DC Arc Single Electrode Smelting Furnace

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by
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Twelve years ago ASEA started to apply the dc technology for development of a new generation of arc furnaces. The applications are in two principle fields: the dc furnace for scrap melting and the dc smelting furnace for production of DRI, non-ferrous metals and ferroalloys.

The most important feature of the dc furnace is the use of a single central graphite or selfbaked electrode and the positive polarity (anode) connected to the bottom, which is electrically conductive.

Two types of dc smelting furnaces have been developed. One is operating with a submerged electrode as in a conventional smelting furnace. The main part of the material (70-85 %) is fed through charge openings in the roof, while a fraction (15-30 %) of fine-grained material is charged through the selfbaked electrode, which is provided with a hole. The other type of dc furnace, the Plasmarc furnace, operates with an open arc and 100 % of fine-grained material is charged through the hollow graphite electrode.

The advantages of the dc arc single electrode smelting furnace in general are:

- high metal yield
- low electric energy consumption
- reduced electrode consumption (>50 %)
- high productivity
- high flexibility regarding choise of raw materials
- low investment costs

The above mentioned advantages have been shown by pilot plant tests and in production furnaces. Two existing furnaces (1.2 MVA and 2.0 MVA) at Gullspång Alloys AB, Sweden, have been converted (1981 resp 1985) to dc arc single electrode smelting furnaces operating with submerged arc and producing special ferroalloys. Early in 1984 ASEA was commissioning the world's first dc arc furnace at Middelburgh Steel & Alloys Ltd, South Africa. This furnace is designed for a power input of 20 MVA and operates with an open arc where 100 % of the chromite ore fines is directly charged into the dc arc via the hollow electrode.

INTRODUCTION

In the beginning of the seventies ASEA started to apply the dc technology for development of a new generation of arc furnaces. The development work has been done on dc furnaces for different applications: steel scrap melting, ladle refining and production of DRI, non-ferrous metals and ferro-alloys.

BASIC CONCEPT OF THE DC ARC FURNACE

The most important feature of the dc furnace is the use of a single, centrally located graphite or self-baked electrode which is acting as a cathode. The current passes the melt and the furnace hearth which is electrically conductive and is via a bottom copper plate (anode) conducted to the positive pole of the rectifier.

Comparison with the single phase ac arc furnace

In many ways a dc arc furnace reminds on the the old single phase ac furnace which was developed in the beginning of this century. Furnaces of this type have been used for production of carbides and ferro-silicon and even today there are furnaces of this type in operation for production of ferro-tungsten and other special alloys.

Also the single phase ac furnace has only one vertical electrode and the current goes through the metal bath and the conductive hearth to a bottom electrode which is connected to the furnace transformer. Normally the bottom electrode consists of a water cooled copper discus which is inbedded in a lining of rammed carbon.

There have been built single phase ac furnaces up to the size of 10 MVA and an arc current of more than 50 kA.

Excellent metallurgical conditions are achieved in the single phase ac furnace. However, very bad conditions for the power supply network can be created due to the high reactive power generated in this type of furnaces and today no such furnaces are built.

In the dc furnace most of the metallurgical advantages of the single phase ac furnace have been taken care of but the problems with the power supply have been solved by the dc technology.

Polarity

By experience it has been shown that it is important that the self- or pre-baked electrode is connected as cathode and the bottom electrode as anode. In this way the electric energy is most efficient transferred and at the same time gives the least electrode consumption. With negative charged electrode and a positive charged melt, the arc power is directed to the melt.

Conductive hearth

Carbon blocks or rammed carbon lining, of the same type as used in many conventional ac submerged arc furnaces, gives a good conductive hearth. An air duct with an integrated axial fan, cools the outside of the furnace bottom shell. The electrical resistance of such a conductive hearth is relatively low. In a shell with an inner diameter of 5.8 m a resistance of about $2.2 \cdot 10^{-6}$ ohm is typically achieved. Thus when such a furnace is operating with an arc current of 100 kA, a voltage of 2.2V would exist between the melt and the furnace bottom. Therefore the furnace bottom shell is provided with an electrically insulated flange to separate the bottom at 2.2V in the related case, from earth. The furnace shell is earthed, and thus also the melt. The electrical energy developed in the conductive hearth amounts to 22 kW in above case. The temperature distribution in the hearth is shown in Fig. 1. The lowest curve illustrates the temperature distribution from pure thermal condition i.e. without any electrical current load. The middle curve shows the temperature distribution at the rated current with the top curve representing a continuous 50% overcurrent.

These curves suggest that the bottom lining temperature rise resulting from the current passage is manageable. Fig. 2 shows similar temperature distribution for an alternative lining of the conductive hearth with a wear lining of steelclad magnesite bricks and back up lining of magnesite-graphite bricks. This type of lining is used in the Plasmarc furnace for production of HcFeCr at Middelburg Steel & Alloys Ltd, South Africa.

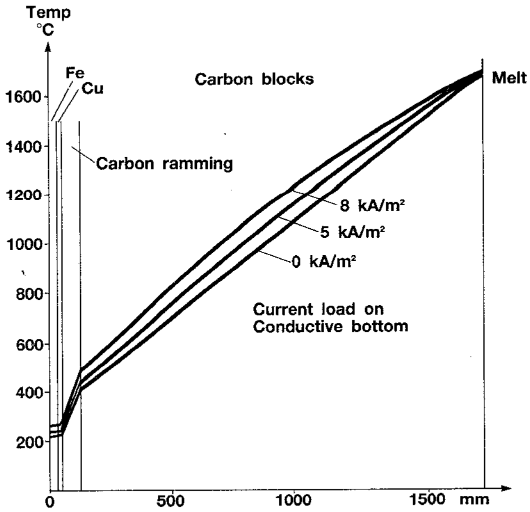


Fig. 1 Temperature distribution in an electrically conductive hearth consisting of carbon lining

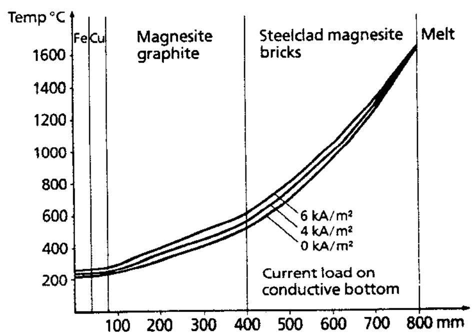


Fig. 2 Temperature distribution in an electrically conductive hearth consisting of wear lining of steelclad magnesite bricks and back up lining of magnesite graphite bricks.

Bottom electrode

Basically, the bottom electrode consists of a large circular copper plate, resting directly on the furnace bottom shell. The copper plate covers approximately the same area as the melt and is provided with terminals which are connected to the water-cooled cables.

Conductors

The current conductors are arranged symmetrically around the furnace to ensure a vertical and stable arc.

Rectifier

Electrical equipment can be designed either with a diode rectifier or a thyristor converter (Fig.3).

When using a diode rectifier short circuit currents are limited and the arc current stabilized by a reactor which is installed on the high voltage side of the furnace transformer. Such a reactor also effectively dampens the amount of harmonics fed back to the supply network from the rectifier.

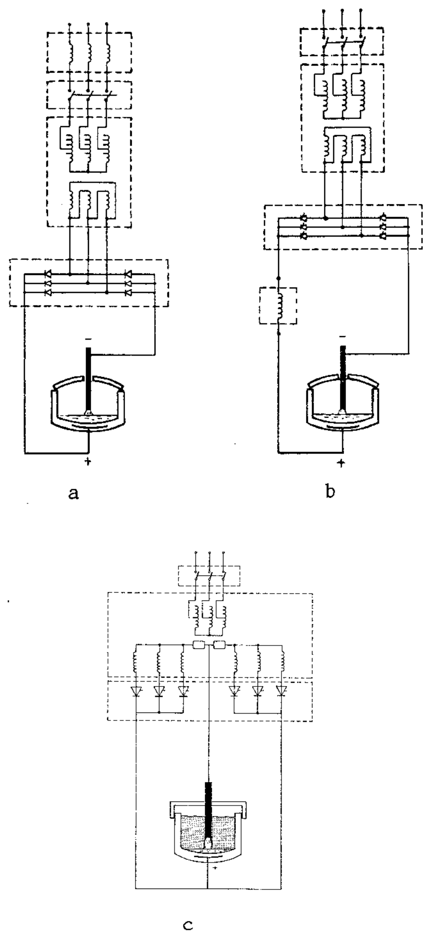


Fig. 3 Main circuit diagram for dc arc furnaces
a) diode rectifier two way connected
b) thyristor converter two way connected
c) thyristor converter one way connected

The other alternative, a thyristor converter, provides additional control possibilities. The current surges can be dynamically controlled by automatic regulation of the firing pulse delay. Short circuit current limiting reactors can then be eliminated or reduced, depending on the supply network conditions and requirements. Thyristor control, however, increases the amount of harmonic generation which, again depending on the network may call for counter measures such as filter circuits tuned to the harmonic frequencies. The rectifier can be connected in the secondary system either in a one way or two way connection. The one way connection is recommended when operating with very high arc currents. A thyristor converter is shown in Fig.4.

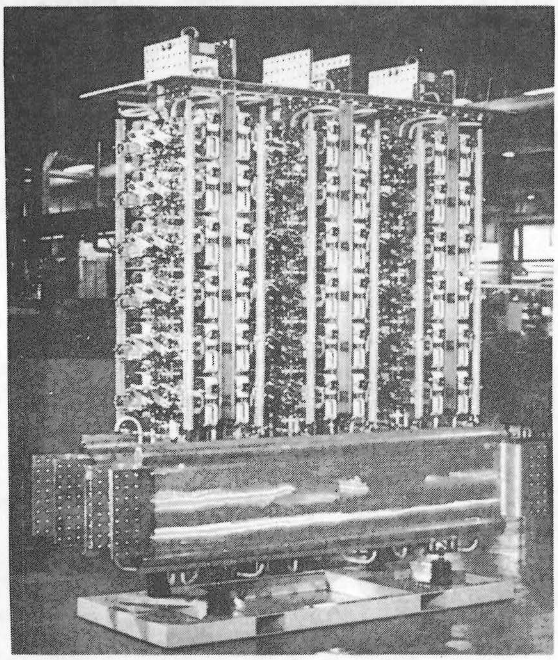


Fig.4 60 kA thyristor converter

THE DC SUBMERGED ARC FURNACE

The dc submerged arc furnace, Fig.5, is operated in the same way as the conventional ac submerged arc smelting furnace.

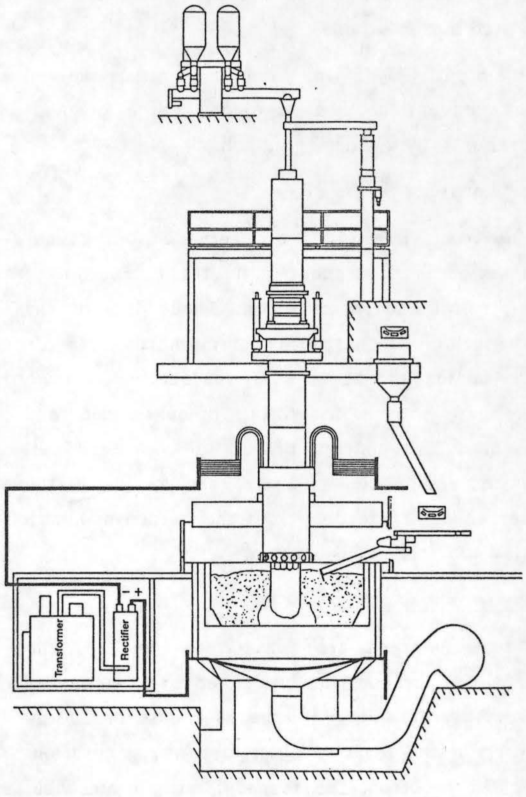


Fig.5 The dc submerged arc furnace

Hollow electrode

For many years a portion (0-25%) of fine mix feed has been charged via a hollow electrode system for production of calcium carbide. The fine mix feed, being delivered cold at the tip of the electrode, is believed to result in a lower temperature of the electrode in the vicinity of the arc. The most significant benefit received from the fine feed operation has been the decrease in electrode consumption.

The technology of fine mix feed via a hollow electrode system has been adapted in the concept of the ASEA dc submerged arc furnace. About 15-25% of the fine-grained material is charged through the self-or pre-baked electrode, which is provided with a central hole. A downward flow of inert gas (N_2-gas) through the hole of the electrode ensures proper flow of the particles through the electrode. It also provides a seal for the CO gas generated in the furnace.

The main part (75-85%) of lumpy material is charged in the conventional way through charge openings in the roof or by a charging machine.

Pilot plant tests

The above dc submerged arc furnace concept has been tested in pilot plant scale for production of silicon metal and ferro-silicon. About 80% of the raw material was charged as lumpy material on top of the burden and about 20% was charged through the hollow electrode in the form of quartz-sand and coke fines. This concept proved to work very well with good possibilities to control the position of the submerged electrode deep into the burden and with very low electrode consumption.

Energy recovery

The dc submerged arc furnace, as well as the conventional furnace, can be connected to an energy recovery system. Fig.6 illustrates a case of energy recovery in the form of electric power generation. Hot off gases from the furnace, with a closeable hood, passes the waste-heatboiler with integrated preheater and supheater. The superheated steam drives a turbo-generator unit with condensor turbine. Energy recovery systems of this type have been installed by ASEA Stal in conventional ac submerged arc furnaces for ferro-silicon production at Bjoelvefossen AS and at Orkla AS in Norway. About 25% of the total electrical energy requirement is recovered. The waste gas temperature behind the boiler is below 200°C. Therefore, the dust collecting system could be designed on a small scale.

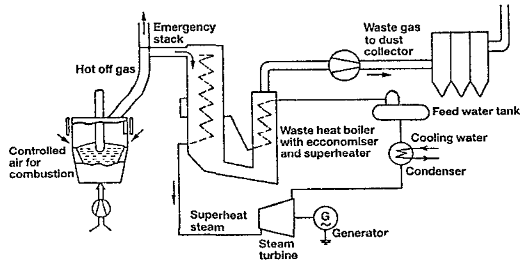


Fig.6 Recovery of energy on a submerged arc provided with a closeable hood for control of the intake of combustion air.

THE PLASMARC FURNACE

Operating characteristics

The most important feature with the Plasmarc furnace is that it can operate directly with ore fines, without prior briquetting or pelletizing. All the raw materials are charged into the furnace through the hollow electrode. The furnace operates with an open arc, Fig.7.

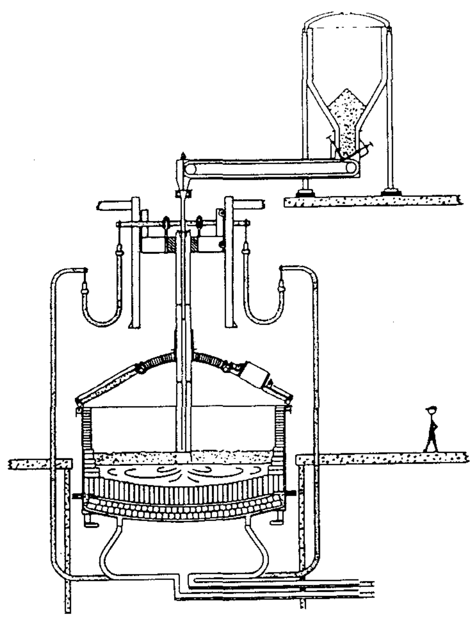


Fig.7 The Plasmarc dc arc furnace for reduction of ore fines.

Larger fractions, up to 25 mm, can also be charged through the hollow electrode.

There are several reasons for the process concept of the Plasmarc furnace. The raw materials are delivered directly to the hottest areas, the arc plasma itself and the anode spot in the melt. This provides a close and efficient coupling between the arc power and the process.

The arc, by repulsing slag, provides an open path for the charge into the bath with the result that only a small quantity of fines is lost to the slag.

The continuous flow of charged material cools and deionizes the arc. This leads to an increase in arc resistance which in turn, means that the process can operate with higher arc voltages and lower currents thereby contributing to a lower electrode consumption and electric power supply losses.

The melting process is easy to control with the feed rate being matched with the power input. The charge is consequently reduced as it is being fed and their is no accumulation of unreacted charge material in the furnace.

The Plasmarc furnace is not tilted for tapping or deslagging. Instead, these operations are performed in the same way as in a submerged arc furnace through tapholes at appropriate levels in the furnace sidewall.

Very good reduction results have been obtained by the Plasmarc furnace, both at pilot plant test runs with iron ore reduction in the ELRED DRI-process and with chromite ore fines in the 16 MW production furnace at Middelburg Steel & Alloys Ltd, South Africa.

Characteristics of the dc arc

Observations from above mentioned processes have contributed to the picture of the characteristics of the dc plasma in the Plasmarc furnace.

Fig. 8 depicts a frame from a high-speed film for a 30 kA, 270V dc arc. The arrows indicate the convective gas movements which can be observed on the film. From this film it was determined that the velocity of the convective gas movement in the middle of the arc is approximately 200 metres/s. The arrows indicate that the arc actually operates in a similar manner to an efficient gas pump. This effect is the result of the pinch forces caused by the heavy current in the arc plasma. The arc develops a waist half an electrode diameter from the tip. In this area, gases surrounding the arc are pulled in and then forcibly propelled towards the melt, which is the anode. Thus not only surrounding gases but also any type of fine material delivered close to the arc will also be pulled into the arc stream and propelled towards and into the melt.

The dc arc has a natural tendency to burn from the centre of the graphite electrode. This results in wear of the graphite electrode, giving the electrode tip a typical concave shape.

Observations with high-current dc arcs show that above a certain current level the arc undergoes a transition from one with a defined, highly mobile core to a diffuse arc without a visible core. This transition also depends on arc voltage and furnace temperature. The arc in Fig.8 represents an arc in its diffuse state.

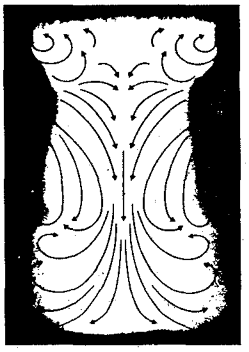


Fig. 8 DC arc plasma, 30 kA, 270V

Pre-reduction and pre-heating

In the ELRED process pre-reduction of ore fines takes place in a fast fluidized bed from which the pre-reduced material is continuously discharged and directly transferred to the Plasmarc furnace for final reduction. An alternative would be to use a rotary kiln for pre-heating the raw material which is illustrated in Fig.9.

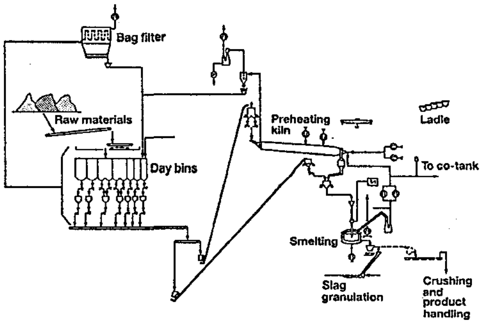


Fig. 9 The Plasmarc furnace with pre-heating of material in a rotary kiln.

ADVANTAGES WITH DC FURNACES

Both the dc submerged arc furnace and the Plasmarc furnace have several advantages of economical interest.

- High metal yield
- Low engergy consumption
- Low electrode consumption
- High productivity
- Low investment costs
- High flexibility

Yield

The first point, high metal yield, can be exemplified by the chromium yield in the Plasmarc process compared to an ac submerged arc furnace. The chromium balance for smelting of chromite to HCFeCr is presented in Fig.10. Chromite and HCFeCr have the following compositions:

Chromite Component	Mass%	HCFeCr Component	Mass%
Cr_2O_3	40.1	Cr	53.7
FeO	23.8	Fe	37.7
SiO_2	7.6	Si	1.6
CaO	1	C	7
Al_2O_3	16.1		
MgO	11.4		

The Plasmarc furnace is charged with ore fines while the conventional closed ac submerged arc furnace is charged with lumpy ore or alternatively with pellets.

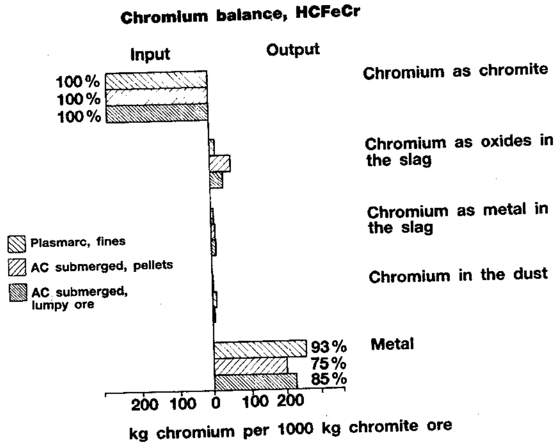


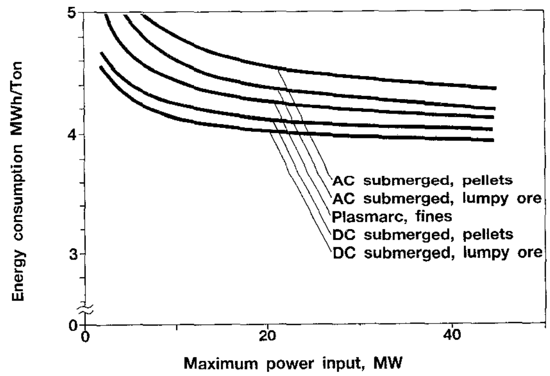
Fig. 10 Chromium balance for HCFeCr produced in different types of smelting furnaces.

The chromium yield is about 93% for the Plasmarc furnace which is superior to the yield of 75% achieved in the conventional ac submerged furnace charged with pellets. The Plasmarc furnace works closer to equilibrium, the concentration of chromium oxide in the slag is about 3-4%. The amount of dispersed metal droplets in the slag is small compared to conventional ac submerged furnaces.

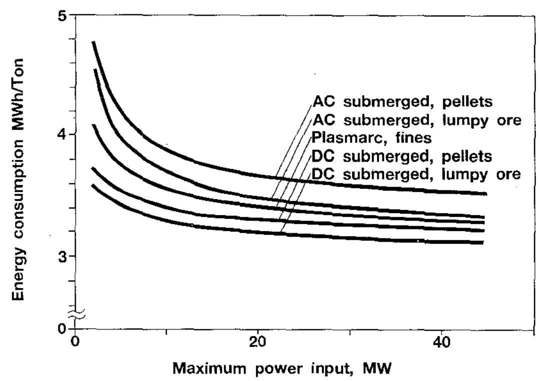
A dc submerged arc furnace with a possibility to charge up to 25% of the material through a hollow selfbaked electrode will work with higher chromium yield compared to a conventional ac submerged furnace. Fines can be fed through the electrode with the margin yield of the same order as in the Plasmarc furnace.

Energy consumption HCFeCr

The high yield and the low electrical losses for the Plasmarc furnace is favourable for the energy consumption. The Plasmarc furnace consumes less energy than the ac submerged furnace. The savings in the example in Fig. 11a-b are about 200 kwh/t HCFeCr. The dc submerged furnace combines the advantages of the counter current submerged reactor, to some extent the good metal yield in the Plasmarc furnace and the small electrical power supply losses when using the dc technology. The resulting energy balance is superior to any competitive process.



a



b

Fig.11 Energy consumption for production of HCFeCr with different types of processes
a - without pre-heating
b - with pre-heating of raw material to 700°C

Detailed energy balances for smelting of chromite to HCFeCr for some of the different processes have been calculated with the following assumptions:

Chromite Component	Mass%	HCFeCr Component	Mass%
Cr_2O_3	49.5	Cr	56
FeO	25.5	Fe	34
SiO_2	3.0	Si	3
CaO	1.0	C	7
Al_2O_3	12.0		
MgO	9.0		

The raw materials are pre-heated to 700°C and the furnace rating is 20 MW. The submerged furnaces are charged with pellets and the Plasmarc furnace with concentrate. The result of the calculations are shown in Fig.12.

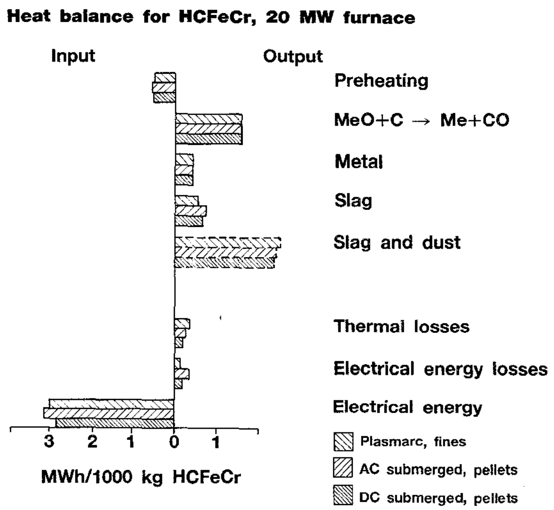


Fig.12 Heat balances for production of HCFeCr with different types of processes. Furnace size 20 MW.

The relatively high thermal losses for the Plasmarc furnace are compensated by the high yield and the small electrical power supply losses. The energy consumption is 3 020 kWh/t compared to 3 160 for the ac submerged furnace. The dc furnace is the best alternative in respect of energy consumption, 2 860 kWh/t.

Energy consumption silicon metal and ferro-silicon

The energy consumption is of great importance for smelting of silicon metal and ferro-silicon. Pilot plant tests in a 2 MVA dc submerged arc furnace have proved that the formation of SiO is very small for the materials that are fed through the hollow electrode. The yield when smelting FeSi75 is increased by some 2% when 25% of the quartz is charged through the electrode. The reduction of quartz to SiO demands nearly the same amount of energy as the reduction to Si. Losses of Si as SiO increases the energy consumption.

A comparison of the energy consumption for smelting FeSi75 in a dc and an ac submerged arc furnace gives a lower value fo 5-10% in the dc furnace, Fig.13. This is explained by the better yield, less electrical power supply losses and less thermal losses due to a more compact furnace. Another thing is that the dc furnace operates with only one central electrode. The heat distribution is, on the contrary to the ac furnace with three electrodes, completely uniform which is illustrated by Fig. 14. For the same electric power input the furnace shell diameter can be smaller for the dc furnace compared to the ac furnace.

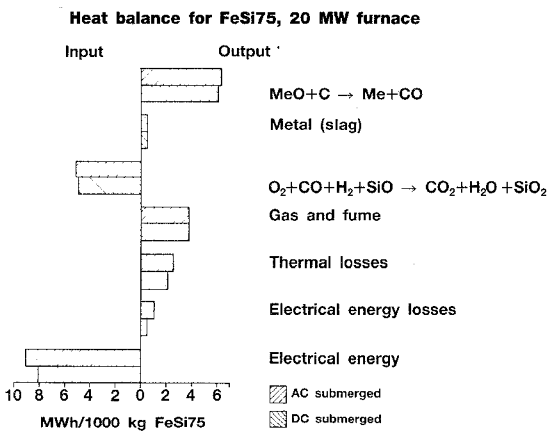


Fig.13 Heat balances for production of FeSi75 in a dc resp ac submerged arc furnace

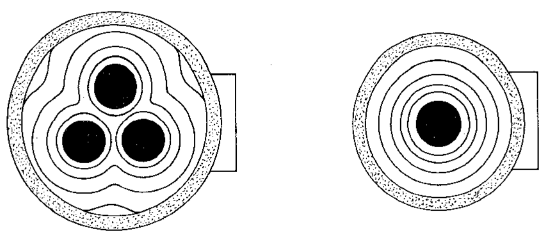


Fig. 14 Heat distribution comparison between a 3-phase ac submerged arc furnace (left) and a single electrode dc submerged arc furnace (right)

Electrode consumption

Three factors mainly contribute to the low electrode consumption in the dc furnaces. In the dc furnace only one electrode is exposed to the process as compared to three in an ac furnace. The sideburn of the electrode is thus reduced. With the negative charged electrode and the positively charged melt, the arc power is concentrated to the melt. The electrode is consequently cooler, with less carbon evaporation from the tip. In the Plasmarc and the dc submerged arc furnace with raw materials charged through the hollow electrode, the electrode tip is cooled by the raw materials. Thus the consumption of the electrode tip is reduced.

The electrode consumption differs between different processes and between grahpite, pre-baked and self-baked carbon electrodes. For most cases the electrode consumption is reduced by some 50% with the dc technology. Table 1 presents the electrode consumption for some processes. All given values are measured consumption data in production units or in pilot plant furnaces except for those of smelting silicon metal and HCFeCr in dc submerged arc furnace which are estimated.

Table 1. Electrode consumption for different processes

Process	dc (kg/MWh)	ac (kg/MWh)
ELRED, graphite iron	2-3	
Plasmarc, graphite HCFeCr	2-3	
Submerged, graphite slag smelting	1.9	4
Submerged, graphite Ferro-silicon	3.3	
Submerged, carbon Silicon	4.7	9-10
Submerged, selfbaked HCFeCr	3.0	5-6
Scrap melting, graphite Stainless steel	3.8	9.5

Productivity

The high metal yield and the low energy consumption contributes to a high productivity for the dc furnaces. In addition a dc furnace furnished with a thyristor converter can normally operate at a higher power factor compared to an equivalent ac furnace.

In general terms, the productivity can be calculated using the following formula:

$$P = \frac{A x B x C x \cos\varphi x 365 x 24}{Q} [t/y]$$

where

A= Transformer capacity (MVA)

B= The furnace availability (%/100)

C= The average power utilization $\frac{P(min)}{P(max)}$

Q= Energy consumption (Mwh/t)

The formula can be exemplified by smelting of FeSi75 in a conventional ac submerged furnace and in a dc submerged furnace.

	ac	dc
A	24	24
B	0.97	0.97
C	0.98	0.98
$\cos\varphi$	0.74	0.82
Q	9.0	8.2
P	16.432	19.985

A conversion from ac to dc can with the same transformer increase the production with some 20%.

Investment costs

For a new furnace the capital outlay is less by some 10-25% (depending on process) for a dc furnace than for a conventional ac submerged furnace.

Flexibility

The flexibility of the dc furnace can be expressed regarding different things:

- raw materials (ore fines can be used without prior briquetting or pelletizing)
- metal produced (relatively easy to change from one product to another)

SUMMARY OF OUR EXPERIENCE

Since 1972 ASEA has worked to develop the dc arc technology for metallurgical processes. In the course of this work the dc technology has been tested in the following plants:

Plant	Product	Capacity (t)	Rating (MVA)	Production(t)
Mefos 7275	Iron	7	4.5	1000
Kanthal 7576	CSteel	30	9	8000
Domnarvet 7779	CSteel/ Iron	30	11	3500
Gullspång since 81	FeW	4	1.2	1800
Avesta 8384	Stainless Steel	55	18	17500
MS&A since 84	HCFeCr	70	16	15000
Gullspång since 85	Recovery of Mo and Co	6	2.0	~1000
Gullspång 85	FeSiW	6	2.0	~ 200
Gullspång 85	FeSi	6	2.0	75

Furthermore at the present time we are converting a 35 t, 20 MVA steel scrap melting furnace at Florida Steel Corp to dc operation. Together with INCO we will also build a dc arc pilot furnace, 800 kVA, for process development of nickeloxide ore reduction. The pilot furnace will be in operation autumn this year.