The use of carbonaceous materials in steelmaking*

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SYNOPSIS

An overview is given of the present state of traditional and new steelmaking equipment and techniques, and one of the direct steelmaking methods that are currently being developed is described. In steelmaking processes, coal is used to supplement the energy input and to reduce iron oxides in the slag. Foamy slag practice is discussed, and the most widely used types of ladle recarburizers, their properties, and manufacture are described.

It is concluded that the use of carbon sources, mainly for supplementing energy and as reductants, will increase in the future, but that demands on the purity of the materials will probably become more stringent. If hydrogen were manufactured at a competitive cost, it could become an alternative fuel and reductant in the field of iron and steelmaking.

SAMEVATTING

Daar word 'n oorsig gegee van die huidige stand van tradisionele en nuwe staalvervaardigingstoerusting en -tegnieke en een van die regstreekse staalvervaardigingmetodes wat op die oomblik ontwikkel word, word beskryf. Steenkool word in staalvervaardigingsprosesse gebruik om die energie-inset aan te vul en die ysteroksiede in die slak te verlaag. Die skuimslakpraktyk word bespreek, en die soorte gietpotherkarburiseerders wat die meeste gebruik word, hul eienskappe en vervaardiging word beskryf.

Die gevolgtrekking is dat die gebruik van koolstofhulpbronne hoofsaaklik om die energie aan te vul, en as reduktante, in die toekoms sal toeneem, maar dat die vereistes wat betref die suiwerheid van die materiaal waarskynlik strenger sal word. Indien waterstof teen 'n mededingende koste vervaardig word, kan dit 'n alternatiewe brandstof en reduktant op die gebied van yster en staalvervaardiging word.

INTRODUCTION

Throughout the history of iron- and steelmaking, carbon has always played a dominant role as a fuel and a reducing agent.

The volume of carbonaceous materials used in steelmaking today is still modest compared with the quantities consumed in ironmaking, but steelmakers are using coal on an increasing scale to supplement their energy requirements. Coal is also the energy source and reductant used in most of the direct steelmaking processes being developed at present. However, this will not significantly change the total consumption of carbon per tonne of crude steel produced, because the first step in most of the proposed concepts is the smelting reduction of iron ore with carbonaceous materials.

At present, carbon is used in steelmaking processes as a supplementary source of energy, for the reduction of iron oxides in the slag, in foamy slag practice, and for the recarburization of liquid steel.

STEELMAKING TECHNIQUES

The Basic Oxygen Furnace

Nearly 60 per cent of the world's steel production, which, in the past few years varied between 720 and 780 Mt per annum, is produced in basic oxygen furnaces (BOFs).

The sizes of the heats vary between 20 and 400 t, the majority being in the range 100 to 300 t. The tap-to-tap

times average about 45 minutes. In the past 15 years, extensive modifications have been made to the classical LD process, as well as to the bottom-blowing converter processes, and the new techniques comprise the injection of gases and solid particles into the converter.

BOFs are currently also being tested as in-bath smelting reduction vessels[1,2] and for the production of stainless steel direct from chromium ore[3,4]. The suitability of the BOF as a gas producer is also being investigated[5]. All these new processes use coal as a fuel, a reductant, or a source of gas.

The Electric-arc Furnace

Nearly 30 per cent of the steel produced in the world is made in electric-arc furnaces (EAFs). Furnaces of up to 370 t capacity are in operation. The tap-to-tap times depend on the operating conditions, and are usually between 90 and 120 minutes.

The melting techniques and equipment design have been modified to a considerable extent during the last ten to fifteen years. The new techniques include the lance injection of carbonaceous materials and the bottom-blowing of oxygen.

An increasing number of direct-current arc (DC) furnaces have been ordered or commissioned in the past few years, mainly because they perform very well with respect to productivity, electricity and electrode consumption, noise level, and flicker effect on the electrical-supply network[6].

The Energy-optimizing Furnace

The concept of an energy-optimizing furnace (EOF) was developed by the mini-steelworks pioneer, Willy Korf, and his team, and the first unit went into production in 1982[7]. Several furnaces, with capacities of up to 80 t, have been commissioned since then. The principle of the EOF is shown in Figure 1. Scrap is preheated to about 850°C in a two- or three-chamber system before being tipped into the reactor, and hot metal is then charged through a launder. During the melting, oxygen and coal are blown into the

bath, and additional oxygen is blown into the slag–gas–iron droplet system above the bath to enhance post-combustion (oxidation of carbon monoxide to carbon dioxide).

Excellent productivity has been reported for the EOF: averages of 44 heats per day with a charge of 70 per cent hot metal and 30 per cent scrap[8]. Production trials using 100 per cent scrap were also successful.

The EOF is currently the fastest commercially available melting unit, and seems to have a significant operating cost advantage over the EAF[9].

Direct Steelmaking

An American development in direct steelmaking, which is being evaluated at present, is financed jointly by the Department of Energy (DOE) and the American Iron and Steel Institute (AISI).

The smelter contains a bath of liquid iron to which coal, scrap, and pre-reduced pellets of iron ore are added while oxygen is blown into the slag–metal system. Energy is supplied by the combustion of coal, which also reduces the iron oxide to produce a carbon-containing iron. It is aimed to keep the iron oxide in the slag to around 5 per cent. Post-combustion is essential to the economics of this technology, but a delicate balance needs to be maintained between the carbon monoxide required as a supplementary source of energy, and that required for the pre-reduction of the ore. Post-combustion of about 40 per cent is suitable for the production of wustite in the pre-reduction unit.
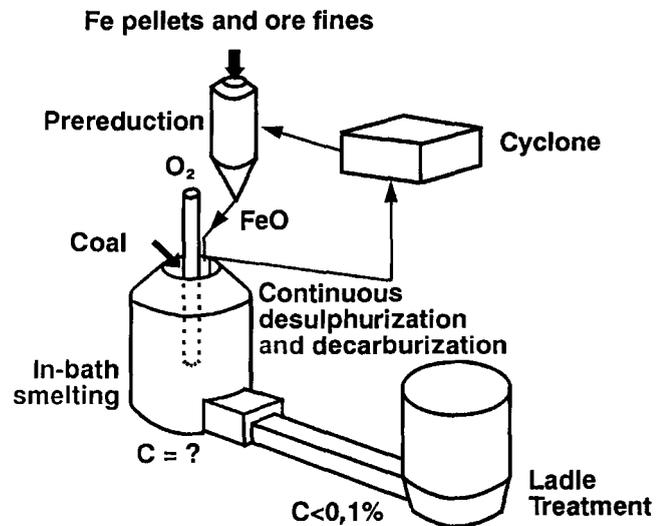

Figure 1—Schematic diagram of an energy-optimizing furnace

Figure 2—Schematic layout of the DOE–AISI direct-steelmaking process

The bath smelter produces metal of a lower carbon content than that of pig iron but, since the carbon is not low enough for the metal to qualify as steel, the metal is routed directly into a refiner, where it is decarburized by oxygen-blowing. The principle of the process is shown in Figure 2.

APPLICATION OF CARBONACEOUS MATERIALS

Supplementary Heat Input

Basic Oxygen Furnace

The energy efficiency of a BOF converter is mainly a function of the effective use of the carbon in the hot metal. Depending on the analysis of the liquid iron and the temperature of the charged materials, BOFs can usually accommodate about 20 to 25 per cent cold scrap in the charge.

If scrap prices are low compared with the costs of hot metal, or if there are constraints on the supply of hot metal from the blastfurnace, it is beneficial to increase the scrap ratio in the charge. This can be achieved in one, or in a combination, of the following three ways:

* preheating the scrap
* increasing the oxidation of carbon monoxide to carbon dioxide in the converter
* adding energy sources.

The last of these alternatives is technically the least complicated, and for some time steelmakers have been investigating the use of carbonaceous materials as additional sources of energy[10–12]. Extensive pilot-plant studies have shown that the powder injection of coal is suitable for very large additions over a long period whereas, for moderate additions, the charging of lumpy coal during the melting process appears to be satisfactory and has the advantage of requiring little extra equipment[13].

In the early 1980s, the addition of lumpy coal was adopted at several steel plants, among them the Newcastle Works of Iscor Ltd.

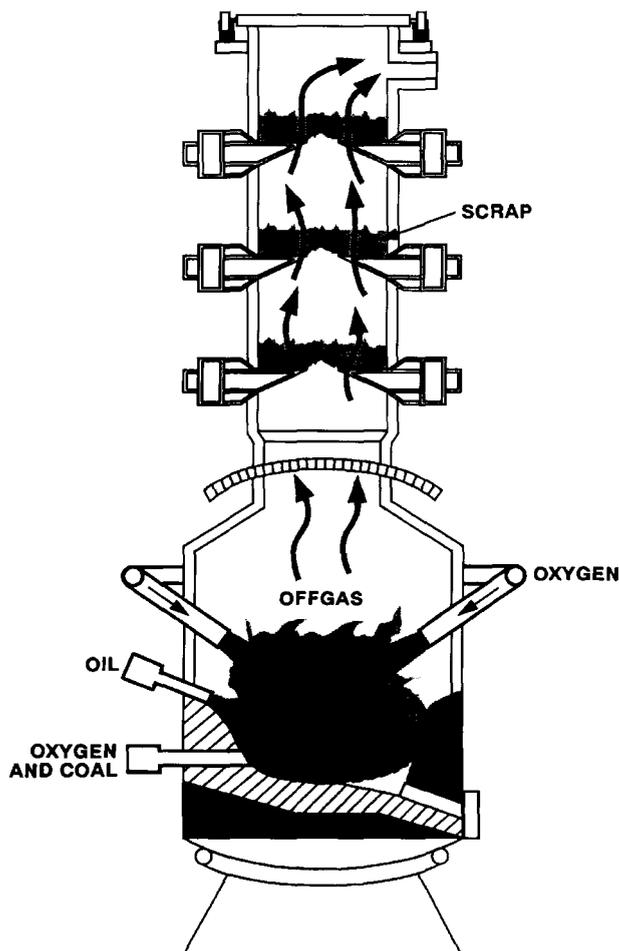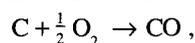The carbon in the coal is oxidized predominantly to carbon monoxide according to the reaction

$$C + \tfrac{1}{2}O_2 \rightarrow CO,$$

which generates 9,2 MJ of energy per kilogram of carbon. However, not all this heat is available for the steelmaking process since the gases generated leave the converter at about 1600°C, removing 4,3 MJ of sensible heat. The yield of the remaining energy for steelmaking depends on the efficiency with which this energy is transferred to the slag–metal system. Control of the combustion and heat transfer is the key to the success or failure of the utilization of energy from the coal.

Under well-controlled operating conditions, with the use of 1 t of coal containing 75 per cent fixed carbon, scrap can replace about 3 t of hot metal without the application of post-combustion. Table I lists the carbonaceous materials generally used to provide supplementary energy. Anthracites are preferred because of their higher carbon and lower ash contents. Futhermore, the transfer of energy in the system increases with decreasing volatile matter in the carbon source.

The sulphur level in the coal can have a limiting effect on the coal addition. Any sulphur in the carbon will add to the total sulphur input to the converter, and will be distributed between the metal, slag, and gas phases. An extensive study showed that 55 per cent of the sulphur reported in the steel, 20 per cent in the slag, and 25 per cent left the system, presumably in the off-gas[14].

Shortly after the practice of coal addition to the BOFs had been adopted at Iscor's Newcastle Works, an excessive amount of fine carbonaceous material was found in the off-gas. The origin of the material was traced to the converter, where, presumably, rapid heating of the charged coal had caused the lumps to decrepitate. Rapid-heating tests, which were carried out on a laboratory scale in Iscor's Research Department, revealed that excessive decrepitation of some types of semi-anthracite occurred under conditions of fast heating, and that the decrepitation increased with increasing particle size[15]. Consequently, the steelworks changed the specified coal size, from between 6 and 25 mm to between 6 and 12 mm, resulting in a significant reduction in coal fines in the off-gas.

Testing for decrepitation behaviour during rapid heating is now part of the standard procedures at Iscor; it is also used in the evaluation of coals for use in the direct-reduction and Corex processes.

Once reliable techniques had been developed for the bottom-injection of coal, researchers, interested in varying the steelmaking processes in the bottom-blown BOF, tried injecting carbon fines into the converter. Processes such as COIN, developed by Krupp, and the KMS and KS technologies, developed by Klöckner, were found to give good steelmaking performance[16–18]. The KMS process has been in operation for years using 50 per cent scrap in the charge. The KS process, designed for a charge of 100 per cent

Table I
Typical analysis of South African coals used as energy sources in steelmaking

Carbon source	Volatile matter %	Ash %	Sulphur %
Bituminous coal	25 to 30	12 to 18	0,4 to 0,8
Semi-anthracite	10 to 12	10 to 14	0,8 to 1,2
Low-volatile anthracite	3 to 6	10 to 18	0,6 to 1,0

scrap, has been evaluated extensively with good results, but its operation has been suspended because of rising scrap prices and declining scrap quality[19].

The high scrap ratios used in these processes were made possible by post-combustion and effective transfer of the generated heat to the slag–metal system. Post-combustion involves the oxidation of carbon monoxide according to the reaction

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2 ,$$
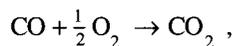
which produces 10,1 MJ of energy per kilogram of carbon dioxide. The degree of post-combustion is defined as

$$\frac{CO_2}{CO_2 + CO} . 100\% .$$

Electric-arc Furnace
The cost of electricity has always been a major factor in the production of steel in arc furnaces. For many years, use has been made of oxy-fuel burners, and of the oxidation of scrap by oxygen infiltration to supply additional energy, to either reduce the consumption of electricity or increase the melting rate. Oil and gas have often been used for combustion but, during the past few years, considerations of cost and long-term strategic supplies have given rise to the investigation of coal as an alternative source of fuel.

The addition of lumpy coal to the charge has become standard practice in various steelworks, since supplementary heat for melting the scrap as well as carburization of the steel bath are achieved. However, the amount of heat generated, and the degree of utilization of the coal for carburization, can vary widely, depending on operational practices. Because of the capacity restriction of the off-gas system, low-volatile coal is preferred.

In the KES process, another Klöckner development, fine coal is injected into the bath through nozzles in the bottom of the furnace. In a prototype furnace, a post-combustion degree of 50 per cent was achieved with special tuyères installed above the level of the bath.

With an addition of 30 kg of coal per tonne of steel, the consumption of electricity could be reduced by 25 per cent. Simultaneously, the tap-to-tap time was shortened by 20 per cent[20].

Energy-optimizing Furnace
The energy input for this process arises from

- oxidation of the carbon contained in the hot metal
- preheated scrap
- combustion of coal
- post-combustion of carbon monoxide.

With 50 per cent scrap in the charge, 15 kg of carbon per tonne of hot metal has to be combusted to give the same tap temperature as with a charge of 70 per cent hot metal and 30 per cent scrap and no coal. The degree of post-combustion is over 90 per cent for about two-thirds of the melting time. Carbon monoxide gas leaving the reactor is oxidized in the preheating chamber by controlled mixing with air.

Reduction of Iron Oxides in the Slag
Appreciable quantities of carbonaceous materials are added to arc furnaces when directly reduced iron (DRI), produced by coal-based direct reduction, is melted. DRI contains typically between 7 and 10 per cent iron oxide. Since the product from coal-based iron-ore reduction pro-

cesses has a low carbon content (about 0,1 per cent), deoxidizers must be added to the slag to ensure that it will not contain excessive amounts of iron oxide. A high concentration of iron oxide in the slag results in losses of iron units, makes the slag more aggressive towards the refractory material, and lowers the sulphur capacity of the slag.

The reduction of iron oxide involves the following reaction steps:

$$FeO + C \rightarrow Fe + CO, \qquad [1]$$

$$CO + FeO \rightarrow Fe + CO_2, \qquad [2]$$

$$CO_2 + C \rightarrow 2\ CO. \qquad [3]$$

Since CO_2 is not stable at steelmaking temperatures, reactions [2] and [3] take place almost simultaneously.

Iron oxide in the slag may react with

• solid carbon suspended in the slag or at the slag–metal interface
• carbon dissolved in the steel bath or in steel droplets in the slag
• carbon monoxide generated in the bath or in the slag.

These reactions have been investigated extensively on a laboratory scale[21-27]. Under the pertaining experimental conditions, the rate of iron oxide reduction was about five times higher when the slag was brought into contact with a carbon-containing liquid iron than with solid carbon. The reaction with solid carbon was about five times faster than that with carbon monoxide.

Coal is the cheapest and most extensively used material for the reduction of iron oxides in slag, low-volatile coals being preferred for this task. Coke has a low reactivity and slow dissolution rate in steel, and can result in uncontrolled reactions. A problem encountered when sulphur-containing sources of carbon are added is the transfer of sulphur to the steel and the slag.

The following is a simplified description of the mechanisms and reactions involved in the transfer of sulphur. The two dominating sulphur forms in coal are pyritic sulphur (FeS_2) and organic sulphur. When the carbon source is heated to temperatures exceeding 350°C, fractions of both sulphur forms begin to be transformed into volatile compounds. A portion of these compounds leaves the particle with other volatile matter, and is transformed into sulphur dioxide upon contact with oxygen. The other portion undergoes secondary reactions within the particle, where the sulphur is recombined with organic and inorganic matter. Most of the pyritic sulphur is transformed into FeS. Of the sulphur that remains in the particle, the organic compound is eventually oxidized together with the fixed carbon and enters the gas phase, while the non-organic sulphur is either absorbed in the slag or is oxidized to a gaseous product. The gaseous sulphur compounds pass through the slag–iron droplet system, where a certain degree of sulphur absorption occurs, but some of the gaseous compounds can become entrapped in bubbles of carbon monoxide and may escape into the off-gas.

Foamy Slag Practice

After the operation of arc furnaces with foaming slag had been developed independently at several steelworks, the process was rapidly adopted by steelmakers around the world.

Foaming is achieved by the passing through the slag carbon monoxide bubbles, which originated in the slag, steel, or slag–metal interface. The height of the foam depends on the distribution, size, and speed of the bubbles, and on certain properties of the slag. For instance, the efficiency of the carbon and oxygen in slag foaming increases with the viscosity of the slag. In general, the slag viscosity increases with CaO-to-SiO_2 ratios above 1,2, and with decreasing FeO and CaF_2 contents[28-30].

Foamy slag practice has the following benefits:

• protection of the side walls of the furnace, particularly at the 'hot spots' opposite the electrodes, which are shielded against heat radiation and splashing slag
• better protection of the roof
• long arc operation, which either increases the energy input, or reduces the electrode consumption when the throughput of current is lowered at a maintained power level
• protection of the electrodes from excessive oxidation
• greater heat retention in the slag–metal system, which increases the melting efficiency or saves electrical energy
• lower consumption of graphite at the electrode tip.

In foamy slag operation, almost all carbon sources containing more than 50 per cent fixed carbon can be used. However, the efficiency of the process increases with increasing carbon content of the reagent.

Recarburization of Liquid Steel

With most melting practices, the end-point carbon content is approximately 0,04 per cent and, if the carbon specification for the final product is higher, the steel must be recarburized.

Reliable carbon yields are achieved with high and constant carbon levels in the recarburizer, proper size grading, and a high dissolution rate in the steel. The maximum size of rapidly dissolving recarburizers is usually 12 to 16 mm, while that of more slowly dissolving materials is between 1 and 6 mm. The lower limit is about 0,1 to 0,2 mm because excessive dust can result in erratic carbon yields.

Recarburizers are almost invariably added to the ladle either during tapping or during secondary treatment, and vigorous reactions with steel can occur when excessive moisture and residual volatile matter are present in the material. A maximum of 1 per cent each is usually specified. Mineral matter present in the recarburizer decreases the carbon yield, presumably by forming a liquid film upon melting and consequently preventing the carbon and iron from coming into intimate contact[31]. Part of the sulphur and nitrogen in the recarburizer is transferred to the steel during the reaction, the quantities adsorbed depending on the amount of free oxygen in the steel. Trials with rimming and semi-killed steels showed that the yield of sulphur and nitrogen from a carbon source tended to be similar to that of carbon, and concentrations in the melt increased proportionally with the carbon content in the steel[32].

The composition of the most commonly used recarburizers is shown in Table II. Fixed carbon is defined as

$$C_{fix} = 100\ \text{per cent} - (\%M + \%VM + \%A),$$

where M is moisture,
VM is volatile matter, and
A is ash.

Synthetic Graphite. Because of its high purity and fast dissolution rate, synthetic graphite is the most versatile re-

Table II
Typical analysis of ladle recarburizers

Material	Typical analysis, %					
	M	VM	A	C_{fix}	S	N
Synthetic graphite	0,1	0,1	0,3	99,5	0,05	0,05
Acetylene coke	0,3	0,1	0,2	99,4	0,05	0,05
Low-sulphur petroleum coke	0,3	0,3	0,4	99,0	0,2	0,5
Medium-sulphur petroleum coke	0,3	0,3	0,4	99,0	1,5	1,5
Pitch coke	0,5	0,5	0,5	98,5	0,4	0,7
Calcined anthracite (from South Africa)	1,0	2,0	9,0	88,0	0,5	0,5
Natural flake graphite	0,5	1,5	13,0	85,0	0,3	0,2
Metallurgical coke (from South Africa)	0,5	1,0	16,0	82,5	0,8	0,8

* Dried

carburizer on the market. It is generally manufactured from needle coke, which, in turn, is obtained from very pure petroleum or coal tars resulting from the cracking of heavy aromatic oil. Figure 3 shows a flow diagram for the production of heavy aromatic oils and routes for the manufacture of high-carbon materials. The production of synthetic graphite is expensive, which prohibits the use of primary material as a recarburizing agent. The main supply is derived from secondary sources, such as machinings and scrapped or broken primary products, e.g. arc-furnace electrodes.

Acetylene Coke. Acetylene coke and carbon black are materials that can be categorized as high-purity carbon sources. The coke is obtained by confined exothermic cracking of acetylene, and carbon black is manufactured by carefully controlled partial combustion of hydrocarbons, mainly heavy aromatic oils that were synthesized during the processing of crude oil or coal. For recarburizing purposes, the fine powders are agglomerated with organic binders that burn off during the calcining after pelletization or extrusion. The carbon contents of the final products are over 99 per cent.

Calcined Petroleum Coke. This is the most extensively used recarburizer outside South Africa. It is produced from green petroleum coke by calcination at temperatures between 1100 and 1400°C. Green coke is obtained from the by-products of petroleum refining, and the quality produced depends on the characteristics of the feedstock. Medium-sulphur or regular aluminium coke is made from a direct residue of crude-oil distillation, and is used mainly for electrodes in the production of aluminium. The sulphur content can be up to 2 per cent. The more expensive low-sulphur needle coke is made from very pure tar and contains about 0,2 per cent sulphur.

Pitch Coke. Pitch coke is produced in modified coke ovens that are charged with hard pitch, which is derived from coke-oven tar. The charge is held at approximately 1300°C for about 20 hours in the ovens.

Electrically Calcined Anthracite. Low-sulphur anthracite with a grain size of about 12 to 25 mm is charged into a shaft furnace and heated to above 1800°C between two vertically placed electrodes. The residence time is about 4 hours, during which some graphitization takes place.

Natural Graphite. Natural graphite appears in two forms: microcrystalline or flake graphite, and amorphous graphite, both types being low in sulphur and nitrogen. The crystalline type has a particle size smaller than 1 mm, and has to be agglomerated unless it is injected into the ladle. The amorphous graphite is found in larger pieces, and can have a water content of up to 4 per cent; it has to be dried before use.

Metallurgical Coke. This material is made by the destructive distillation of coal in coke ovens at a temperature of about 1300°C. Carbonization proceeds over a period of about 16 hours, and the final temperature of the coke is approximately 1050°C. It is usually water-quenched when being discharged from the furnace, and must be dried before being used as a recarburizer.

The recarburizers that are mostly used at present in South Africa are synthetic graphite for critical applications and calcined anthracite for general-purpose use.

The required quality of a recarburizer is a function of the performance expected. If the specification for chemical
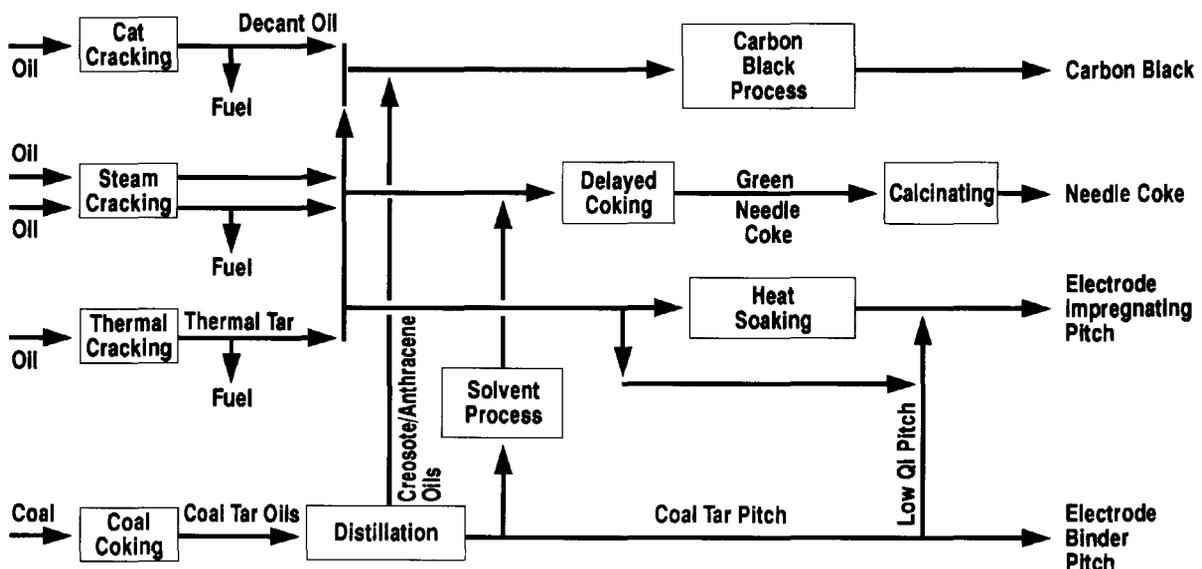

Figure 3—Flow diagram for heavy aromatic oils (after Stokes and Guericio[33])

analysis is not stringent, carburizers containing about 80 to 90 per cent fixed carbon can be used. However, when narrow carbon ranges are specified, recarburizers with 98 to 99 per cent carbon are generally applied.

With the increasingly stringent specifications for steel properties, it is usually a better option to use the more expensive, high-purity recarburizer than to risk a heat being scrapped because of an erratic carbon yield from a low-cost and low-purity material.

OUTLOOK

As the resources of crude oil and natural gas diminish, and the prices of natural gas and electricity increase, the use of carbonaceous materials in steelmaking can be expected to increase, provided the costs involved in the cleaning of the off-gas to meet increasingly stringent environmental specifications can be justified economically.

Future steelmaking technologies will possibly include faster processing in smaller units. Improvements in the control of these processes will be essential, and this will result in more-stringent requirements regarding the quality of the raw materials used. Volatile and mineral matter, sulphur, phosphorus, and nitrogen may become unwanted compounds in rapid, precision-melting technology, and other sources of energy may have to be substituted for coal. Hydrogen is one of these, and there are a number of reasons, including the prevention of environmental pollution, that favour the use of this clean energy source when hydrogen prices are becoming competitive. High-quality carbon is another substitute, and clean chars, or products derived from coal tars, may become sought-after materials in future steelmaking technologies.

CONCLUSION

Most carbonaceous materials used in today's steelmaking processes serve to supplement the energy input into melting furnaces, either to lower the consumption of other types of energy or to increase the melting rate. In electric-arc furnaces, carbon sources are used additionally for the foamy slag practice or to lower the iron oxide in the slag, especially when low-carbon directly reduced iron is melted. For most of these applications, coal with a low content of volatile matter and sulphur is preferred.

In future technologies, such as direct steelmaking from iron ore, carbonaceous materials will be the main source of energy for heating and as reductants for the ores. However,

coal is not environmentally friendly and, should hydrogen become available at competitive prices, it could replace coal in new steelmaking technologies. For the ladle recarburization of steel, carbonaceous materials are the almost exclusively used reagents.

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Software for underground use *

The first low-cost fully-supported software developed locally for underground mine survey is now being marketed by VI Instruments for use with Topcon electronic theodolites and certain other makes of instrument.

The INFO/SURV package developed by Welkom-based Advancing Mining Software (AMS) improves the productivity and quality of survey information by verifying and displaying results on-site, thus reducing errors and the need for re-surveys. Its use also reduces survey time, and significantly cuts time spent in the survey office. Hard-copy output is produced for storage as required by law. The system has

already been adopted by President Brandt and Beatrix Mines.

When used in conjunction with a total station, the small hand-held Psion data-logger is interfaced with the total station from which the data are tansferred automaitcally. When a manual thoedolite is used, the data are keyed into the data-logger manually, but the AMS program still identifies and rejects incorrect information. Data are stored on removable RAM packs from which the information can be downloaded onto an IBM or compatible PC. RAM packs can be wiped for re-use or can be stored. The data-logger has sufficient storage capacity for up to 20 pegs, and can be expanded by the use of larger data of RAM packs.

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* Issued by Nigel Walker Publicity cc, P.O. Box 430, Florida Hills 1716.

Underground Operation

Reviewer: K.C. Owen

Proceedings of the 5th AusIMM Underground Operators Conference—Ballarat—14–16 July 1992. Melbourne, The Australasian Institute of Mining and Metallurgy, 1992.

The theme of the 5th AusIMM Underground Operators Conference was one of improvement in the fields of safety, organizational structuring, and ground support.

The safety-related papers deal with the auditing of safety systems, design ergonomics, and education aimed at the improvement of employees' knowledge and awareness.

The papers dealing with organizational restructuring, team building, and multi-skilling are very pertinent to the South African industry. Mount Isa, Mount Lyell, and Woodlawn have all shown improvements. Renison has shown significant improvement in labour output, while Mount Pleasant achieved world-record standards in the labour efficiency of its development crews, which reached an advance of 1 metre per manshift. Quality and accuracy are the issues discussed in the papers on drilling and blasting, which deal with deviant holes, the control of overbreak, and the designing of more economic mass blasts.

The papers on ground support closely follow the central theme—improvements in standards at lower cost. The benefit of specialist geotechnical input to ground control design is illustrated by reference to the number of unexpected falls of ground.

These Proceedings demonstrate the Australian industry's resilience to the adverse economic environment, and illustrate its determination to improve. The volume contains much that is of interest to the South African Engineer and will serve as a useful reference.

The life of Julius Kruttschnitt

Reviewer: R.D. Beck

The man from ASARCO. A life and times of Julius Kruttschnitt, by D. Chaput and K.H. Kennedy. Melbourne, The Australasian Institute of Mining and Metallurgy, *Publication Series* no. 5/92.

Born in 1885, to parents of German origin, Julius Benjamin Kruttschnitt grew up in a region of the American west that was dominated by the rail lines of his father, Julius senior, who monopolized transport in the region. Julius junior selected a career in the mining industry but chose Yale, rather than the reputable mining schools of the time. His choice was influenced by the American mining engineer, John Hays Hammond, who, an Alumnus of Yale, was later to rise to prominence in South Africa, including taking part in the Jameson Raid. Julius Kruttschnitt joined ASARCO three years after graduating and built up a network of mines and mills in a area based on Tucson and also into Mexico. All the major mines of this region are covered in this narrative of Kruttschnitt's career.

In 1930, when Leslie Urquhart of the Mining trust signed an agreement that acquired for ASARCO a substantial equity in the Mount Isa project, H.A. Guess offered the position of General Manager to Julius Kruttschnitt. Little did Kruttschnitt know that he was committing himself to the Mount Isa project for the next forty years of his life.

The comment he made in an interview after this appointment is worth quoting. 'If you're a mining engineer, you don't say 'Where is it?' and 'What kind of living accommodation?', and 'How much am I going to get?', you go—that's your profession to go where the mines are'.

Kruttschnitt's early years at Mount Isa were hard. He initially saw the poor accommodation and low morale of the work force as problems, and set out to rectify them. This proved a continuous up-hill struggle, with poor metal prices giving limited financial resources. ASARCO management regarded Mount Isa as a serious blunder, but Julius Kruttschnitt extolled its reserves and potential. A clear insight into the life in those early years of this pioneering mine are given. The women found life particularly difficult. His own wife, Marie, never really settled down, although she entertained in the style that was reminiscent of their years in Arizona.

The Second World War changed the Company's fortunes, with the discovery of a copper orebody below the developed lead–zinc ore at a time when copper was required for war material. Kruttschnitt managed the changeover of facilities to the production of metallic copper from lead in double-quick time and then the expansion to produce both metals after war. He stayed at Mount Isa as Company Chairman until his retirement in 1953.

Kruttschnitt was committed to the mining profession. He found time to participate in the activities of the Mount Isa Branch of The Australasian Institute of Mining and Metallurgy, and was elected President of the whole Institute in 1939. He served as President again in 1952.

In 1946, he received the Australasian Institute's medal for the development of ore treatment in Australia and New Guinea.

His name is recognized by the Julius Kruttschnitt Research Centre at the University of Queensland, the university he supported actively during his life in Australia. He died in 1974, still taking an active interest in the minerals industry.

For those interested in the history of the minerals industry, particularly the personalities involved, this book makes great reading. It describes the life of one of the doyens of the minerals industry world-wide, together with mining in two continents, over a period of 89 years.

The location of critical slip surfaces in slope-stability problems*

by R.J. Thompson

CONTRIBUTION BY R.W.O. KERSTEN†

The method described for the evaluation of FLAC results is seen to be of fundamental importance to the future development of rock engineering, and evaluations that could give rise to misunderstandings should to be allowed to go unchallenged.

In the addendum, the author gives the input to two basic models, the Mohr and the strain-softening models. His evaluation of the results, however, ignores this difference, or he has failed to annotate the figures accordingly. From my own FLAC runs, the difference between the two models is fundamental, and the referee should have picked this up.

The physical properties of the three materials used in the models differ significantly in terms of the friction angle and cohesion, but maintain the same shear and bulk moduli. According to the author's own comment, the more sophisticated the computer programme, the more accurate the input requirements should be. Again, the referee should have picked this up.

The plot of the yield state and the yield history is of dubious value, and does not contribute to the paper, in fact it tends to cast doubt on the findings. The referee should have pointed this out, and commented accordingly.

REPLY BY R.J. THOMPSON

I thank Mr Kersten for his perceptive and valuable comments.

He is correct in his comment that the Mohr–Coulomb and stress-softening models are fundamentally different.

The question surrounding the choice of model and the model parameters themselves was alluded to in the paper, in which non-linear models were seen to be very much site and material specific. The aim of the paper was to illustrate how numerical modelling methods can be applied to the problem of resolving the location of the critical slip surface and slope factor of safety (FOS), and how more complex constitutive and yield relationships could be accommodated in the analysis.

The evaluation of the results is limited to illustrating (for a hypothetical slope) the ability of the combined FD/DP technique to provide the engineer with more information concerning the behaviour of the slope during destabilization, together with the critical slip surface location and FOS. To this end, data and results from the Mohr–Coulomb model were illustrated. The inference from Figure 7 is that both models (Mohr–Coulomb and strain softening) give comparable results, which could give rise to misunderstandings; such is not the case unless, and as, model parameters are specifically chosen for that purpose. The FLAC coding given in the addendum and the figure itself are illustrative of how the technique may be implied to incorporate non-linear models, but do not go as far as embroiling the paper in a discussion of specific constitutive and yield-model applications. This was not the aim of the paper and motivates why a hypothetical slope was chosen.

Research is in progress to ascertain the extent to which the extra data required to conduct such a complex analysis is practically, as opposed to academically, justifiable, and this should go a long way towards clearing up misunderstandings that may exist concerning the appropriate choice of model and parameters when the method is applied to practical slope problems.

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