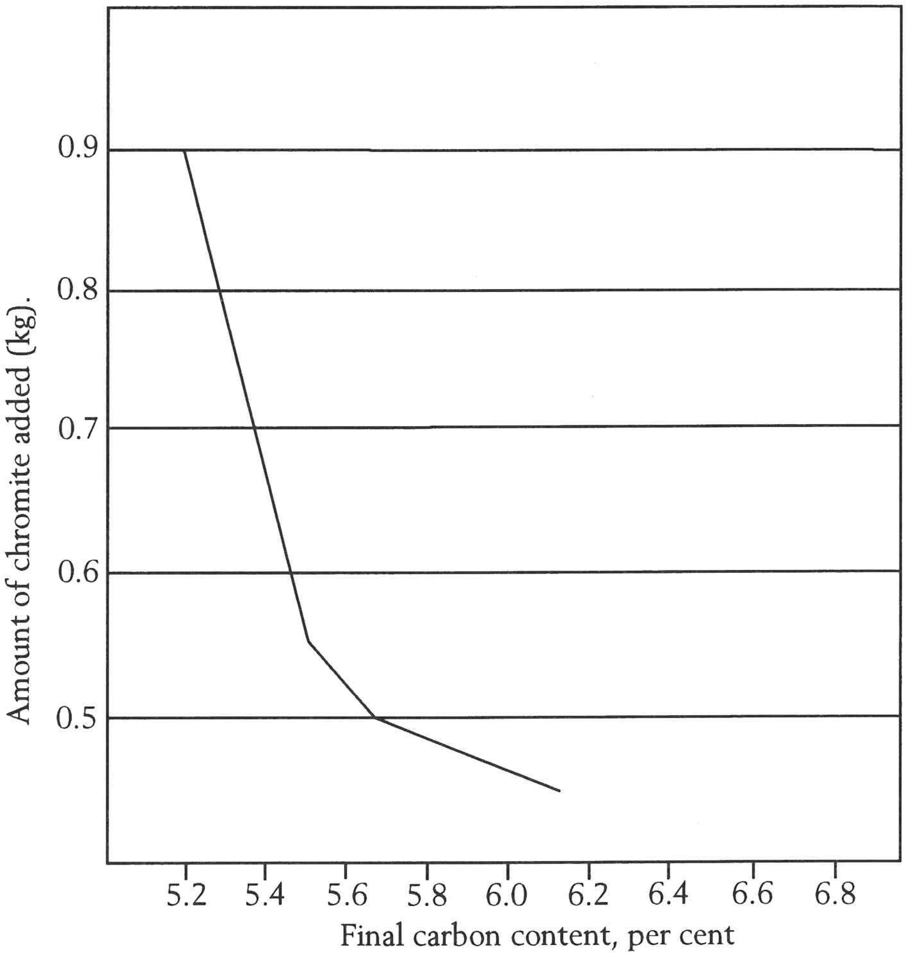
$$-\overset{|}{\underset{|}{\mathrm{Si}}}-\mathrm{O}-\overset{|}{\underset{|}{\mathrm{Si}}}-+\mathrm{O}^{2}\rightleftharpoons 2-\overset{|}{\underset{|}{\mathrm{Si}}}-\mathrm{O}$$

in which the reduced size of the polyanions obtained by the breakdown of the silicate structure resulting from the addition of basic oxides leads to increased ionic mobility, and, hence, reduced viscosity.

It is known that the thermodynamics and refining behaviour of a slag phase with respect to the liquid metal is a function of temperature and the composition of the metal and slag phases. However, in the present investigations the initial metal composition was maintained constant, and only the composition of the slag phase was varied. The refining behaviour, or the extent of carbon elimination was determined relative to the amount of oxidising medium (chromite) present in the slag phase.

Figure 1 shows how the extent of carbon elimination varies with the amount of chromite ore present in the refining slag. A direct proportionality exists between the amount of chromite ore and the extent of carbon elimination achieved, though the process kinetics tend to

Figure 1. Relationship between chromite content and amount of carbon removed



modify the characteristic shape of the graph as illustrated in Figure 1. Increasing the chromite content beyond 200 per cent more than the theoretical value required does not significantly lower the carbon content, other parameters being maintained constant. Previous results have shown that within a typical slag composition, the process kinetics are essentially consistent.

The correlation between the slag activity as measured by the content of reactive oxides in the slag $\{FeO + Cr_2O_3\}$ and the reaction kinetics as monitored by the rate of carbon elimination was also studied. It is evident that as reduction of the chromite ore in the slag phase proceeds, the carbon in the alloy is similarly depleted. Different routes were tested. A single stage process with top addition of the refining slag and a two-stage process incorporating a blended charge and slag removal.

An analysis utilizing the oxygen potential parameter instead of the composition of reactive species in the slag phase yields exactly similar results. The distribution ratio of iron in the slag and metal phases was used as an indicator of the oxygen potential of the system.

An attempt made to correlate the carbon and silicon contents in the alloy showed that the concentrations of the two elements decreased simultaneously during the reaction. The variations were again found to highlight the process route. However, an attempt to clarify the relation between the carbon and silicon contents in the alloy shows a substantially linear variation between the two elements in the case of a single-stage process whereas for a two-stage process, the results seem to highlight the nature of the process route, as in the case of oxygen potential.

In the two stage process it is evident that the silicon content initially decreases with the carbon content. It then increases sharply after addition of a fresh slag former following slag removal from the furnace, after which it decreases as the carbon content decreases. The decrease in silicon content of the alloy was observed to be directly related to the decrease in FeO content in the slag, and it seems correct to assume that the following reaction is taking place:

$$2FeO + Si \rightarrow 2Fe + SiO_2$$

On the basis of the experimental results obtained, it appears that the above reaction runs parallel with that of FeO and Cr_2O_3 reduction by carbon. This fact would explain the simultaneous drop in both carbon and silicon contents of the alloy. From structural analysis of the alloy, it is evident that as the carbon content increases, so does the volume fraction of chromium carbides, and the silicon in the alloy dissolves in the ferrite phase.

Conclusions

In the two-stage process, the effect of the second refining slag points to chemical control as being the rate controlling within a given operating temperature range. Thus, initially bulk transport and later chemical control are the rate determining factors for the system.

Although it is necessary to carry out a full chemical analysis of the slag samples, it appears that determination of $\{FeO\}$ only will give a good indication of the reaction kinetics. Although the use of this parameter in the present investigations sounds plausible, extrapolation to ores of different Cr/Fe ratios need not be attempted, unless backed by satisfactory laboratory results.

The present results serve to define the variations of rate and extent of carbon elimination with oxygen ($FeCr_2O_4$) potential and provide a basis for more elaborate experiments whereby temperature changes will be monitored as well. ■

Mineralogy

Measurements of magnetic properties of chromite

by T R C Fernandes

Research into the magnetic properties of the chromites from Zimbabwe has been conducted at the School of Metallurgy and Materials, University of Birmingham. This was part of continuing exercise in the mineralogical characterisation of these materials. A Curie-Faraday balance was used to measure the change in magnetisation with temperature, and hysteresis loops were measured to verify earlier results. The results revealed differences between the ores. The plots of magnetisation versus temperature exhibit points of inflection that indicate phase transformations in some of the minerals that constitute the ores. The magnetic properties are indicative of small amounts of magnetite which may have formed during the shearing evident in some ores. It is likely therefore that ores that have been subjected to shearing and deformation, and consequently are inferior for the production of premium brands of high-carbon ferrochromium, can be easily identified by their magnetic properties. As part of the activities in mineralogy, the X-ray diffraction (XRD) facility at the IMR was upgraded by the installation of the SIE112 System from Sietronics for the control of the diffractometer and for data analysis with the aid of a computer. A workshop in XRD analysis held at the IMR by Dr J I Langford from Birmingham proved to be very popular. Fifteen invitations to participate in the workshop were issued but twenty-five people replied! ■

Mineral economics

Development of a new menu system for the IMR Databases

by A. Mutemererwa

The database system at the Institute of Mining Research was developed and set up in 1987. It was constructed mainly to hold information on the six monthly foreign currency allocations to the mining sector for the importation of inputs. At that time the searches and data manipulations were fairly simple. The tasks mainly involved determining which companies got how much and what inputs they imported using this money.

As the system of allocating the scarce foreign currency changed in complexity (a new scheme was introduced for exporting and non exporting mines), so did the demands made upon the IMR databases. The searches and data manipulations became complicated since some of the larger companies operated both exporting and non exporting mines. Almost simultaneously the IMR and the Ministry of Mines (MoM) launched a project to look into the feasibility of some type of import substitution for some of the imported inputs, based on the information on imported inputs in the databases. This required a further widening of the scope of this database. By then the database system had grown to include mining and processing operations not only in Zimbabwe but the whole SADC region. Unfortunately nobody at either IMR nor MoM thought of carrying out a thorough system analysis of the original architecture, past performance and future development of the database. After four years of data addition, the database system had become bloated, slow and unreliable.

This led to consultations with people who ran similar systems with special reference to mineral information. In 1990, the IMR invited the Raw Materials Group (RMG) from Sweden. The RMG had for the previous ten years worked on and developed a database on structural changes in the world mining industry with a special emphasis on ownership on the structure of ownership and control of production, and experienced problems that were similar to what the IMR was experiencing.

Four serious limitations to the IMR database were identified.:

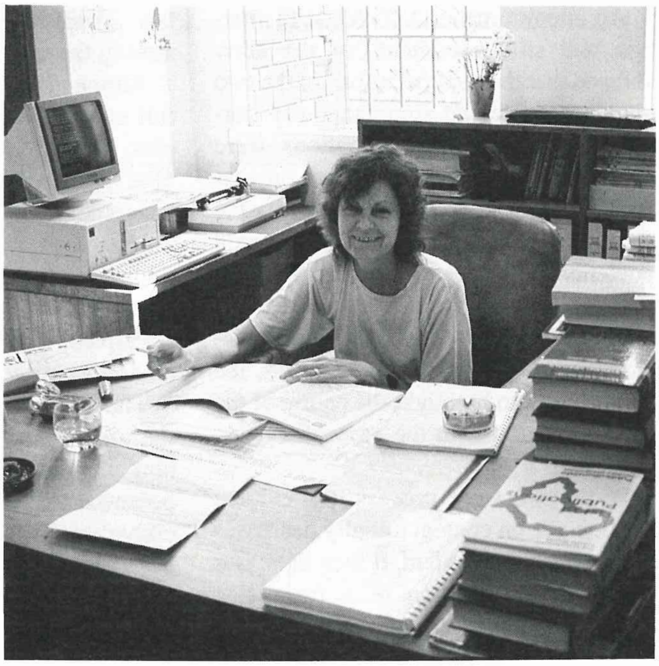
1.The database was hierarchically structured meaning many files could only be accessed using one parent data type. This slowed down searches and increased disk space consumption.

2. Inconsistency. As a result of different sources of data and people doing the data entry, a company like Anglo American would be entered in four different ways; as AAC, Anglo American, Anglo American Corporation, Anglo American Corporation of South Africa. This should not have been so as there should be unique identifier for each and every different item in the database, whether company, mine or imported input. The end result was an erroneous and incomplete database search.

3. Redundancy of information; information repeated over and over again in different files consuming unnecessary disk space, aggravated by continuous addition of new data. The database had also been designed with what is known as hierarchical structure instead of a relational one. The main difference between these two structures relates to the number of parent or common data that can be accessed by different files and the amount of storage disk space consumed. A relational system is more flexible, less disk consuming and makes for easy data manipulation.

4. The programming skills of the IMR mineral economists needed to be developed so that the database structure, once designed by the RMG would be maintained and developed locally without bringing in a consultant every time it needed to be changed or modified.

A list of activities to be undertaken were drawn up. The structure of the database was to be redesigned and training of IMR mineral economists was to take place. The inconsistencies in the names of different mines, companies etc were taken away.



Pam Barry, librarian of the Institute of Mining Research in Harare, Zimbabwe.

A suite of programs was written to validate the data entry so as to avoid, as much as possible, the typographical errors which generally lead to the inconsistencies referred to earlier. This system is based on a series of inverted files, one for each of the mines, owners, mining companies and mining inputs. For instance, if a new data file is being created and new data on a mine is to be entered, the person doing the data entry is given a list of mines from the inverted file. He or she then just picks the correct one from this list by highlighting it and striking a pre determined key. The name of the mine is immediately entered into the new file. If it happens to be a new mine altogether, the inverted file is automatically updated. This system is currently being tested.

A mineral economist at the IMR was trained in advanced database management and to improve programming skills. The basic skills have to a large extent been acquired. The main techniques learned were menu system handling, low level file manipulation, object oriented programming (at least within the CLIPPER environment) and also a better general understanding of programming design and development (debugging). New third party libraries and utilities which make for easy data manipulation in an increasing number of different and quicker ways, the increasing flexibility of data storage resulting in a tremendous reduction in disk storage. The program code for displaying and outputting of data in the format developed by the IMR with input from the Ministry of Mines and the Geological Survey was written and tested. The framework for a new database system has thus been laid down. ■

Mineralogy

Compilation of mineralogical data on chromium ores from Zimbabwe

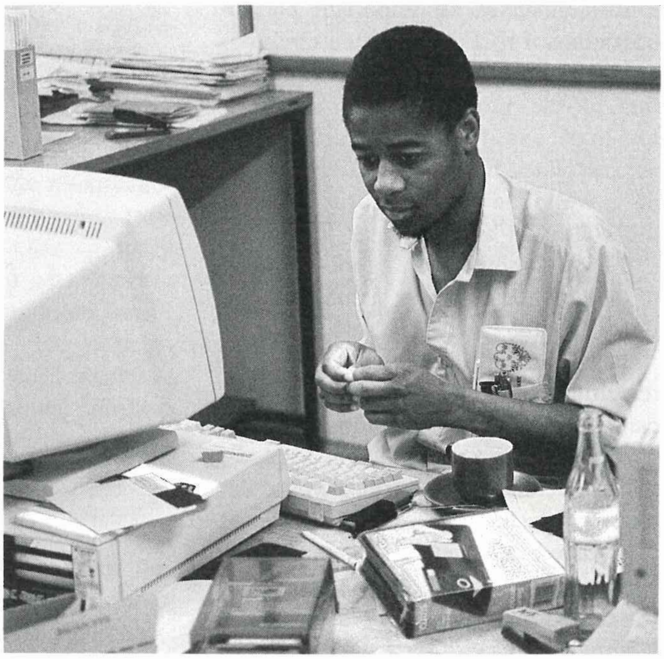
by R. Nzuma

Over the years a lot of data has been collected on the physical and chemical properties of chromium ores from the Great Dyke and podiform chromite deposits in Zimbabwe. The data includes records from the following works:

- investigations involving thermogravimetric analysis of the reduction of Zimbabwean chromium ores carried out at the Technical University of Aachen, West Germany (1975 to 1976).
- determinations of the physical properties of Rhodesian chromium ores by D de L Slatter (1978).
- chemical and physical analyses on forty bulk samples of chromium ores from the Great Dyke and fifteen bulk samples from the podiform chromite deposits in Zimbabwe and analyses of the gangue-free chromium spinels from all of the ores by D de L Slatter (1979 to 1980).
- mineralogy of 23 chromites from seams 1 to 9 and of 11 chromites from the podiform deposits by T R C Fernandes (1987).
- an investigation of the physical properties of chromite samples collected by D de L Slatter from the Great Dyke and podiform deposits, by O Mangwaira (1989 to 1990).

With all this vital information it was found necessary to create a databank which would enable easy retrieval of the information whenever required. This task to compile the data was quickly undertaken and is going to be an ongoing process as long as new data come out.

The databank is based on the computerisation of these previously collected data on chromium ores. It will allow data to be searched and viewed on the computer screen or printed output. The information is stored in a Quattro Pro spreadsheet in tables and each table can be viewed separately depending on the person's needs. Comparisons with, and any references to previously collected data can therefore be made easily. ■



Anderson Mutemererwa in the computer center of IMR.

Metallurgy

High Carbon Ferrochromium microstructure

by A. Lesko

The Great Dyke runs from the south to the north of Zimbabwe for over 500 km. It contains the worlds largest resource of high grade chromite, the second largest resource of platinum group metals and significant reserves of nickel.

The remelting of High Carbon Ferrochromium (HCFeCr) was originally introduced into the manufacturing process for utilisation of stockpiled HCFeCr fines to convert them into market valued bulk material.

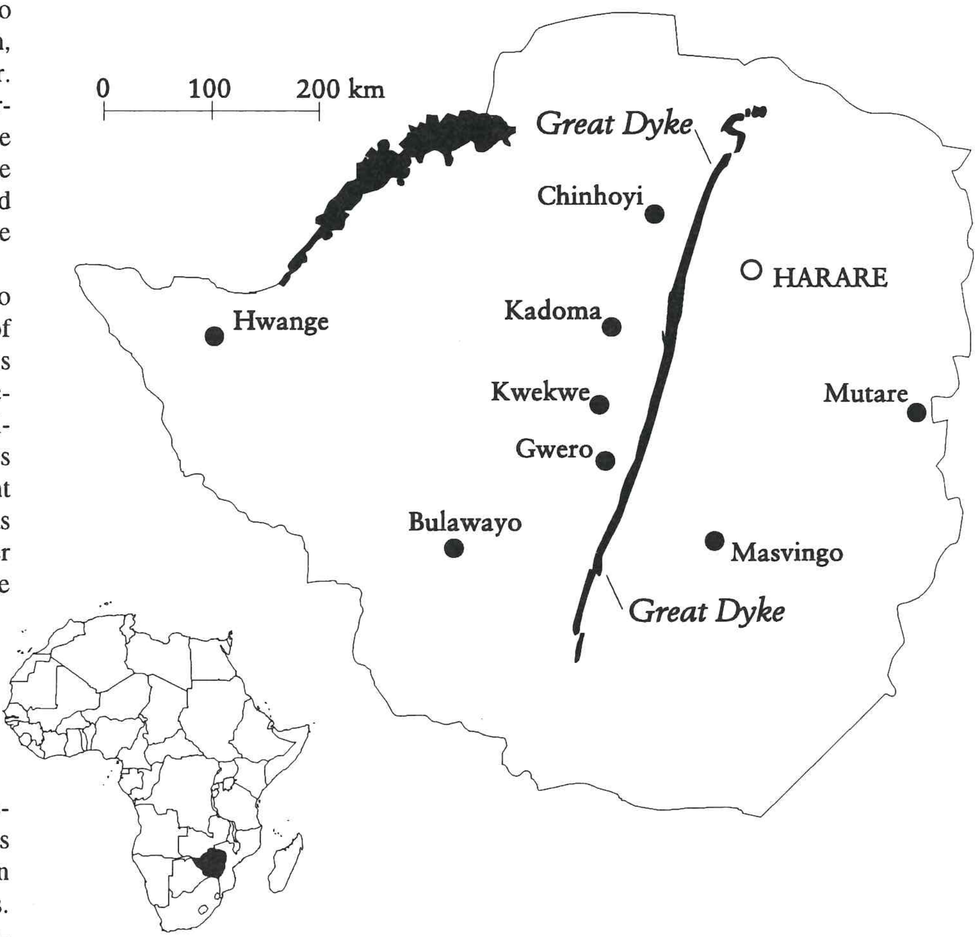
Remelting may serve also as an HCFeCr material upgrading process by adding calculated amounts of chromite. The chromium ore introduces into the system more chromium, which helps to increase the Cr:Fe ratio, and oxygen, which reduces the carbon in HCFeCr. Both chemical processes take place during the remelting period and increase the value of the final ferroalloy product. The results from previous remelting tests and the charge and process optimisation are described in another report1.

The increase in chromium to iron ratio forms/constitutes an important part of upgrading of HCFeCr. Ferrochromium is used, mostly in stainless steel production, for the chromium content of the alloy. In the world market, therefore prices are calculated for the chromium content only, while the iron present is taken as the ballast. It is then clear that better Cr:Fe ratio improves the economic value of the product and has a significant influence on the transport prices.

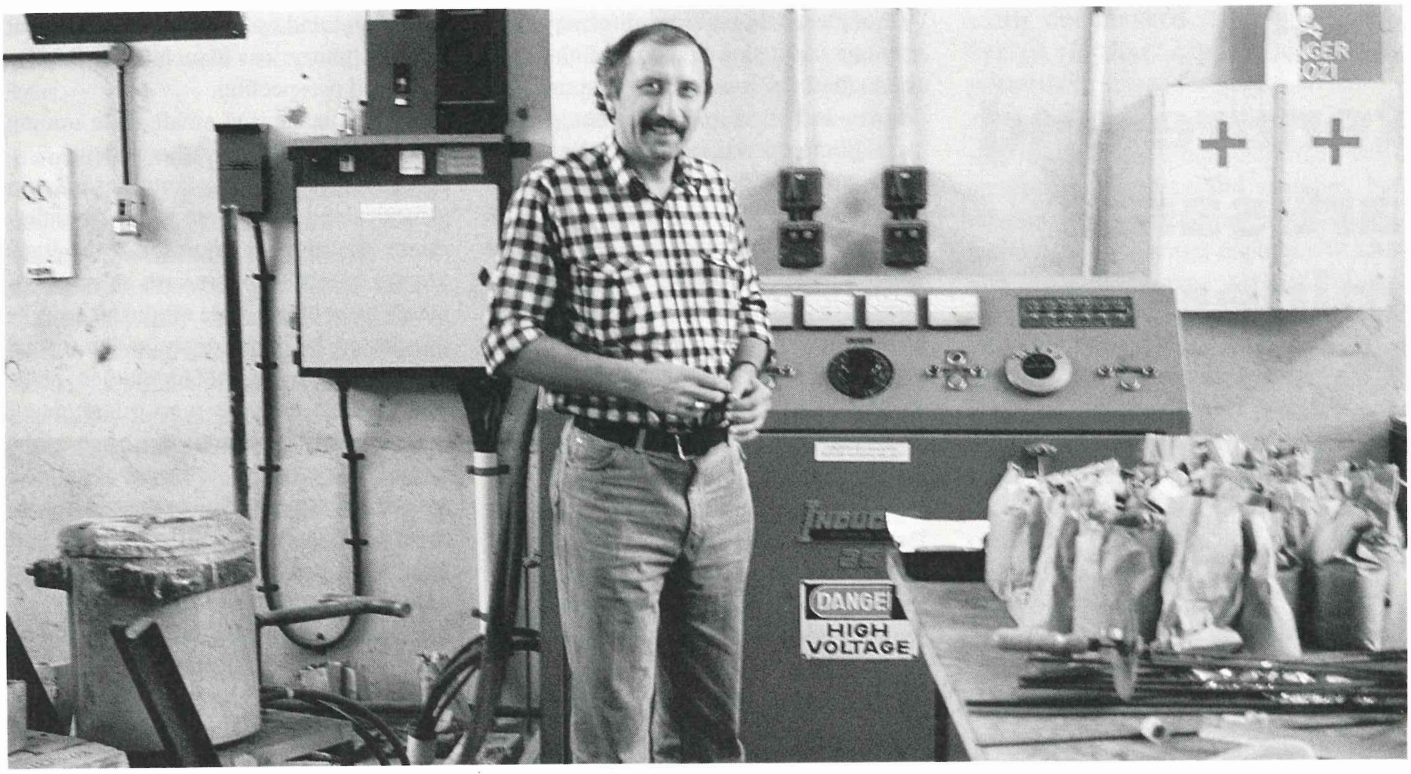
Metal samples taken during selected remelting tests in the induction furnace were subjected to metallographical analysis. The aim of the metallographic microstructural investigations was to determine the changes in structural phases in relation to chemical composition changes during the remelting processes. Chemical reactions giving rise to the upgrading of HCFeCr by reduction in the carbon content of the alloy and improvement of the chromium to iron ratio of the ferroalloy are brought about by induction heating of the blended charge.

In a previous report1 it was shown that the cooling and solidification rate influences the HCFeCr microstructure by forming different structural phases. In the experimental remelting tests, all the samples taken during the reaction are quenched in water to maintain a constant cooling rate. The microstructure of HCFeCr then reflects the chemical composition changes only and monitors the chemical reaction kinetics in accordance with the frequency and periodicity of sampling.

As described before the microstructure of HCFeCr consists of primary carbides and of eutectic, which is the mixture of chromium ferrite and carbides. The total carbon content in HCFeCr varies between 6 to 8 per cent and the primary carbides are the prevailing structural constituents. In the case of primary carbides we mean the M7C3 with 9 per cent C rather than M3C2 with 13.3 per cent carbon content. Most probably the structure of M7C3 primary carbide will contain a



Andrej Lesko, in charge of the metallurgy section of the IMR.



small amount of M3C2 too. We use the expression M7C3 for carbides for simplicity, however, in reality the correct writing would be (Cr,Fe)7C3 or (Cr,Fe)3C2 respectively.

The ratio of Cr to Fe in carbides differs in accordance with the composition of whole HCFeCr metal, but it is about 5 times higher as the Cr to Fe ratio in chromium ferrite, which forms the eutectic. Therefore the increase in Cr:Fe ratio leads to the formation of higher volume fraction of primary carbides. This change, however, is very difficult to evaluate by quantitative metallography due to the simultaneous carbon content decrease, which on the other hand results in primary carbide fraction decrease as well. Additionally, there is a high degree of inhomogeneity in HCFeCr material microvolumes.

The upgrading of HCFeCr material by reducing the carbon content is very important too. The world market distinguishes two grades of HCFeCr, those with carbon content below 6 per cent and in the range of over 6 per cent of C respectively. The prices are in about 30 per cent more favourable for those ferroalloys below 6 per cent of carbon content grade. To provide the ferrochromium fines remelting with addition of proper charge to reduce the carbon content below the 6 per cent brings then a significant economic advantage.

Carbon content decrease leads to remarkable changes in the microstructure of ferrochromium alloy.

It was found out that the microstructure of HCFeCr containing 6 per cent or more carbon exhibits the primary (Cr,Fe)7C3 carbides and an eutectic, which is a mixture of chromium ferrite and (Cr,Fe)7C3 carbides. The primary andeuctectic carbides show, in appropriate cross-sections, hexagonal shapes, which is in correlation with the trigonal lattice of the M7C3 carbide of chromium and iron.

The microstructures of samples taken at the end of the remeltings, when the carbon content in the alloy was lowered to below 6 per cent exhibited differences in microstructural phases. The primary carbides (Cr,Fe)7C3 grow along similar lines as in the previous cases, but the euctectic solidification continues with the formation of chromium ferrite, and due to carbon deficiency, the lower M23C6 carbides crystallize, and these are dendritic in shape.

The volume fraction ratio of eutectics with hexagonal shaped M7C3 carbides and those with dendritic shaped M23C6 carbides depends on the total amount of carbon in the ferrochromium. The nonhomogeneities in microstructure, due to the high melting temperature and fast solidification may lead to the formation of areas with eutectics formed by M7C3 and those with M23C6 respectively. ■