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Plasma-arc Smelting of Fine Chromium Ores

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In the USA only one ferrochromium smelter remains in operation using the conventional submerged-arc technology to produce high-carbon ferrochromium. The submerged-arc process requires coarse feed materials, and cannot smelt significant portions of fine ore. The ability to process fine feed is important because the US strategic-materials stockpile includes fine ores, and the beneficiation of domestic orebodies, if developed, would produce fine chromium concentrates.

A research consortium funded by the Congress and administered by the Department of Defense has designed, built, and operated a 1,5 MW plasma test facility to smelt fine chromium ores. The furnace, which is described in this paper, is a d.c. transferred-arc open-bath closed furnace with a hollow graphite electrode. The furnace uses an electrically conductive refractory bottom-current collector. At various times the furnace was charged entirely through the hollow electrode, through drop openings in the roof, and by a combination of the two methods. The furnace operated successfully using a variety of reductants including coke breeze, fine anthracite coal, low-volatile bituminous coal, and mixtures of coke breeze and coal. Ore and reductant charged to the furnace were all smaller than 3 mesh. Acceptable dust losses were experienced, with very little raw charge reporting to the dust despite the fine nature of the feed materials.

Altogether, eight test campaigns were run. The first six were of one week's duration, and followed a test plan developed to measure specific operating parameters. The final two campaigns were of longer duration, and demonstrated the production capability of the facility.

The information obtained is being used to design a 12 MW semi-commercial demonstration plant.

Introduction

The USA is strongly dependent upon foreign sources of chromium. This dependency, which is expected to continue, is exacerbated by the inability of domestic smelting facilities based on conventional submerged-arc technology to smelt significant amounts of fine ore or concentrates[1]. The US strategic-materials stockpile, accumulated over many years, contains significant amounts of fine ore. In addition, all known domestic ore reserves are low grade and require beneficiation before use. This beneficiation procedure results in fine-grained concentrates. Chromium ores trade internationally, and fine-grained ores are available at substantial discounts. For these reasons, the Congress of the USA has funded a technology development programme to establish capability in the USA to *smelt fine chromium ores and concentrates*. This programme is administered by the Defense Logistics Agency.

The term *plasma-arc process* is used here to refer to the d.c. transferred-arc bath smelting process using a consumable carbon-based cathode and a furnace with an electrically conductive hearth. In the work described here, we have designed, erected, operated, and evaluated a plasma-arc furnace for smelting fine chromium ores.

A research consortium comprising South Carolina Research Authority (SCRA), Massachusetts Institute of Technology, Clemson University, Macalloy Corporation, and Arthur D Little Company conducted this research project. SCRA was the project manager, and the test facility was built in an existing smelting building at Macalloy Corporation's plant in Charleston, South Carolina. One of the first tasks undertaken by the team was a technical assessment of available proven and emerging technologies. Of the plasma processes considered, the three strongest contenders were the Tetronics processing plasma furnace, the PlasmaChrome process, and the d.c. transferred-arc process based on work by Mintek[2,3] and the experience of the Middelburg Steel & Alloys company.

Description of the Test Facility

Major economic benefits accrued from locating the test facility at Macalloy's plant. Existing ore-receiving, shipping, laboratory, drying, and screening facilities were used. In addition, the test furnace was housed in an existing building with overhead crane service. We procured new

and used equipment for raw-materials storage and preparation, a feed system, a power supply, an electrode mast, arm and electrode, the plasma furnace, computer control and data logging, and off-gas handling. Several components were water-cooled, water being supplied from the plant's larger recirculated cooling-water system.

The raw-materials preparation area was designed to process dried materials of less than 6 mm in size. All incoming materials were dried to less than about 1 per cent moisture, and were used dry except when wind-driven rain entered the partially open sides of the storage building. Ore mixes and reductants were prepared separately. Ore and flux additions were weighed, and charged to a double-cone blender. After mixing, the ore mix was dumped into 1,0 m^3 transport hoppers for charging to the furnace feed system. Coke breeze and/or fine coal was processed in a similar manner and transported to a reductant-feed bin. In later tests, the mix of reductant and ore was preblended in the ore-preparation area. This practice introduced some feed segregation in the feed system, but resulted in labour savings. No charge materials larger than 6 mm were used.

The feed system consisted of two live-bottom bins on load cells, two weighbelt feeders, an inclined screw conveyer, and a rotary-valve air lock. Structural-steel platforms supported the hardware of the feed system at the maximum height that allowed the bins to be filled by the overhead crane. The rotary-valve discharge was offset 25 cm from the centreline of the furnace and its hollow electrode. This feed system offered considerable redundancy in process-stream masses, which is fortunate in that various components failed or lost calibration during operations.

Halmar Inc. designed and manufactured the power supply[4] to our operating specifications. It is a twelve-pulse thyristor-controlled rectifier. Incoming power at 13,8 kV a.c. passed through two step-down transformers, one delta and one wye, which could be connected in either series or parallel. This provided a wide range of possible operating d.c. voltages and amperages. Choke reactors on the d.c. helped stabilize the output. The transformers, thyristors, reactor coils, and cabinet were all cooled by internal circulating deionized water, which in turn dumped heat to the plant cooling water through water-to-water heat exchangers. The power supply could be operated either as a regulated constant-amperage supply or as a constant-power source. It was used primarily in the constant-current mode, the voltage being adjusted by moving the electrode. The power supply was equipped with a wide variety of safety interlock devices, including ground fault detection. It ran very well and, except for a water-hose connection breaking loose and flooding the interior, caused few problems. This event burned out two pump motors. In the parallel mode, the power supply would provide up to 10 kA d.c. at up to 250 V. In series mode it would supply up to 5 kA at up to 500 V d.c. We never used its full capacity, but at times approached the current limits at lower voltages. We have operated at a sustained 1,2 MVA d.c. power level.

The furnace was initially designed with two approaches to achieving a conductive bottom. The initial approach, with an array of stainless-steel rods as current collectors embedded in rammed magnesite refractory, failed prematurely. The second bottom, consisting of a copper plate and conductive refractory components, has worked very well, and was used for all the tests described here. Other investigators have made the pin-conductor approach work[5]; we have not given up on it. Failure of our first bottom was at least partially attributable to severe current loading during the initial testing and commissioning of the power supply.

A general cutaway drawing of the furnace is shown in Figure 1. The furnace is encased in a steel shell, with a 25,4 mm bottom plate flanged to 19 mm cylindrical steel sidewalls. The bottom-most layer of refractory is a 50/50 mix of alumina and magnesia ram refractory, used to optimize thermal conductivity through this layer. A copper plate 86,4 cm x 86,4 cm and 12,7 mm thick sat on this refractory layer, with bus connections exiting the furnace through the flanged joint at its bottom. Porous carbon blocks set on top of the copper plate with a conductive carbon paste assured good electrical contact. The working bottom was a soldier layer of carbon-magnesite bricks containing 30 per cent graphitic carbon. These bricks have stood up well.

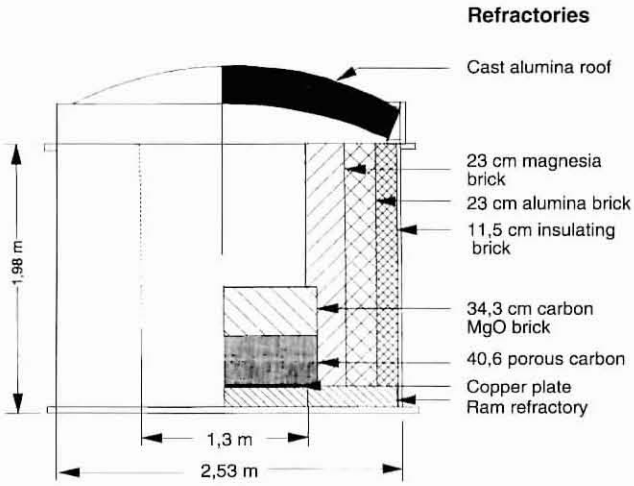

FIGURE 1. Plasma-arc furnace

Several sidewall configurations have been evaluated. The working sidewall lining exposed to the bath has consisted of magnesia brick, magnesia ram refractory, and carbon paste. A 23 cm cylinder of alumina brick backed up the magnesia working lining, followed by 11,5 cm of insulating alumina brick. Crushed bauxite filled the remaining 2,5 cm gap between the brick and the shell. Multiple thermocouples were mounted at several depths in the sidewalls and bottom to monitor temperature profiles and the thermal flux from the furnace. These temperature measurements were also used to verify a finite-element computer model developed during the design phases.

The furnace roof was a shallow cast alumina dome, reinforced with stainless filaments. This was manufactured off-site by a company that makes furnace-roof delta inserts for commercial three-electrode a.c. arc furnaces. The roof was cast into a water-cooled steel skewback ring. It had several openings cast in place, including the electrode entry hole, off-gas port, auxiliary feed holes, and an observation port. Two roofs were purchased in anticipation of refractory failure. All tests were made with the initial roof. Although its original 30 cm nominal thickness has been eroded to about 10 cm near the centre, it is still functional.

The off-gas handling system combusted carbon monoxide from the furnace, cooled the combustion products with dilution air, and removed particulates in a pulse-jet baghouse. Because of material hang-up in the baghouse and its discharge hopper, the baghouse discharge was sporadic. Dust collection did not correlate well with the furnacing operations, and varied from about 5 to 12 per cent of the mass of ore charged to the furnace. The dust composition was depleted in chromium and iron, and enriched in silica and magnesia. This suggests that the mechanical transportation of charge materials was not as important as the vapour-phase transportation of reduced species in the generation of dust.

The test furnace was highly instrumented. An Allen-Bradley PLC-5 process-control computer was the primary input/output data-logging device, and was serviced by an IBM 386SX personal-computer interface. Indelec's 'Plant View' software was used to manipulate the raw sensor signals, display operating conditions, plot trend lines, and archive data.

The Test Programme

The test programme was conducted between September and December 1990. A total of eight test campaigns were run. The first six campaigns, each lasting five to six days, were executed according to a predetermined test plan. This plan provided for the orderly accomplishment of the tasks required to meet the objectives of the test facility and funding commitments. Typically, target operating parameters were held constant for periods of three tap cycles, and then changed. Depending on operating conditions, tap cycles ranged from about 90 minutes to about 4 hours. The final two campaigns were of longer duration and constituted more of a production-type test. Operating conditions were changed infrequently, and changes were aimed at optimizing furnace performance, as opposed to studying specific variables. Table I summarizes the variables studied in each campaign.

TABLE I
SUMMARY OF CAMPAIGNS

Camp no.	Power	Ore type*	Reductant	Objective
I	Low	Fe–Cr fines Iron ore Turkish	Coke	Start-up all systems
II	Low – interm	Turkish	Coke	Establish operating practices
III	Low – interm	Turkish 50/50 Mix	Coke	Begin mass and energy balances
IV	Interm	Turkish 50/50 Mix	Coke	Vary ore-to-coke ratio
V	Interm	Turkish	Coke Anthracite Low-volatile bituminous	Evaluate alternative reductants
VI	Interm – high	Turkish 50/50 Mix	Coke	Study ore-to-coke ratio, alloy composition
VII	Interm – high	Turkish	Coke	Production test Pseudo-submerged-arc Low voltage
VIII	Interm – high	Turkish 50/50 Mix	Coke	Production test Pseudo-submerged-arc Low-voltage

* The 50/50 mix was a blend of Russian and Turkish ores of the compositions given in Table II.

The chemical composition of the ores and reductants used are presented in Table II. The majority of tests involved the smelting of minus 3 mesh Turkish ore with coke breeze. Figure 2 presents data from campaigns II to VI, in which Turkish ore was smelted with coke. The correlation of ore-smelting rate with power was excellent, and a good straight line was obtained intersecting the axis at about 0,2 MW. This intercept represents the steady-state heat loss from the furnace, and agrees well with calculated losses through the shell, bottom, and roof. The experimental data are in good agreement with the smelting rates predicted by a thermochemical computer model[6] developed during the design stage of the project.

TABLE II
COMPOSITIONS OF ORES AND REDUCTANTS

1. Ores, %			
	Turkish ore #473	Russian ore GSA stockpile	Iron ore
Cr_2O_3	33,14	51,77	
FeO	9,08	13,52	
SiO_2	14,11	8,56	3,00
Al_2O_3	8,54	10,33	
MgO	24,97	14,62	
CaO	0,40	0,31	
Fe_2O_3			93,54
Cr/Fe ratio	3,21	3,37	
2. Reductants, %			
	Low-volatile bituminous	Anthracite coal	Coke breeze
Fixed carbon	68,56	70,05	72,54
Ash	12,02	18,99	19,41
Volatiles	19,42	10,96	8,05
Moisture	0,40	5,60	6,20
Ash analysis			
SiO_2	43,75	52,75	49,66
Al_2O_3	30,59	39,36	25,10
MgO	16,96	12,22	17,43
CaO	1,03	1,11	2,02
FeO	1,24	0,62	1,92

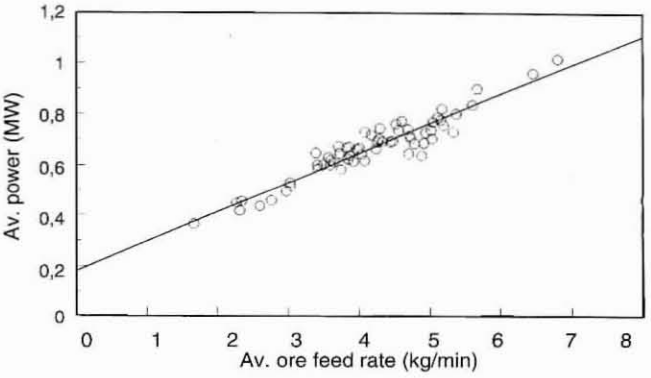

FIGURE 2. Campaigns II to VI (using Turkish ore and coke breeze)

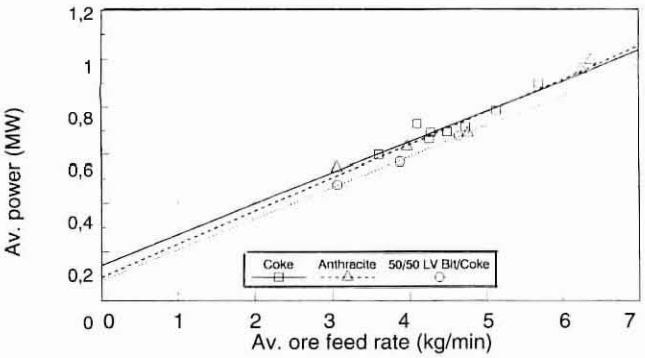

FIGURE 3. Campaign V (using various reductants)

Several reductants were used during campaign V. These included coke breeze, anthracite coal, and a 50/50 mix of low-volatile bituminous coal with coke breeze. The composition of these reductants is shown in Table II. Figure 3 shows the smelting rates obtained with the various reductants. In the region of the measurements, the data for coke and anthracite coal are almost indistinguishable. The data for the reductant mix with bituminous coal is displaced somewhat downwards but maintains the same slope. The reductants were substituted on the basis of an equivalent rate of fixed carbon. It is conceivable that volatiles in the bituminous coal may have made a small positive contribution to the chromite reduction. The process ran well with all the reductants tested.

A hollow graphite electrode of 25,4 cm diameter with a 65 mm central bore was used for most of the tests. The electrodes were purchased in 1,52 m sections and had tapered threaded male-to-female joints. The electrode sections lasted about 30 hours in use – a higher rate of electrode consumption than those reported by other investigators[7]. Inadequate draught control and air in-leakage to the furnace may have contributed to significant electrode oxidation in the hot furnace atmosphere. The charge mix was fed to the furnace down the hollow electrode using a stationary stainless-steel feed pipe of 51 mm diameter inserted in the electrode. A slip joint at the top of the electrode column allowed the electrode to move while the feed pipe was held stationary. This arrangement functioned adequately as long as the electrode was not submerged in slag or unsmelted charge materials. Feed blockages, when detected early, were easily cleared. Severe feed blockages resulted in fines building up in the annulus between the feed pipe and the electrode, and distorted the feed pipe when the electrode was raised.

TABLE III
FOUR-DAY MATERIALS BALANCE, 11TH TO 14TH DECEMBER, 1990
(34 ORE MIXES SMELTED)

Material/Mass	Balance*	Cr	Fe	Si	Al	Mg	Ca
Inputs:							
Turkish ore	Oxide, %	33,14	9,08	14,11	8,42	24,97	0,40
	Metal, %	22,67	7,06	6,60	4,45	15,06	0,29
13 909	Mass, kg	3 153	982	918	619	2 095	40
Russian ore	Oxide, %	51,77	13,52	8,56	10,33	14,62	0,31
	Metal, %	35,41	10,51	4,01	5,46	8,82	0,22
13 909	Mass, kg	5 070	1 462	558	760	1 227	30
Sand	Oxide, %			95			
	Metal, %			44,46			
1 700	Mass, kg			756			
Bauxite	Oxide, %				52,9		
	Metal, %				39,1		
464	Mass, kg				181		
Coke	Oxide, %		0,24	8,30	5,39	3,29	0,20
	Metal, %		0,19	3,88	3,14	1,98	0,14
6 645	Mass, kg		13	258	209	131	10
TOTAL INPUT	kg	8 078	2 457	2 490	1 769	3 453	81
Outputs:							
Alloy	Metal	62,89	27,9	1,29			
9 391	Mass, kg	5 906	2 620	121			
Slag	Oxide, %	12,13	0,81	31,66	20,01	33,93	0,69
	Metal, %	8,30	0,63	14,82	10,58	20,46	0,49
13 864	Mass, kg	1 151	87	2 055	1 467	2 836	68
Dust	Oxide, %	15,12	1,49	36,12	13,64	32,98	0,64
	Metal, %	10,34	1,16	16,90	7,21	19,89	0,46
2 950	Mass, kg	305	34	499	213	586	14
TOTAL OUTPUT	kg	7 362	2 741	2 675	1 680	3 423	81
% of input		91,1	111,6	107,4	94,9	99,1	100,0

*Oxide – as a percentage of the respective oxide
Metal – as a mass percentage of the element or metal

Discussion

During the last campaign, the furnace was fed through drop points in the roof, and a solid electrode column was used. A four-day material balance was made during the smelting of a 50/50 blend of Russian and Turkish ores. Table III presents this balance. Analytical results for ores, fluxes, reductants, slag, and dusts are usually presented as percentages of the respective oxides Cr_2O_3, FeO, SiO_2, Al_2O_3, MgO, and CaO. These oxide percentages are tabulated where appropriate with the elemental or metal content in mass percentages directly below. The balances tabulate input and output masses in terms of the metallic elements. The furnace was tapped 34 times during this four-day period. The input constituent masses are well documented, as are the masses of alloy and dust. The slag mass used is a calculated value, which was chosen to provide a good balance for the gangue minerals.

As would be expected, the design, start-up, and operation of a test facility on this scale involved many trials and tribulations. None the less, all the major goals and objectives of the test programme were achieved. Quality high-carbon ferrochromium was produced from a furnace burden of entirely less than 3 mesh. Acceptable operating parameters were derived, and thermal and thermochemical computer models were validated. The information needed to design an upscaled demonstration ferrochromium smelter was obtained.

Alloy and slag compositions varied considerably. The production of a marketable alloy and clean discardable slags was demonstrated, but the quality of the products was not consistent. Target alloy compositions in terms of chromium, iron, sulphur, and phosphorus contents were routinely attained. The carbon content of the alloy averaged 5,1 per cent as against a target level of 6 per cent, and silicon averaged 2,3 per cent as against a target level of 4 per cent. The low silicon content of some alloy ingots reduced their brittleness to the point that they were difficult to crush or break up for sale. Slag samples from the test furnace generally contained more chromium oxide than was desired. The Cr_2O_3 content, averaged over individual campaigns, ranged from 9,0 to 14,4 per cent. Individual slag taps with as little as 1,7 per cent Cr_2O_3 were obtained. The furnace performance is not sensitive to slag chemistry. Because the plasma arc blows a hole in the slag layer, and the arc seats directly on the metal heel in the furnace, the electrical conductivity of the slag is not an important variable. Therefore, slag compositions did not have to be adjusted to control the conductivity. Magnesia-to-alumina ratios as high as 1,8 were shown to be feasible, and resulted in significant potential flux savings.

Chemical analysis showed that the baghouse dusts collected contained less Cr_2O_3, and much less FeO, than the furnace charge materials. Through the first six campaigns, the average FeO content of the dust was only 2,9 per cent. During campaigns VII and VIII, the FeO content averaged well below 1,5 per cent. Relatively little fine-ore particulate was transported from the furnace to the baghouse. The dusts were enriched in silica and magnesia, indicating the probable transport of SiO and Mg species in the vapour phase.

Conclusions

This project was particularly successful in the smelting of fine charge materials. The particle size of all the feed materials (ores, fluxes, and reductants) was less than 6 mm, and the charges contained large proportions of very fine material. The feeding of material directly to the arc zone through the hollow electrode was successful, and a workable design basis for hollow-electrode charging to a scaled-up furnace was established. The problems that were identified are resolvable. Fine feed was also charged to the furnace through roof drop points and was smelted successfully. The plasma-arc process does not require lumpy or agglomerated feed.

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