CAST IRON PRODUCTION
FROM SPONGE IRON

Final Technical and Financial Report

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C O N T E N T S

ABSTRACT

The foundry industry in Egypt faces nowadays serious difficulties in securing the proper raw materials, especially those needed to produce molten metal. Both foundry grade pig iron and special types of pig iron; needed for ductile cast iron production are imported. In the meantime, classified steel scrap of the proper qualities is becoming a real scarcity.

This report discusses the results obtained, on pilot scale, when using locally produced sponge iron - or directly reduced iron (DRI) as a main charge constituent in both induction furnaces as well as cupolas. It has been shown that melting of sponge iron in both of furnaces is technically and economically feasible. The pilot findings of this research gave much of the background needed to begin commercial applications in three Egyptian foundries.

Sponge iron was utilized to produce either high purity pig iron in induction furnace, and that HPPI was later used for the production of ductile iron; or to directly produce ductile iron castings when added to a molten pool of Egyptian pig iron, steel scrap or foundry grade pig iron. On the pilot scale no difficulties were encountered in removal of excessive amounts of slag formed during melting - the influence on lining life was as well insignificant. On the other hand, the life time of lining of commercial scale induction furnaces was reduced by about 25% when using up to 30% sponge iron in the charge. This extra cost was, however, counterbalanced by the price difference of raw materials and the production cost of one ton of HPPI was still about 30% cheaper in favour of charges containing sponge iron.

The results of adding sponge iron to Egyptian pig iron were very attractive, as the slag formed from the gangue of sponge iron could oxidize most of manganese and phosphorus contents of that pig iron. The Mn-content was reduced from 2.1 to 0.1% and the P-content from 0.45 to 0.05%. This result opens new prospects for the use of Egyptian pig irons as foundry material.

Up to 25% sponge iron was introduced to cupola charges without difficulties. Increasing additions up to 50% resulted in slight increase in coke consumption, increase in the slag volume, decrease in both carbon and silicon contents. The utilization of sponge iron in cupola charges resulted in cost advantage of about 15%.

Results obtained on the pilot scale were upscaled to commercial applications in three foundries where quality castings, with special critical services requirements were produced. Measurement of the mechanical properties, particularly fracture toughness together with performance analysis of the castings showed that the properties and performance of castings produced from charges containing sponge iron are comparable to those produced from commercial materials.

INTRODUCTION

The main raw materials used for the production of iron castings are :

- foundry grade hematite pig iron
- steel scrap
- high purity pig iron (low in S, P and Mn).

The first two are used for the production of grey iron castings while the use of the third is restricted to the production of ductile cast irons.

The foundry industry in Egypt relies on importing both types of pig iron at 200 and 300 US$ per ton for the hematite and high purity pig irons respectively. The locally produced pig iron is not suitable for foundry purposes due to excessive contents of phosphorus (0.4-0.5%) and manganese (1-2%). Reduction of such contents to those accepted for the production of quality iron castings; 0.1% P max. and 0.4% Mn) is technically unfeasible. Presently, about 50,000 tons of hematite pig iron and 30,000 tons of high purity pig iron are imported per year at total import cost of about 16.5 million U.S. dollars.

Recently, 800,000 ton/year of very high purity sponge iron are being produced at the Alexandria National Iron and Steel Co. using "Midrex" technology of reducing pelletized iron ore with cracking products of locally available natural gases. Although the production relies on iron ore import, the production cost is still lower than that in USA and comparable to the cheapest available sponge iron produced in Latin America.

In recent years the use of ductile iron has been increasing, and this is bound to have a significant effect on the type of charge material that will be required in the future. For example, the chromium content of ductile iron must be kept to a minimum on account of its chill inducing effect, and in some specifications for ferritic ductile iron, the manganese content must be kept below 0.35%. Tramp elements such as titanium, tin, lead and arsenic which are often contained in commercial scrap, must also be avoided because they inhibit the formation of nodular graphite in ductile iron.

For ductile iron, the charge will contain 40-55% return material (home scrap). The new iron units that make up the balance of the charge generally comes from the cheapest source that can be obtained, providing that the chemical composition of the melt does not include element, that are harmful to the physical properties of the castings. Generally the cheapest source available is steel scrap; however, it often contains undesirable tramp elements.

The availability of suitable scrap as charge material for the manufacture of ductile iron is limited, in particular because of the accompanying elements which must not exceed certain levels. It must be expected that in the future the portion of accompanying elements in the scrap, for instance, chromium, nickel, molybdenum and the like will increase further. A certain amount of pig iron must be charged in order to keep the portion of accompanying elements in the melt within acceptable limits. It will be more difficult in the future to provide this pig iron and this will entail increased cost. It is anticipated that sponge iron will be used increasingly for making steel. This means that more reduction facilities for producing sponge iron will be installed which, in turn would allow sponge iron production at lower cost. Thus, pig iron would be replaced more and more by sponge iron with the cost relation developing favourably for sponge iron.

Amongest the considerations that make sponge iron attractive as foundry melting stock are :

(1) A source of virgin metal with a low "tramp" element content.
(2) The chemical composition is known and is consistent.
(3) The availability and price should be stable as commercial production became established in Egypt.
(4) A lower furnace charge cost might be possible depending on price differentials between sponge iron and competing charge materials.
(5) The material is magnetic and can be handled conveniently by a crane and magnet. Its size and shape also make it ideal for mechanical handling by an automated storage and charging system.
(6) Is not friable and can withstand the roughest treatment without creation of fines.

The main objectives of this work were identified as follows :

(1) Develop a process for reproducibly producing high purity pig iron from Egyptian sponge iron in an induction furnace of 10 kg capacity.

(2) Develop processes for reproducibly producing high purity pig iron, on the pilot scale in induction and cupola furnaces.

(3) Decide between the alternative routes developed for producing high purity pig iron as a raw material for the production of ductile iron and engineering quality grey iron.

(4) Using a chosen high purity pig iron produce ductile iron in induction furnaces.

(5) Using a chosen high purity pig iron produce grey iron castings of engineering quality by melting in a cupola.

(6) Develop producers for making ductile iron directly from Egyptian sponge iron in induction furnace.

(7) Perform techno-economic evaluation of the production of engineering quality grey iron and ductile iron castings by the alternative routes developed.

(8) Perform technology transfer, disseminating the processes developed for the production of these higher quality cast iron from sponge iron.

Indirect benefits will result from the following consequenceis :

- Less dependence on import of such a strategic material as foundry pig iron.

- Having the proper raw materials locally available, more small and medium sized foundries will be motivated to produce ductile and high grades of iron castings with more added value.

- Decrease of the import needs for quality castings with the additional savings of hard currency.

- Better performance of high quality castings used as spare parts, will reduce the machienry stoppage times needed to replace those parts and hence increase productivity in other fields as textile, machine tools ... etc.

CHAPTER 1

PILOT MELTING EXPERIMENTS

1.1. Melting Procedure in Induction Furnaces

The purpose of this work was to evaluate in a preliminary way the general behaviour of sponge iron which added in different ratios to a molten pool of different materials, i.e. steel scrap (S.S), Egyptian pig iron (EPI) or hematitic pig iron imported from Russia (RPI). Heats of about 100 kg were made by first melting different amounts of the pool from one of the above-mentioned three materials (80, 65 and 50 kg). After melting, the sponge iron was added onto the surface of the pool to complete the weight to 100 kg (20, 35 and 50 kg).

The chemical analysis of the used raw materials is shown in the following table :

	C	Si	Mn	S	P
Egyptian Pig Iron	3.5/4.5	1.0/1.2	1.8/2.3	0.03 max.	0.35/0.45
Steel Scrap	0.15	0.2	0.6	0.08	0.02
Russian Pig Iron	4.0/4.3	2.0/2.5	0.1/0.3	0.025	0.03/0.07

The sponge iron used was in the form of spherical pellets with fairly uniform shape and size (5-15 mm). The chemical composition of sponge iron was as follows; %

Fe (Total)	Fe (metallic)	C	CaO	MgO
91.90	86.50	1.70	0.71	0.33
Al_2O_3	**SiO_2**	**BaS_2**	**P**	**Degree of Metallization**
0.50	1.20	0.59	0.02	93.5

Melting was carried out in medium frequency (1000 Hz) 100 kg capacity acid lined induction furnace. Sponge iron was added to the molten pool in batches of 5-10 kg. After melting of the sponge iron batch, the surface of molten metal was thoroughly deslagged and sample for chemical analysis taken from the molten iron.

Because of the low density of the sponge iron, it floated on the surface of the metal bath. Cold pellets of sponge iron up to 15 mm in diameter melted within a matter of seconds, mainly because of the heat transferred from the molten metal to the pellets. As the pellets melted, the increasing amount of slag gradually covered the entire surface of the bath. When more pellets were added, they intended to be retained in the slag or to float on the slag, and melting of such pellets became slow. This is attributed to the low electrical conductivity of the slag which renders its heating by induction impossible. The slag looses heat by radiation and receives heat only by contact with the molten metal. Under these conditions, the slag becomes viscous to a degree that can inhibit further melting of sponge iron added to the furnace; intermediate deslagging was therefore necessary.

The frequency of deslagging normally affects the melting time and productivity and some precautions were taken to minimize the deslagging frequency. Optimum meltdown conditions were obtained when the charging speed of sponge iron corresponded to the meltdown capacity, allowing the sponge iron to melt as it contacts the bath. With charging speeds too high, too much unmelted sponge iron remain on top of the melt surface, which leads to bridging and melting difficulties. With too low charging speeds, the melting capacity of the furnace is not properly utilized and the pool of liquid metal may become overheated. It should be added that addition of sponge iron is better made to the central slag-free proportion of the bath. In this respect, strong agitation of the bath by induction is advantageous since sponge iron is drawn into the bath by the stirring effect. The synchronization of charging and melt down results in saving of actual charging time.

When melting was carried out in the 100 and 350 kg induction furnaces at CMRDI experimental foundry, deslagging was made at the lowest possible temperature to keep heat losses to a minimum and to simplify deslagging due to high slag viscosity. In these small furnaces, however, deslagging was

(a) Charging

(b) Pouring

Fig. (1.1) : Induction melting of sponge iron containing charges at CMRDI pilot foundry.

carried out manually without any serious problems. A special metallic spoon was used to collect the formed slag and the latter was accurately weighed, ground for better sampling and then chemically analysed. For industrial scale melts, it is recommended that the slag-off operation be mechanized, for example, by using a gripping device shown schematically in Fig. (1.2), thus keeping the slagging time to a minimum. It is also advised to rate the sponge iron input in such a way that for the removal of a partial quantity for processing, deslagging is necessary only once.

1.2. Experimental Cupola

(i) Basic design principles

An experimental cupola has been designed and erected at the pilot foundry of CMRDI. The main design parameters were selected to give a melting rate of about one ton per hour with fairly close control of the molten metal temperature and composition. The design of a cupola has an important bearing on the efficiency and economy of its operation. The main design features affecting the performance of the furnace and discussed below :

(ii) Optimum blast rate as basis for design

A cupola melts most efficiently and economically when it is operated at a certain blast rate. There is always an optimum blast rate to give the maximum metal temperature at a given metal: coke ratio. In our experiments, where the charge composition widely varies with the change of sponge iron percentage in the charge, the optimum blast rate was expected to vary to some extent with the nature of material melted. However, it has been found, both experimentally and practically, that this optimum blast rate approximates fairly closely to 115 m^3/min. per square meter of cupola cross sectional area at the tuyeres. This figure was taken as the first, fundamental basis of design.

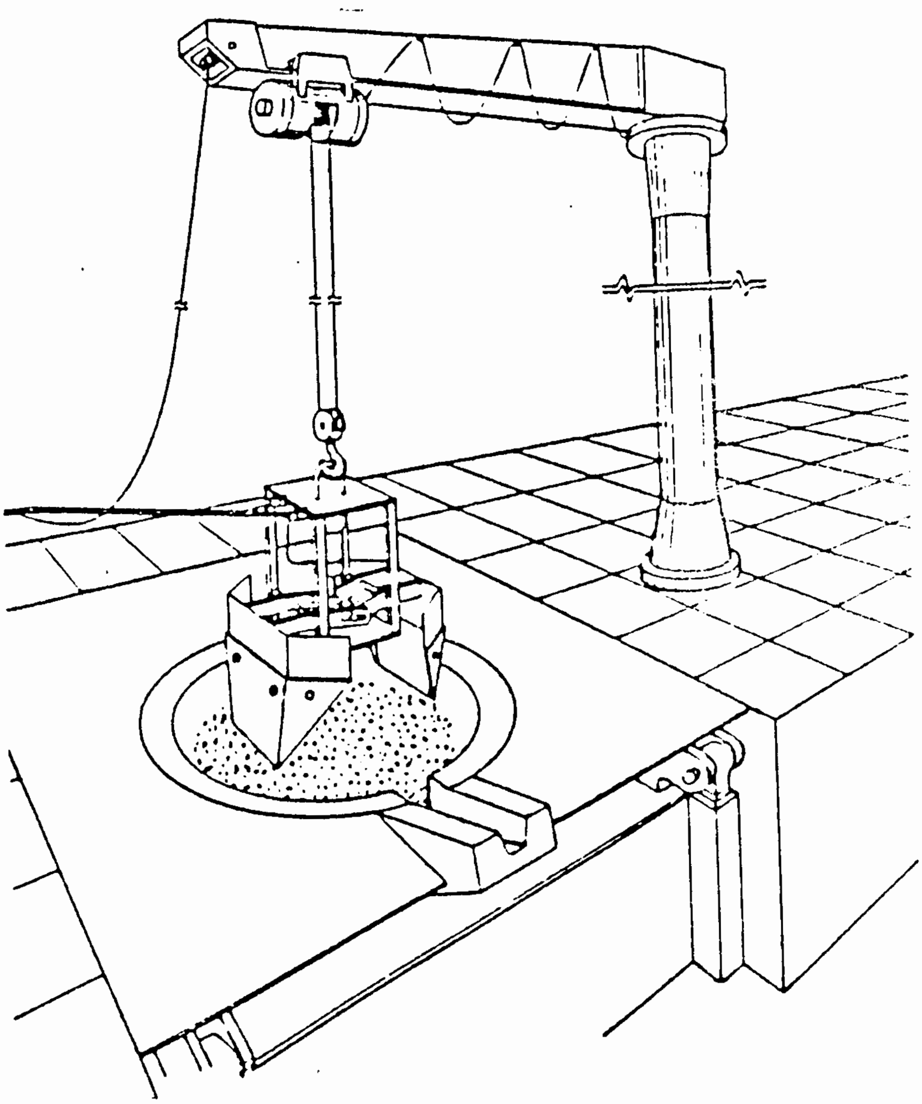


Fig. (1.2) : Schematic illustration of a specially designed grab bucket for removing slag from a large electric induction furnace.

(iii) Cupola diameter related to melting rate

The melting rate of a cupola is dependent upon the metal :coke ratio, the blast rate as well as on the charge constituents. To obtain a melting rate of about one ton per hour at a metal : coke ratio of 6 : 1, a cupola having an internal diameter of 48 cm is required and the blowing rate should be 130-140 m^3/min. This rather low metal : coke ratio was selected as a basis for design as it was expected that the increased slag formation, associated with the use of sponge iron in the charge, will require higher amounts of coke.

(iv) Blower specification

Although a specific blowing rate of 115 m^3/min./m^2 has been selected as a blast for fixing the diameter of the cupola relative to its output, in actual operation, the output can be varied by altering the blast rate. Normally, a cupola can be operated within a range of about $\pm$ 15-20% of the optimum blast rate without serious consequences (in terms of metal tapping temperatures) of under- or overblowing.

The recommended specification for the blowing equipment given in the following table, therefore allows the cupola to be operated at a blast rate of about 20 per cent in excess of the optimum when required. The discharge pressure at the outlet of the blower must be sufficient to enable the required volume of air to be delivered against the resistance of the blast main, windbelt, tunyeres and above all, the stock in the furnace. For a cupola of a given diameter, this resistance may rary widely according to the nature of the cupola charge materials. With the introduction of sponge iron to the charge, which will certainly reduce the air permeability of the charge, it is expected that higher air pressures will be required to ensure that the required volume of air will be delivered to the furnace under most melting conditions. To facilitate the control of blowing conditions, a butterfly valve has been introduced between the blower and the wind-box.

The main design features of the experimental cupola used throughout this work is shown in the following table, and a picture of the cupola is shown in Fig. (1.3).

Fig. (1.3) : Experimental cupola.

1			2	3	4	5		6	7	8	9
Melting Rate at Various Metal : Coke Ratios Under Steady Operating Conditions, t/h			Recommended Blowing Rate, m^3/min.	Cross Sectional Area of Melting Zone, m^2	Diameter of Melting Zone, cm	Recommended Blower Capacity		Approximate Well Capacity, kg/cm Height	Total Tuyere Area, cm^2	Number of Tuyeres	Approximate Bed Weight, kg/cm Height
Metal : Coke Ratio						Volume, m^3/min.	Discharge Pressure, KPa				
10:1	8:1	6:1									
1.6	1.3	1.1	18.8	0.17	48	25	10.0	6.0	250-480	4	0.7-0.9

1.3. Production of Ductile Cast Iron

After completion of the melting process, the chemical analysis of the melt was adjusted by adding the required amounts of carburizer and ferrosilicon to compensate for the melting losses of carbon and silicon respectively. The molten metal was then treated with magnesium as (FeSiMg 9%) alloy required for graphite spheroidization and then inculated with ZL-80 inoculant to ensure the absence of free carbides in the structure, and hence brittleness and excessive hardness.

For spheroidization and inoculation treatments, the Vortex Technology has been adopted throughout this work. This technology has been acquired and then developed by CMRDI since 1984, and later introduced to seven Egyptian foundries. This technology is rather simple, reliable and economical for adding spheroidizing and inoculating alloys as well as desulpherizing materials to the molten iron. By modifying the structural design of the equipment, this method was adopted for the production of ductile irons, especially for melts weighing between 50-4000 kg.

The principle of the Vortex method is based on generating a reproducible vortex or whirlpool. This vortex is obtained by allowing molten iron to flow tangentially into a funnel-shaped space, the iron exits at the lower side through an opening which lies in the funnel's center line. By adequately dimensioning the entire arrangement, a vertical or swirling action is produced.

The additive is introduced to the metal from a hopper through a calibrated opening in a thermally shock-resistant tube at the center of the induced vortex. The additive is immediately surrounded by the liquid metal and the reaction is instantaneous at the center of the emerging stream. A device mounted in the lower funnel opening of the vortex allows the emerging jet to completely and continually fall prependicularly. The effect of the swirling action which occurs in the apparatus is thereby eliminated.

The main features of the Vortex Method are schematically illustrated in Fig. (1.4.a), where Fig. (1.4.b) shows the Vortex treatment in operation at CMRDI experimental foundry. The main advantages of the process are :

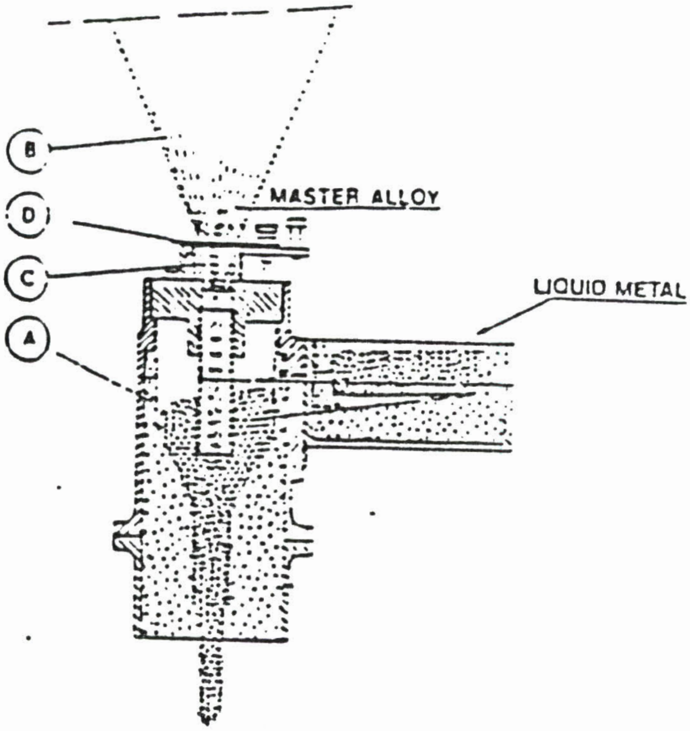


Fig. (1.4.a) : Main features of the Vortex Unit - schematic.

Fig. (1.4.b) : The Vortex Process in operation at CMRDI experimental foudnry.

- o can be applied to both continuous and batch operations
- o low investment costs
- o low maintenance costs
- o versatile applications (inoculation, desulfurization, ductile production)
- o reduces chances for microimpurities in the metal structure
- o simple design
- o adequate reproducibility
- o short treatment period
- o no risk of explosion
- o minimum temperature losses
- o relatively high output
- o adaptable to various operational conditions.

1.4. Production of High Purity Pig Iron in Induction Furnace

The main objective of this section is to investigate the possibility of producing high purity pig iron with a predetermined composition :

C	Si	Mn	S	P
3.5 - 4.2	1 - 2	0.1 - 0.3	< 0.03	< 0.05

Such composition is required for the production of ductile iron after the proper treatment with magnesium. It was of special interest to use sponge iron together with the Egyptian pig iron as the main charge constituents for the production of the high purity pig iron as both materials are locally available. The Egyptian pig iron contains rather high manganese contents (1-2%) and phosphorus contents (0.4-0.6%) which seriously detracts from its value as foundry material.

Preliminary experiments in a small induction furnace (10 kg capacity and 2000 H_2 frequency) showed that the above mentioned analysis could be achieved using different quantities of sponge iron added either to Egyptian pig iron or steel scrap followed by composition adjustment by carburizer and ferroalloy (FeSi and FeMn) additions.

The results were then upscaled to the pilot foundry of CMRDI and high purity pig iron was produced using medium frequency (1000 H_2) induction furnaces of 100 and 350 kg capacities.

The results of sponge iron melting with Egyptian pig iron may be considered to be of a significant value. First of all, it should be mentioned that over the past five years much effort has been directed to removal of some of the Mn- and P-content from the Egyptian pig iron with the purpose of using it as a foundry material. Those efforts, unfortunately, have met modest degrees of success.

The following melt-sheet shows the results obtained during one of the induction melting experiments using a mixture of sponge iron and Egyptian pig iron.

MELT SHEET

Objective	:	Production high purity pig iron
Furnace	:	- Induction furnace, 100 kg capacity, acid lining, max. power 100 kw, medium frequency = 766 at the start. - Starting kwh x 10 = 316.7
Charge	:	50 kg of Egyptian pig iron (EPI) were firstly melted and then sponge iron (S.I.) gradually added up to 150 kg
Other additions	:	Carburizer and ferroalloys (FeSi and FeMn) were added during melting as shown in the melt history.

Melting History :

Time	Activity	
10:23 a.m.	Charging of 49 kg EPI, then furnace on	
11:08 a.m.	Temp. : 1428°C - spectro sample (I)	
11:12 a.m.	Add 25 kg (S.I.)	SI-1

Time	Activity	
11.21 a.m.	Deslagging	
11.24	Add 25 kg more of S.I.	SI-2
11:31	First step deslagging	
11:40	Complete deslagging	

Total weight of slag after melting of 49 kg EPI and 50 kg S.I. = 7.5 kg

11:48	Spectro sample (II)	
11:49	Temp. * 1436°C	
11:50	Tapping of 42.5 kg into sand mould	
11:54	Add 1 kg carburizer	C1
12:01	Temp. * 1588°C	
12:02	Spectro sample (III)	
12:03	Add 50 kg S.I.	SI-3
12:43	Temp. : 1449°C	
12:47	Spectro sample (IV)	
13:25	Temp. : 1486°C	
13:30	Tapping 29.5 kg into a sand mould	
13.33	Add 2 kg carburizer	C2
13:43	Temp. 1484°C	
13:44	Spectro sample (V)	
13:45	Add 50 kg S.I.	SI-4
14:30	Deslagging	

Weight of slag formed after addition of the second 50 kg S.I. = 6.0 kg

14.37	Temp. : 1405°C	
14:39	Spectro sample (VI)	
14:50	Add 2.445 kg carburizer	C3
15:35	Add FeSi (65% Si)	
15:40	Add FeMn (82% Mn)	
15:45	Temp. 1504°C - Spectro sample (VII)	
15:46	Tapping of 95 kg of molten metal into a sand mould	

The samples taken at different stages of melting process (samples I-VII) were analysed and the results listed in the following table :

Sample	C	Si	Mn	S	P	Cr	Ni	Mo	V	Ti	Cu	Al
I	3.82	1.18	2.11	0.02	0.32	0.03	0.004	0.020	0.03	0.03	0.003	0.003
II	2.15	0.007	0.11	0.015	0.18	0.02	0.002	0.016	0.11	0.007	0.002	0.003
III	4.18	0.006	0.11	0.017	0.18	0.02	0.002	0.016	0.012	0.006	0.003	0.003
IV	1.46	-	0.03	0.010	0.10	0.009	0.001	0.015	0.005	0.006	0.006	0.002
V	4.44	0.013	0.03	0.010	0.10	0.010	0.001	0.014	0.006	0.006	0.006	0.001
VI	2.12	-	0.03	0.006	0.05	0.006	0.001	0.015	0.005	0.006	0.006	0.002
VII	4.11	0.948	0.29	0.005	0.05	0.007	0.001	0.016	0.007	0.010	0.007	0.009

From these results, the following conclusions could be reached :

i) High purity pig iron can be obtained with manganese and phosphorus contents as low as 0.03 and 0.05% respectively by adding sponge iron to Egyptian pig iron containing 2.11% Mn and 0.32% P. It is evident that these two elements have been oxidized by FeO of the sponge iron whereas MnO and P_2O_5 have contributed to the increased slag formation.

ii) Silicon in the pig iron is as well oxidized during melting. Late additions of FeSi can restore the Si-content to any desirable value. Although the oxidization of silicon represents an economical loss, the following factors may at least partially compensate for such loss :

- Si-oxidization takes place by FeO of the sponge iron; which means higher iron yield from the sponge iron.

- Lower silicon contents of the pig iron allows for the use of higher amounts of ductile iron return scrap during the melting of base-iron for ductile iron production. Moreover FeSiMg alloys with lower Mg-contents may be used for spheroidization treatments. Both these factors represent a economical benefit.

iii) Mn-content could be controlled to within rather narrow ranges. With low Mn-contents, thin section castings could be produced with as-cast ferritic matrix and expensive annealing treatments could be avoided. On the other hand, thick section castings could be produced free from intrcellular carbides liable to form with higher Mn-contents (over 0.4%).

iv) High purity pig iron could be produced with extremely low S-contents (0.005%) with the following advantages for ductile iron production :

- Smaller quantities of Mg-spheroidizing alloy are required - this material is rather expensive.

- Insignificant dross formation and decreased possibilities for CO-blowhole formation on the upper surface of the produced castings.

v) As sponge iron is almost free from trace elements, the Ti-content of pig iron significantly decreases after addition of the sponge iron. It is known that Ti counteracts the effect of Mg as spheroidizer and any reduction of Ti-content will result in savings of the required Mg-additions.

Analysis of the slag showed that the basisity expressed as :

$$CaO/SiO_2$$

ranges between 0.2 and 0.3 during melting, and this explains why the furnace lining was not considerably affected by the use of sponge iron in the charge.

1.5. Test Results of Experimental Cupola

Preliminary tests showed that with short term feed of sponge iron into cupola furnace, it is hardly possible to obtain definite information on the melting process, operating data and iron analysis and quality. This is related to the fact that in the continuously operated cupola furnace, changes due to a new feed mixture are reflected only after a period of transition. Moreover, shaft furnaces react in a relatively sluggish manner to any changes, thus for a short time use of sponge iron, the real conditions and effects can not be recorded with sufficient accuracy.

Therefore, during the tests discussed herein, the cupola furnace was generally operated with an identical charge mixture as long as the available amounts of raw material permitted which was about 2-3 hours.

The charging sequence was the same as in the case of the normal practice, except that the sponge was added on the top of the charge.

The sponge iron was added in the form of spheres of diameters 10-15 mm, which give very good flow properties. In the initial charges, therefore, no sponge iron was added to avoid the "running ahead" of sponge iron through the other raw materials in the charge. If sponge iron is added to the earlier charges, it tends to reach the tuyeres zone much ahead of the charge to which it is added - this causes chilling of the bath creating problems in smooth flow of the metal through the top-hole. Once molten metal appeared at the top-hole, subsequent charging with sponge iron was started and continued throughout the remaining period of cupola operation. Trials were conducted under four conditions in which 0, 10, 25 and 50 percent sponge iron replaced pig iron charged into the cupola; the balance of the charge was 50% Egyptian pig iron and 50% foundry grade pig iron.

During operation, the blast pressure, the melting rate, metal temperature, slag composition, specific slag quantity and melt composition were observed.

Results of Pilot Heats

Blast pressure

Although it was expected that increasing amounts of pellets would ultimately result in prohibitive windbox pressures due to the decreasing permeability of the charge, the actual increase was not excessive. During normal cupola operation, the pressure was generally in the range of 1200 to

1500 mm WG and in the initial trials with 10 percent sponge, no difference in wind pressure was observed. However, increasing the sponge pellets up to 25% in the charge, the wind pressure was distinetly higher than that during normal operation and increased as much as 1700 mm WG. This was almost certainly a result of small sized sponge filling the voids in the charge, thereby reducing the overall permeability of the burden. Beyond 25% and up to 50% of sponge pellets in the charge, the pressure reached 1800-1900 mm WG. ;This pressure is within the operating range of the used cupola blower installation and would be considered a significant pressure increase, but one that could be handled by the blower of sufficient reserve capacity.

Metal/coke ratio

Two contradictory factors were found to influence the coke consumption :

i) Additional coke is required to melt the slag-forming gangue contained in the sponge iron.

ii) Due to the small size of the pellets and their large specific surface, which is about 20 times larger than that of pig iron, pellets heat up with a considerably higher speed in the upper part of the shaft. Consequently, the heat utilization is more favourable. This may lead to a slightly improved performance with a reduced coke rate.

Temperature measurements of the molten iron in the cupola spout, showed that increasing the sponge iron percentage in the charge resulted in a slight decrease of temperature from 1440 to 1420°C at metal : coke ratio of 6 : 1. To keep the spout temeprature constant, it was found that coke additions should be increased by 10% at 25% sponge additions and by 15-20% at 50% additions.

Metal Composition

i) Carbon and silicon

- With increasing sponge iron percentage in the charge, a general trend of carbon and silicon contents decrease was observed. This may be mainly attributed to the low C-content and very low Si-content of the sponge iron added. The very low FeO-content in the slag indicates that most of the residual FeO in the slag was reduced by C and Si, which may contribute to the decrease of the latter elements in the melt. Up to 10% of sponge iron additions, the carbon content remained unchanged and dropped slightly at 25% addition (from 3.5 to 3.4%).

- It should be noted that a significant, temporary drop in silicon content occurred each time the percentage of prereduced material was increased. This occurrence was definite and could be detected each time a charge was made in the percentage of pellets charged. The silicon drop was especially remakable when the pellets addition was increased to 50% of the charge. It is speculated that the pellets, because of their size and shape, dropped through the open charge and melted several charges in advance of the charge to which they were originally added. This temporarily diluted the metal in the well with respect to silicon and upset the metal : coke ratio. Eventually, a balance was restored as the pig iron portion of the charge "caught up" and the silicon was returned to the normal level. In the same way, one can explain the progressive silicon depletion of the last charges remaining to be melted during the last 20-30 minutes of the heat as these charges contained decreasing proportions of pellets.

- It was found that, to obtain a uniform Si-level, ferroalloy additions should be adjusted at the beginning and end of the heat to compensate for the melting of the pellets in advance of their respective charges. The degree of this running ahead of pellets in determined by the relationship between sponge iron dimensions and shape, number and size of holes between the charge mixture components. This phenomena is expected to be reduced if sponge iron from lump ore or in the form of hot briquetted iron (HBI) is used. These two materials are expected to be on sale in the Egyptian market in the near future, and that will facilitate operation and control of cupola furnace using sponge iron.

- The rather slight decrease of C-content noticed with increasing sponge iron additions in the charge may be explained by the fact, that carburization (or C-pick up) and hence, the resulting C-level is related directly to spout temperatures. With the fairly constant temperatures encountered throughout this work, no significant variations in carbon were observed to occur with a charge in pellet charges.

Manganese and phosphorus

At the beginning of the heat, with the charge consisting of 50% Egyptian pig iron and 50% of foundry pig iron, the Mn- and P-contents of the molten metal reached 1.2 and 0.26% respectively. The results obtained with increasing additions of sponge iron in the charge are similar to those obtained with induction melting. Considerable degree of Mn- and P-removal from the Egyptian pig iron was noticed with the addition of sponge iron in the charge.

The following table shows the variation of Mn- and P-contents of the molten metal produced from different charges. This analysis represents the composition of the third ladle filled with molten metal produced from a certain charge composition. The first two ladles (each weighing 300 kg) were thought to still have instable analysis due to the charge in the charge make-up. Again as with induction melting, the slagging of Mn and P takes place on the account of the reduction of FeO in the sponge iron.

Charge, %	Egyptian P.I.	100	50	45	375	25
	Foundry P.I.	-	50	45	375	25
	Sponge Iron	-	-	10	25	50
Mn/P		1.8/0.45	1.2/0.26	0.7/0.1	0.3/0.04	0.15/0.03

Sulphur

The sulphur content of the molten iron ranged between 0.07 and 0.10% and there was no clear dependence of S-content on the sponge iron additions. However, sulphur contents in sponge iron melts were expected to be lower mainly because of the markedly lower sulphur content of sponge iron as compared to that of pig iron, but this factor is counter-balanced by other two parameters :

i) Extra coke added at higher percentages of sponge in the charge might off-set this advantage by increasing the sulphur load on the furnace.

ii) Decrease of slag basicity with increasing additions of sponge iron may lead to increased S-contents in the molten metal.

No definite trends could, therefore, be established for sulphur content as a function of sponge iron addition to the charge.

Cupola Slag

It was observed during the trials that addition of sponge iron containing contributed to a gradual increase in the amount of slag generated with 25 and 50% sponge in the charge, the slag volume increased by about 12-15% and 20-25% respectively. The increased slag volume arose out of the presence of gangue materials in sponge iron.

With additions of 5% limestone and 0.5% fluorspar in the charge, the gangue combined with the normal cupola slag and flowed freely from the slag spout.

The chemical analysis of slag samples taken at $\frac{1}{2}$ hour intervals indicated that the slag compositions fell with the range of normal acid slags. Increasing the amounts of pellets in the charge did not appreciably alter the slag composition.

The slag basicity ranged between 0.5 and 0.7 (SiO_2: 46-48%, Al_2O_3: 15-18%, CaO: 24-28%, and MgO: 4-5).

1.6. Utilization of High Purity Pig Iron HPPI in Production of Ductile Iron

The high purity pig iron (HPPI) produced in the induction furnace was used for the production of ductile iron as an alternative to the imported high purity Sorel metal. The microstructure shown in Fig. (1.5) indicates that there is no remarkable difference in the microstructures taking into consideration that the chemical composition of both melts were almost kept the same.

1.7. Direct Production of Ductile Iron from Sponge Iron in Induction Furnaces

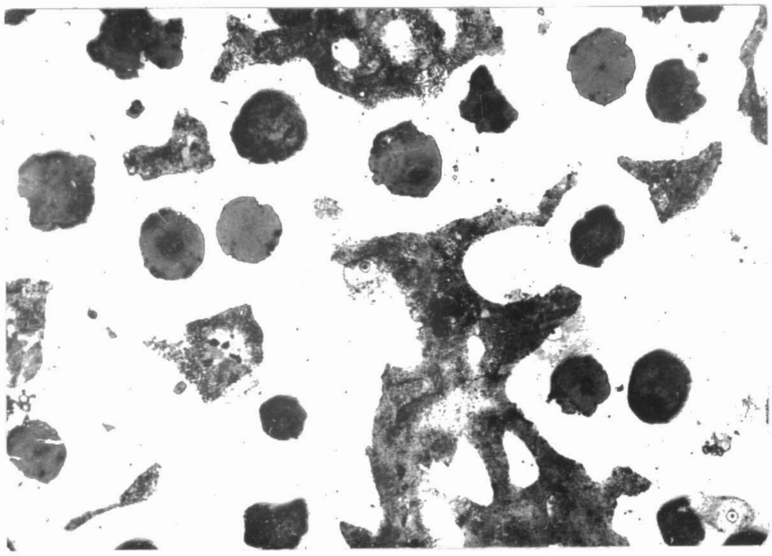
Three series of experiments were conducted aiming at investigating the possibility of using sponge iron together with the conventional raw materials available in the Egyptian market for the direct production of ductile iron. Sponge iron was added in quantities ranging from 20 up to 50% of the metallic charge, while the balance was either steel scrap, Egyptian pig iron or normal grade of foundry pig iron.

As explained before, the conventional material was firstly melted and the sponge iron was added in batches to the molten pool. The variation in chemical analysis was followed in the course of addition, and slag formed was collected, ground and sampled for chemical analysis. The Vortex Method was then adopted for FeSiMg alloy addition to the molten metal for graphite spheroidization in the iron.

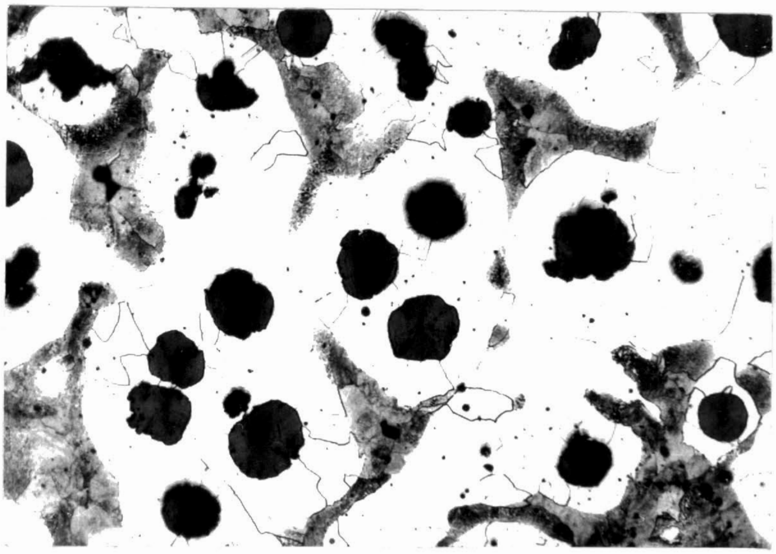
Analysis of molten metal

Figures (1.6) to (1.8) show the variation in chemical analysis when adding sponge iron to a molten pool of Egyptian pig iron in quantities of 20, 35 and 50% respectively while Fig. (1.9) shows the change in the composition of slag formed during addition of sponge iron up to 50% from the molten pool. Figs. (1.10) to (1.13) show the same relations when sponge iron is added to a molten pool of steel scrap.

It is of special interest to notice that the addition of sponge iron to the Egyptian pig iron results in considerable decrease of Mn-content



(a)



(b)

Fig. (1.15) : Microstructures of ductile iron produced from :
(a) Sorel metal.
(b) HPPI produced from sponge iron.

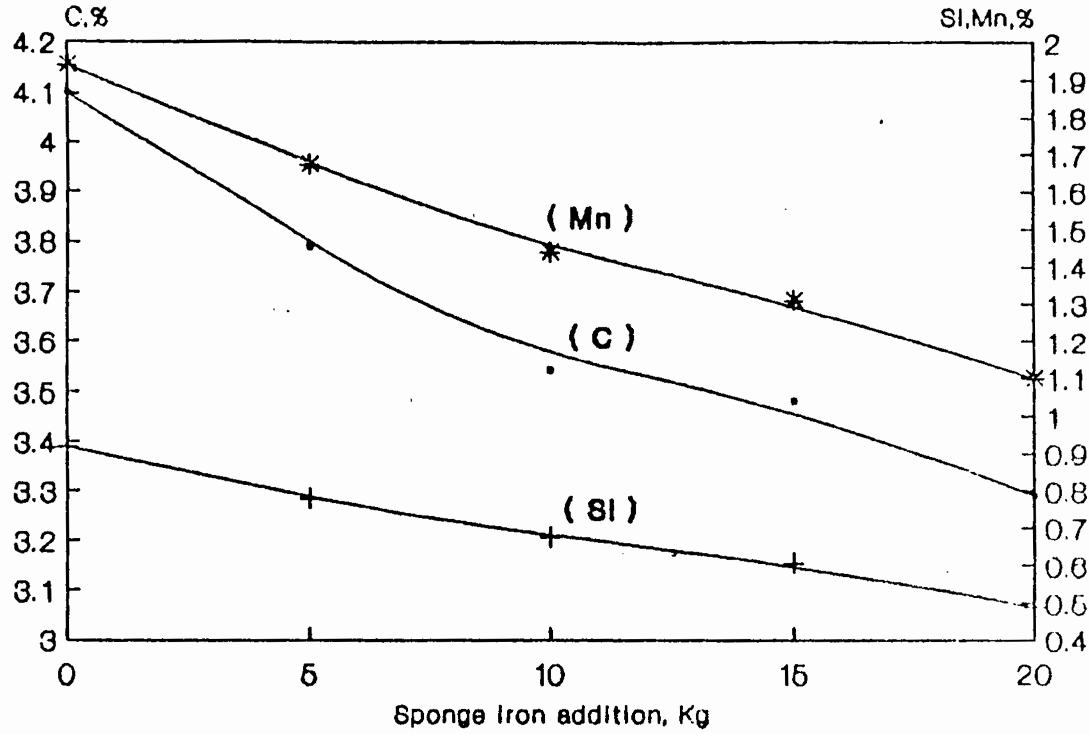


Fig. (1.6) : Effect of sponge iron addition on C,Si,Mn% in Egyptian pig iron pool metal.

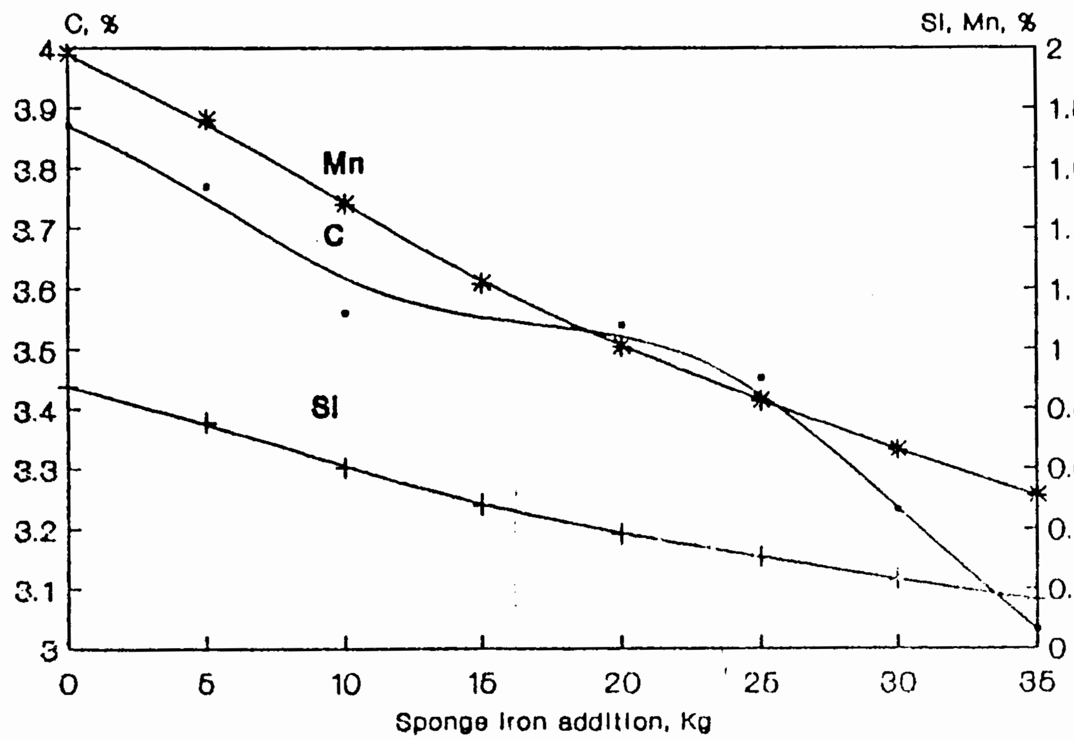


Fig. (1.7) : Effect of sponge iron addition on C,Si,Mn% in Egyptian pig iron pool metal.

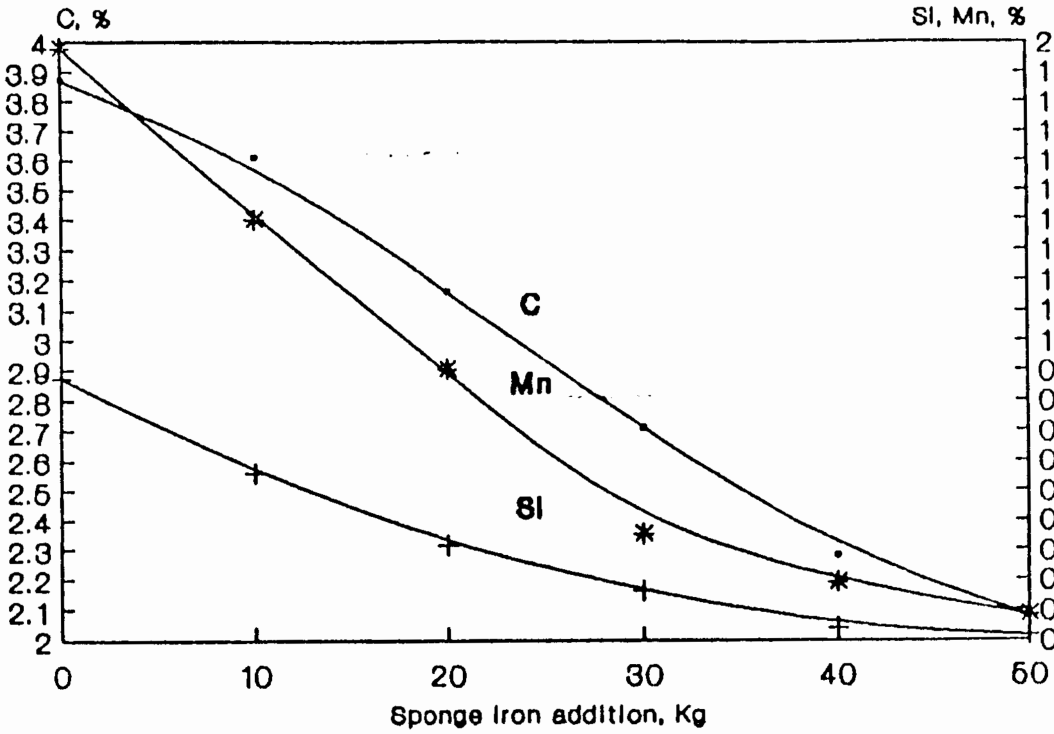


Fig. (1.8) : Effect of sponge iron addition on C,Si,Mn% in Egyptian pig iron pool metal.

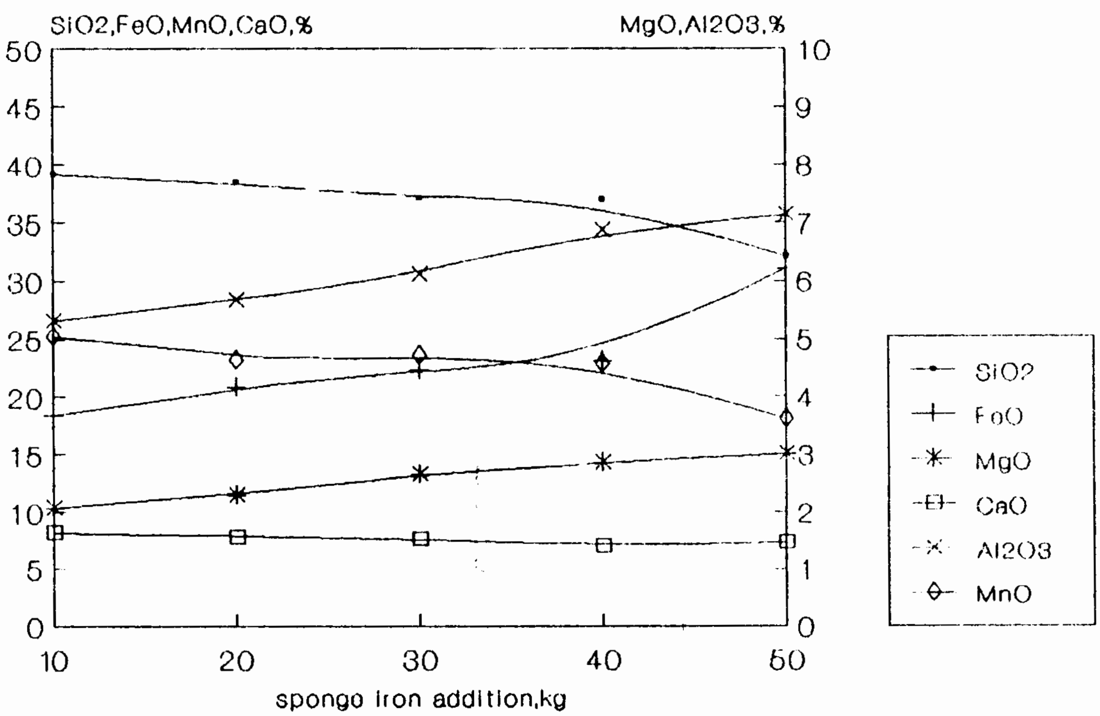


Fig. (1.9) : Behaviour of slag resulting from addition sponge iron in Egyptian P.I.

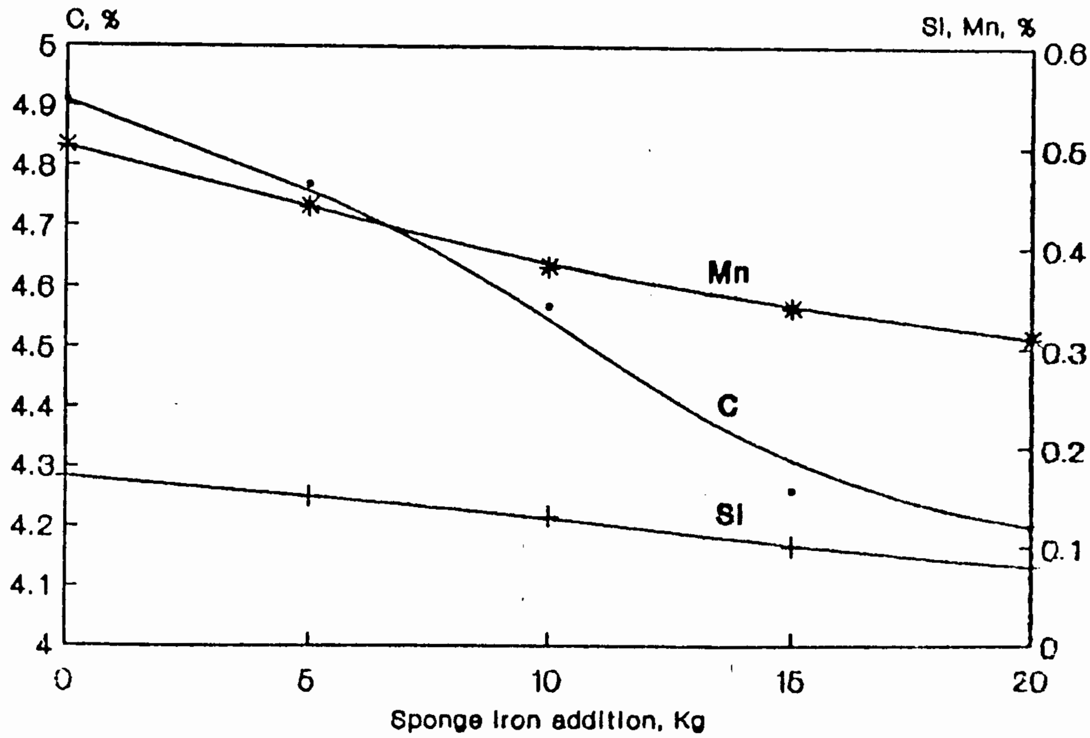


Fig. (1.10) : Effect of sponge iron addition on C,Si,Mn% in steel scrap pool metal.

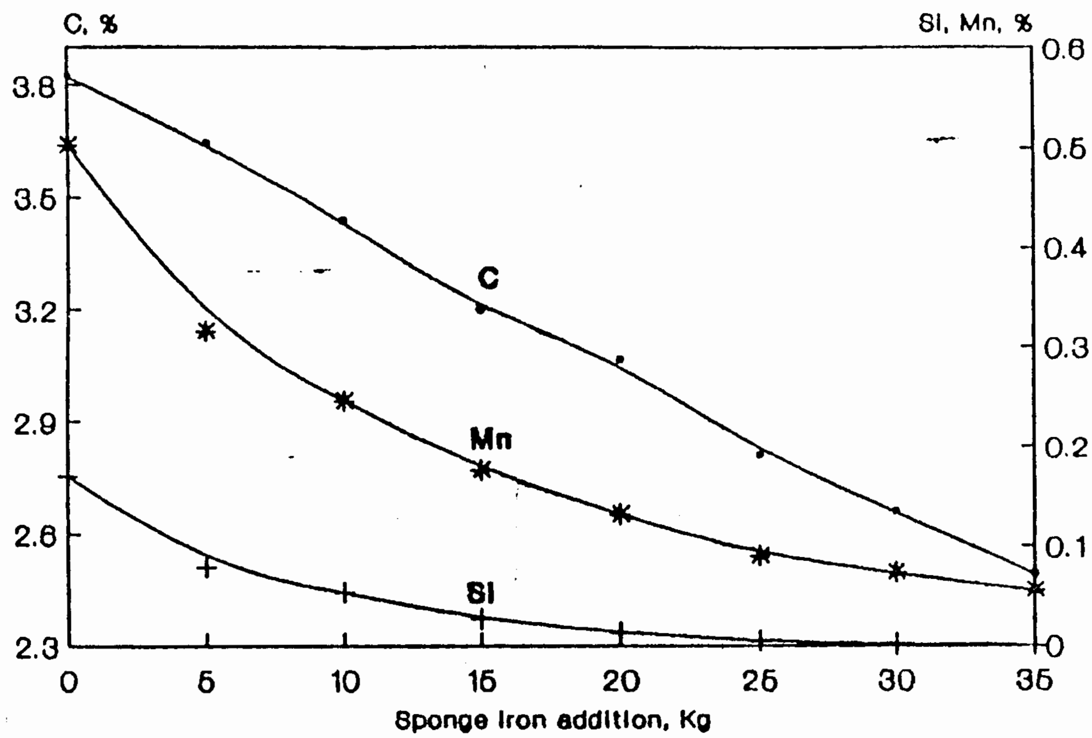


Fig. (1.11) : Effect of sponge iron addition on C,Si,Mn% in steel scrap pool metal.

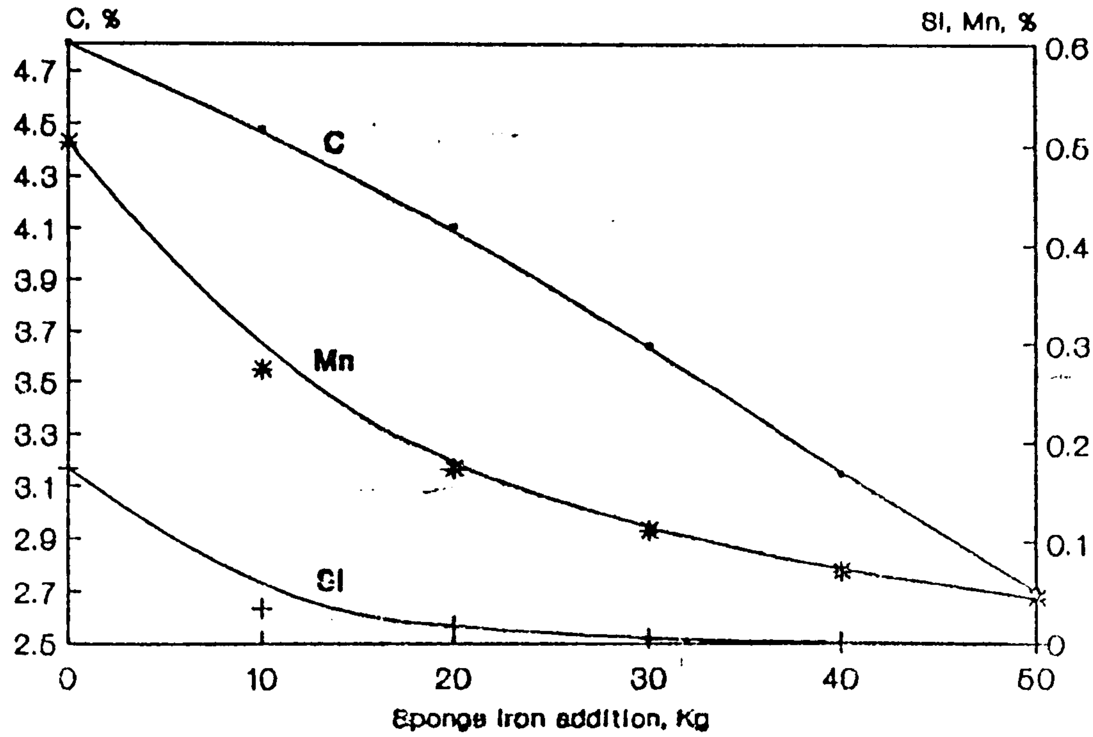


Fig. (1.12) : Effect of sponge iron addition on C,Si,Mn% in steel scrap pool metal.

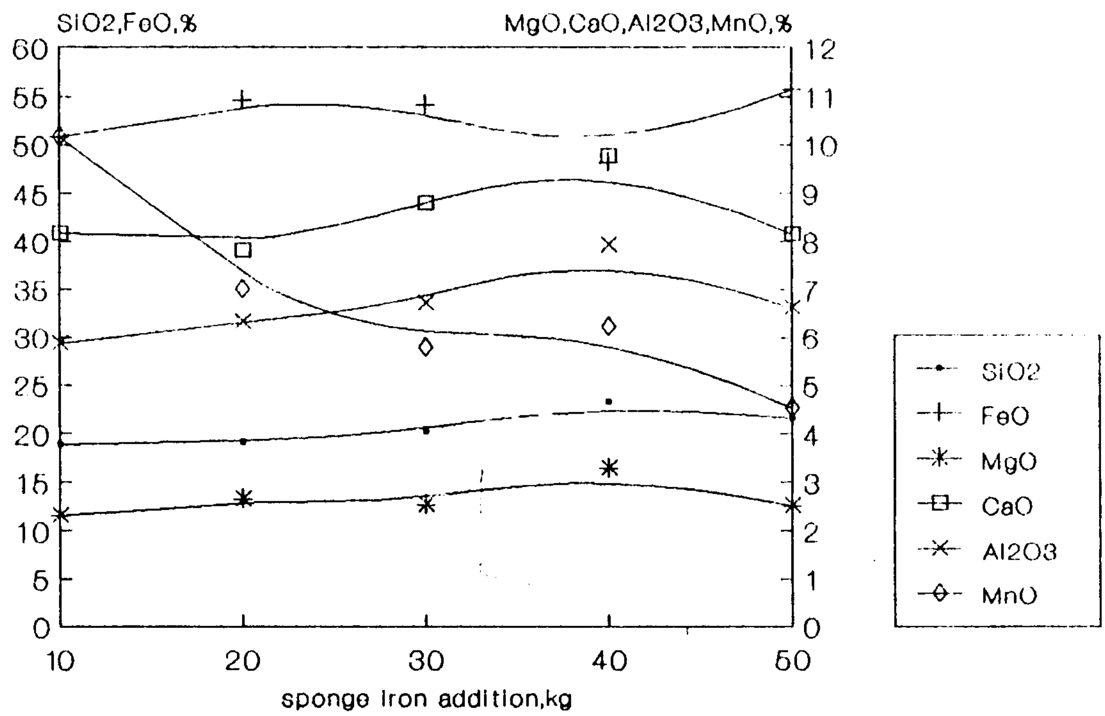


Fig. (1.13) : Behaviour of slag resulting from addition sponge iron on steel scrap.

in the latter. Addition of sponge iron in percentages of 20, 35 and 60% resulted in the decrease of Mn-content from 2.0 to 1.1, 0.5 and 0.1%, respectively. The same trend was noticed with P-content, which was decreased from 0.45% to 0.03 when adding 50% sponge iron to the Egyptian pig iron. This influence of sponge iron is of significant importance as the high Mn- and P-contents of the Egyptian pig iron represented a serious obstacle towards its use as a foundry material until now. This result will certainly open new possibilities for using the locally produced pig iron as a foundry material, if added in the appropriate proportions with the sponge iron.

Analysis of the composition of the bath shows that the Mn-contents decreased more rapidly when starting with a molten pool of steel scrap of lower C-content, Fig. (1.14). This suggests that under the conditions of these tests, the higher carbon content in the bath tended to make carbon the more active reducing agent.

Slag composition

The variation of slag analysis with increased sponge iron addition to molten pools of Egyptian pig iron (EPI) steel scrap (ST.SC.) and imported pig iron of Russian origin (RPI) is shown in Figs. (1.15) to (1.17). It is noticed that the decrease of FeO in slag is usually associated with an increase in SiO_2. The residual FeO in the sponge iron seems to be reduced partly by means of silicon and partly by means of carbon. The ratio of FeO reduced by these two elements depends on the melting temperature and the carbon-silicon activity ratio. It is shown from the slag analysis that the highest degree of FeO reduction takes place with a molten pool of the Egyptian pig iron with relatively high contents of C and Si, whereas the minimum degree of reduction (i.e. maximum FeO-content in the slag) is noticed with molten pool of steel scrap of lower C and Si contents.

The results of Fig. (1.17) show that manganese also plays a certain role in FeO reduction. FeO oxidizes Mn from the molten pool. The high MnO-contents of slag are associated with using molten pool of higher Mn-content; the manganese here is oxidized by FeO in sponge iron.

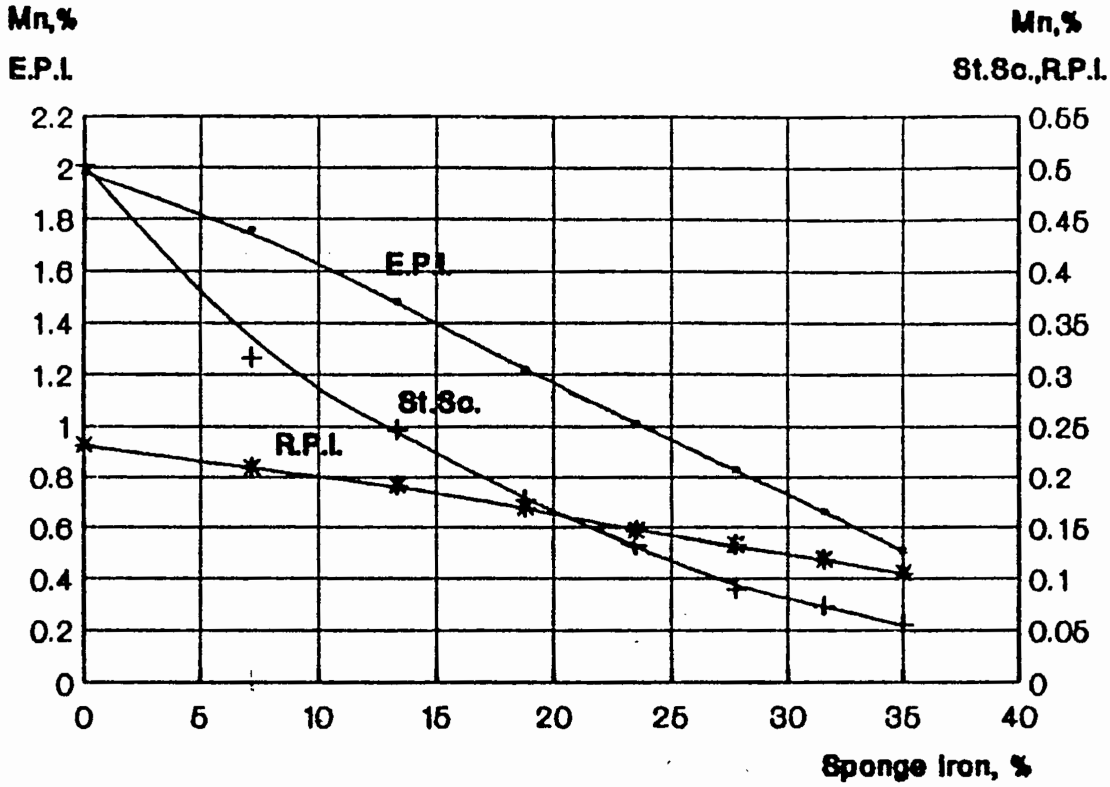


Fig. (1.14) : Change of Mn% in pool metal with sponge iron addition.

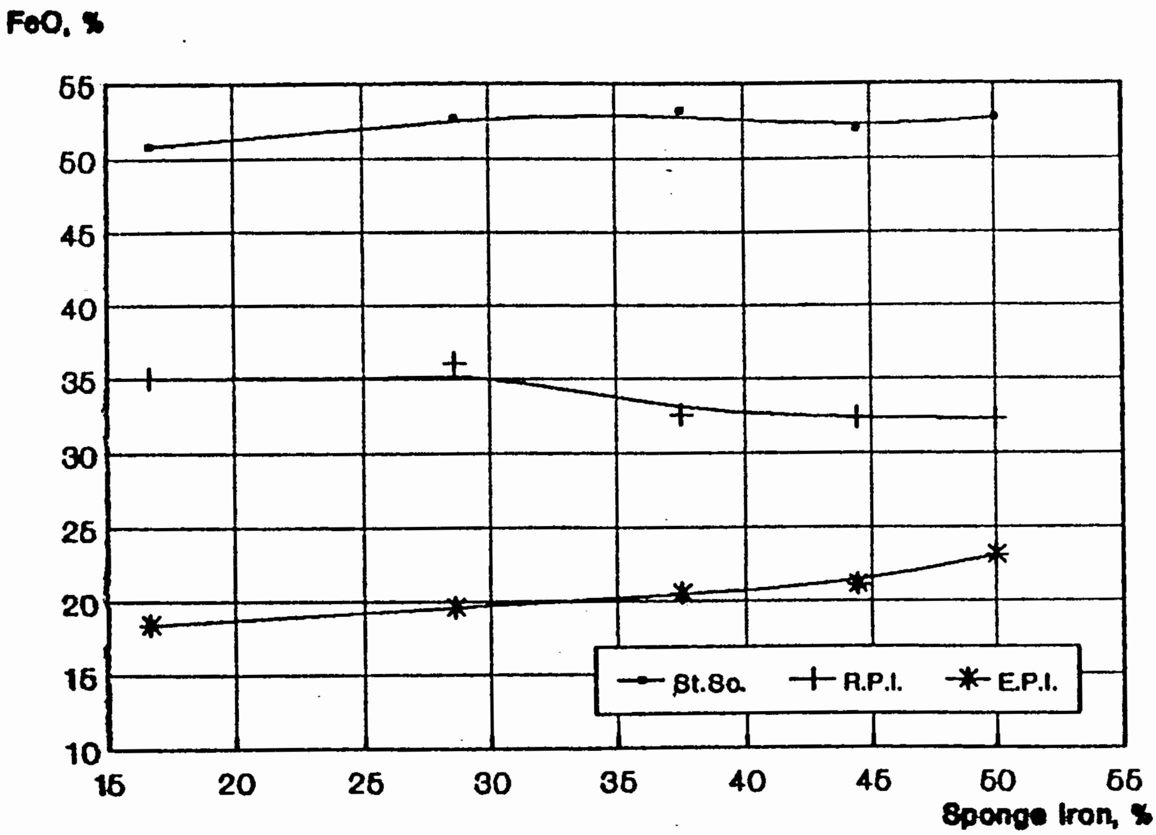


Fig. (1.15) : Variation of FeO-content in slag with sponge iron addition.

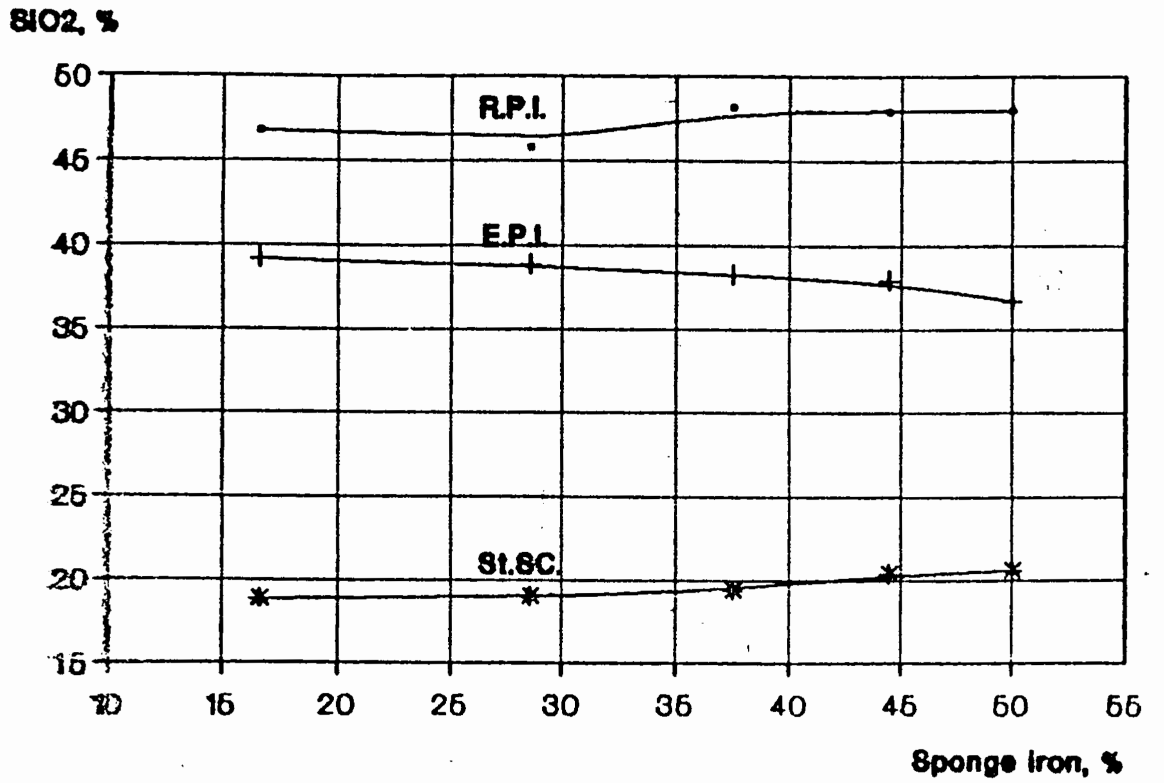


Fig. (1.16) : Variation of SiO_2 content in slag with sponge iron additions.

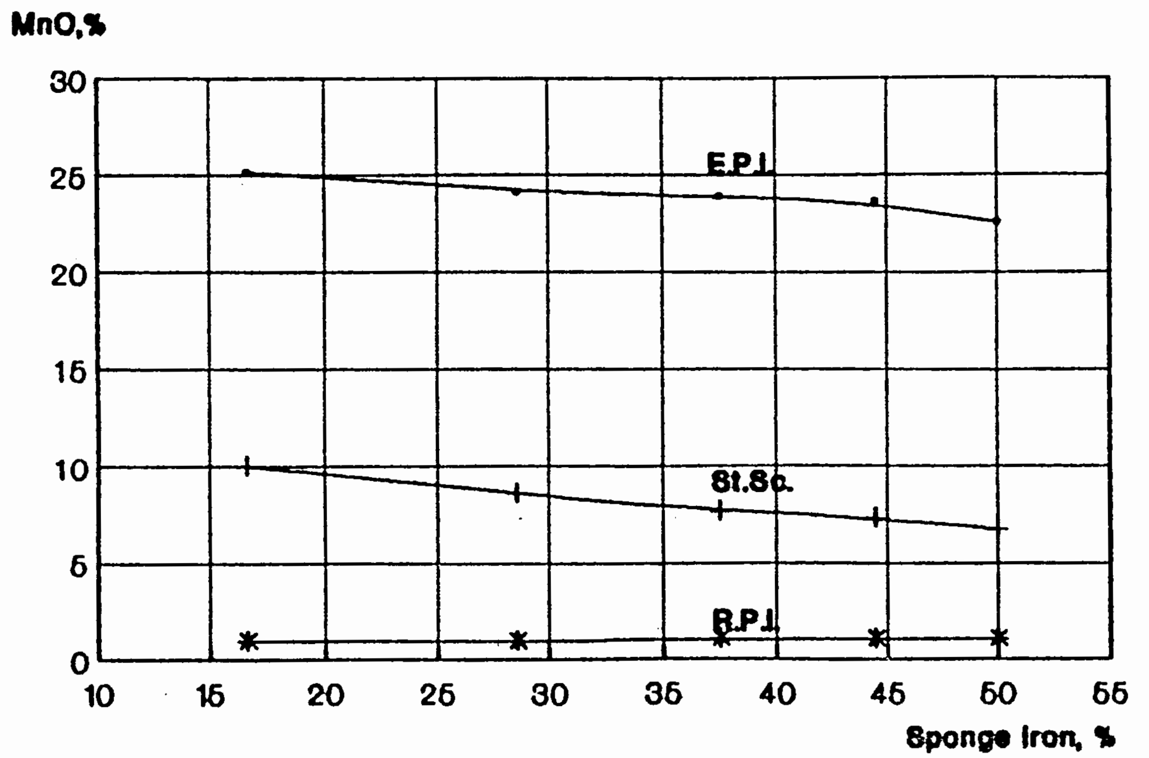


Fig. (1.17) : Variation of MnO-content in slag with sponge iron additions.

X-ray analysis of the formed slags showd that iron, silicon and manganese in the slag take the forms of Fe_2O_3, $(Fe,Mn)_2SiO_4$ and Fe_2SiO_2, Fig. (1.18).

With the scope of the present work, it could not be observed that the refractory life of the induction furnace was effected by the increased slag formation. Nevertheless, it may be expected that if sponge iron is used regularly, the refractories must match the analysis of the gangue components of sponge iron in order to obtain acceptable refractory life. With the results observed throughout this work, it may be concluded that the low basicity of slags formed from the locally produced sponge iron, the normal quartz lining used in induction furnaces may perform very adequately.

1.8. Slag-Metal Reactions During Induction Melting

Addition of sponge iron in different proportions (20-50%) to the Egyptian pig iron pool metal caused changes in the chemical composition of the hot metal poured out of the furnace. Figs. (1.6) to (1.9) show the change of carbon, silicon and manganese contents during addition of 20, 35 and 50% sponge iron to the pool metal, respectively. A gradual decrease in the C, Si and Mn contents can be seen with the increase of the amount of sponge iron added. Figs. (1.19) and (1.20) for sulphur and phosphorus, respectively, indicate the decrease of the contents of both elements due to sponge iron addition at different proportions. Therefore, using 50% sponge iron in charge with the Egyptian pig iron used in this investigation ends up with a hot metal having the following composition :

C : 2.08, Si : 0.014, Mn : 0.081, S : 0.013 and P : 0.225

The decrease in the contents of the above mentioned elements due to sponge iron addition can be attributed to two main reasons. The first one is the dilution which resulted from the addition of sponge iron with lower contents of C, Si, Mn, S and P compared to those in the Egyptian pig iron. The second reason is the transfer of the above mentioned elements from the hot metal to the slag due to slag/metal reactions. In order

Element	%	Element	%
Si	18.74	Al	2.79
Fe	15.10	Mn	21.14
Mg	1.26	Ni	0.009
V	0.18	Cr	0.05
Ca	5.85	C	0.44

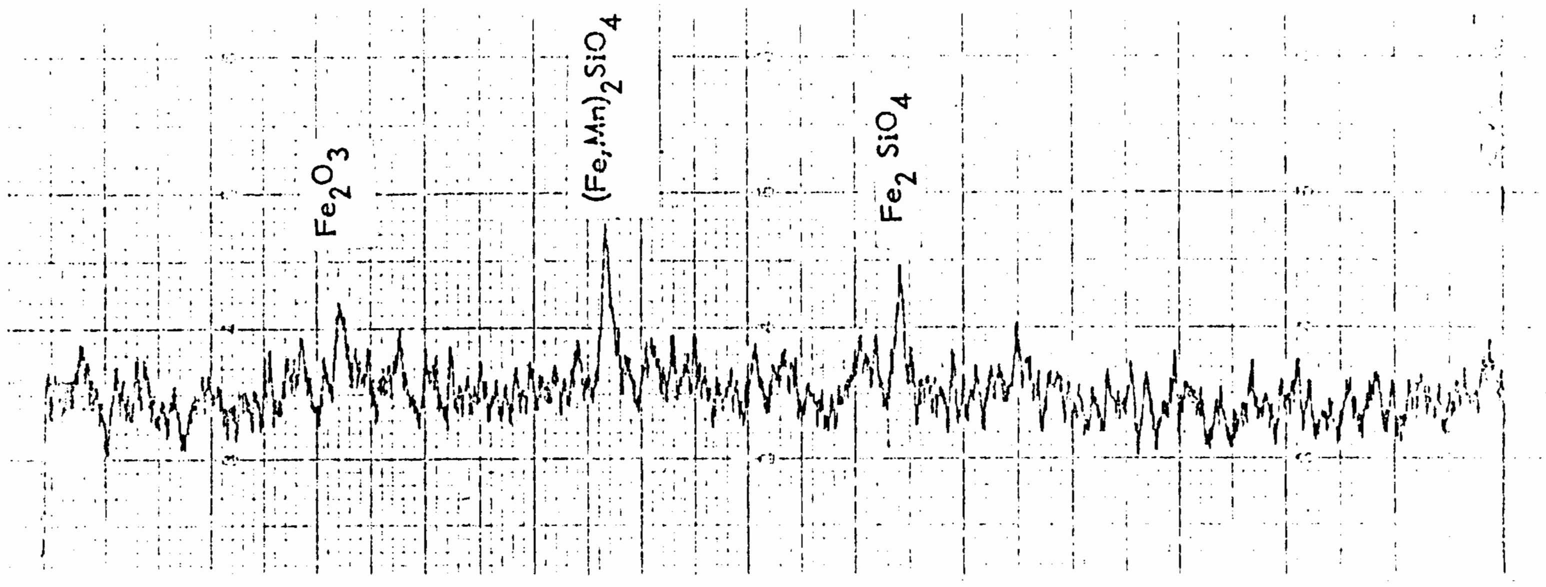


Fig. (1.18) : An example of the chemical analysis of heat (6% S.I. and 94% E.P.I.) at the X-ray chart of the same slag.

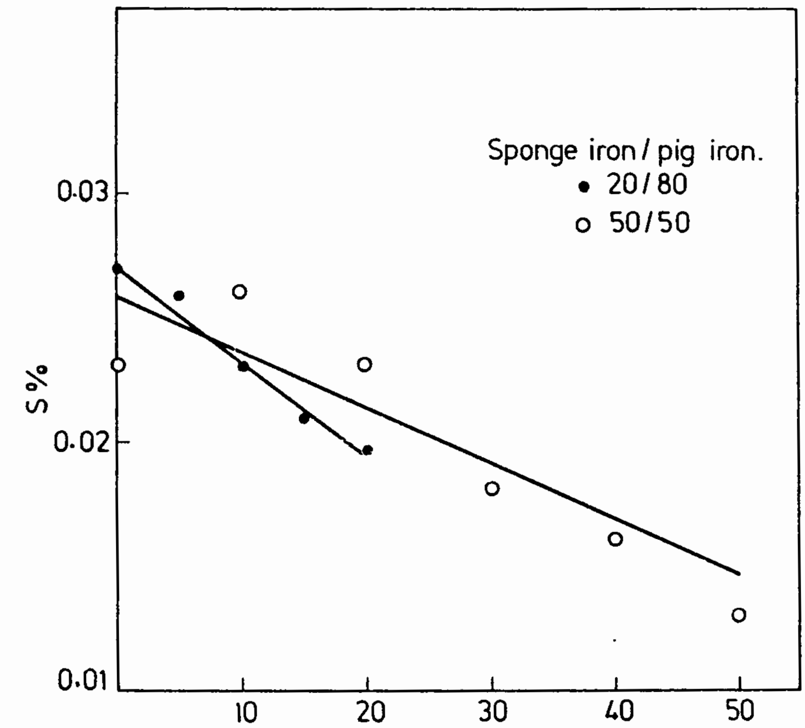


Fig. (1.19) : Variation of S-content during addition of sponge iron.

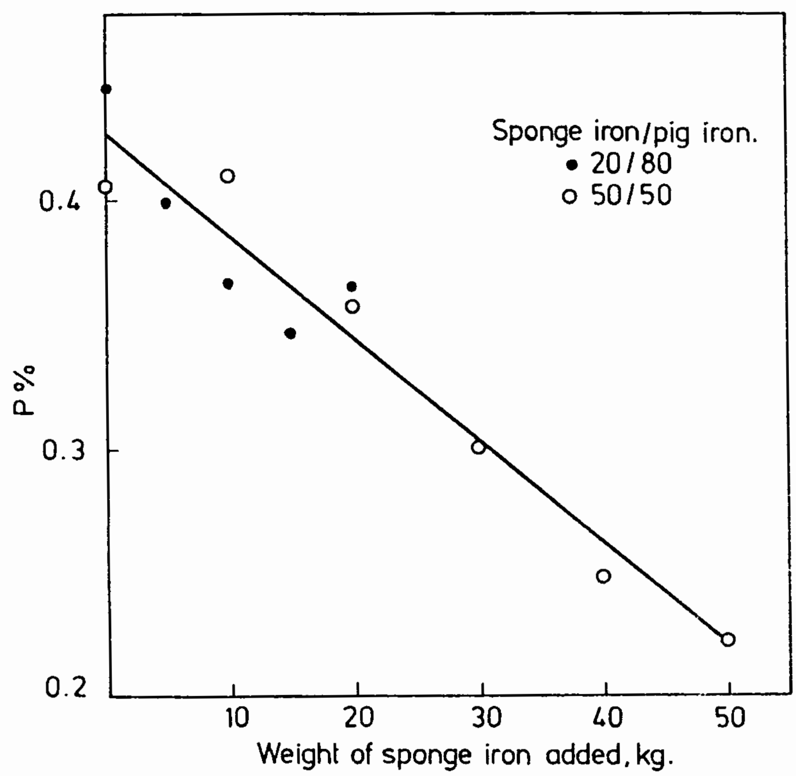


Fig. (1.20) : Variation of P-content during addition of sponge iron.

determine which of the two reasons contributes to the decrease of the elements in the hot metal, calculations were made to determine the composition of the hot metal if dilution was the only factor to be considered. The obtain composition was then compared with the actual hot metal composition. If the actual element content in the metal is equal to the calculated value, this means that the decrease of the element composition is mainly due to the dilution effect. On the other hand, when the calculated value is greater than the actual element content, this means that some of the element in the metal is consumed in a chemical reaction and transferred to the slag. The difference between the calculated and actual values of the element content will be called, hereinafter, the element removal. The fraction of the amount of the element present in the metal, after considering the effect of dilution, which removed to the slag will be called the percent removal.

Figures (1.21) to (1.23) show the variation of the percent removal of carbon, manganese and silicon during addition of 20%, 35% and 50% sponge iron to Egyptian pig iron pool metal, respectively. It can be noticed that the percent removal of silicon is greater than that of manganese while carbon shows the lowest removal values for the three proportions of sponge iron addition. The Si, Mn and C in the hot metal react with FeO in the sponge iron according to the following reactions :

$$2\ FeO + Si = 2\ Fe + SiO_2$$
$$FeO + Mn = Fe + MnO$$
$$FeO + C = Fe + CO$$

forming SiO_2 and MnO which are transferred to slag and CO gas which evolves out of the system. The temperature of the hot metal was kept around 1400°C during sponge iron addition. At this temperature, the affinity of Si to oxygen in FeO is greater than that of Mn while C shows lower affinity as can be concluded from the ΔG values calculated at 1400°C and given below :

$$\Delta G_{SiO_2} = -158.20 \text{ k.cal./mole}$$
$$\Delta G_{MnO} = -\ 67.42 \text{ k.cal./mole}$$
$$\Delta G_{CO} = -\ 56.21 \text{ k.cal./mole}$$

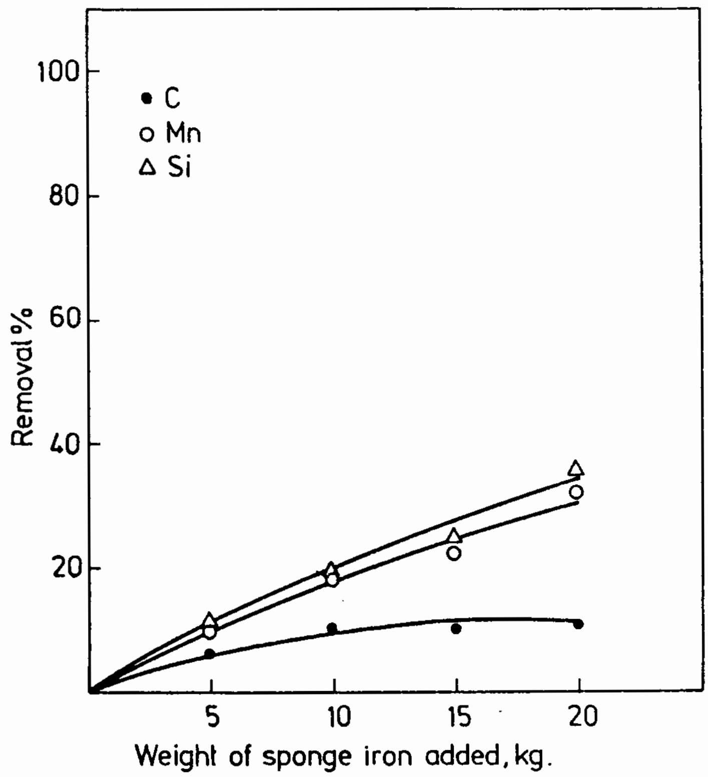


Fig. (1.21) : Variation of the percent removal of C, Mn and Si during addition of 20 kg sponge iron to 80 kg pig iron pool metal.

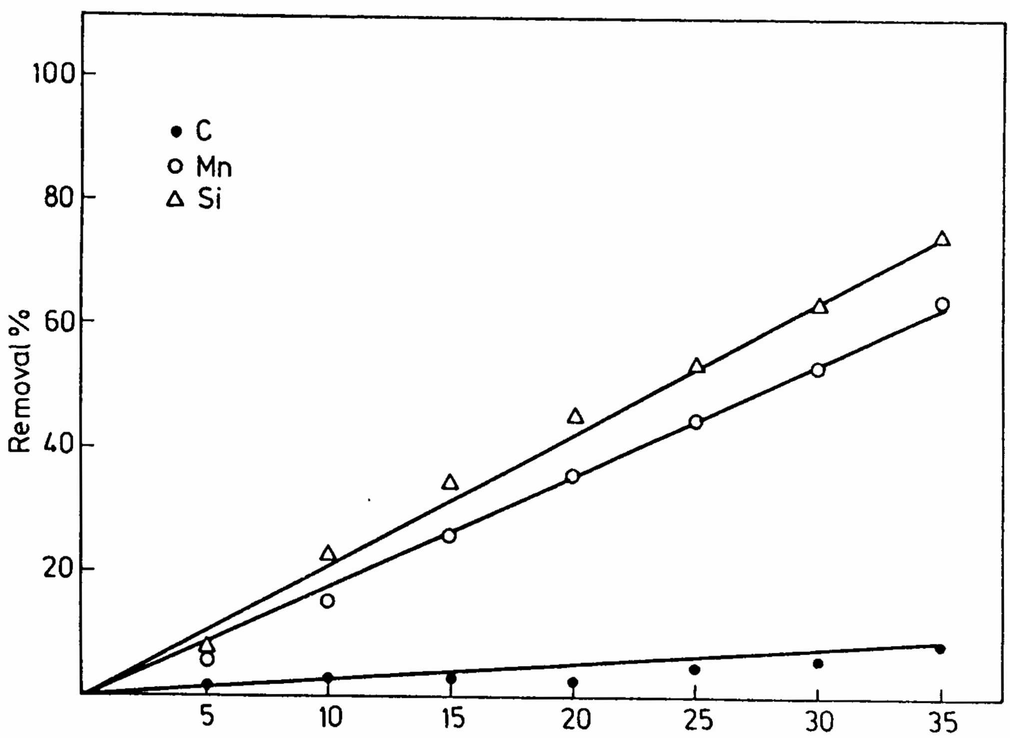


Fig. (1.22) : Variation of the percent removal of C, Mn and Si during addition of 35 kg sponge iron to 65 kg pig iron pool metal.

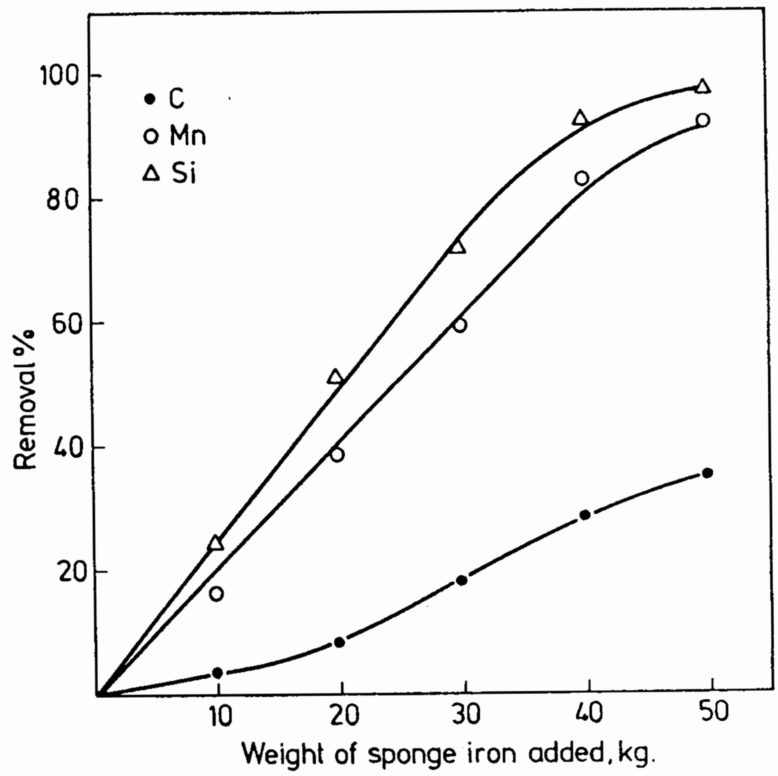


Fig. (1.23) : Variation of the percent removal of C, Mn and Si during addition of 50 kg sponge iron to 50 kg pig iron pool metal.

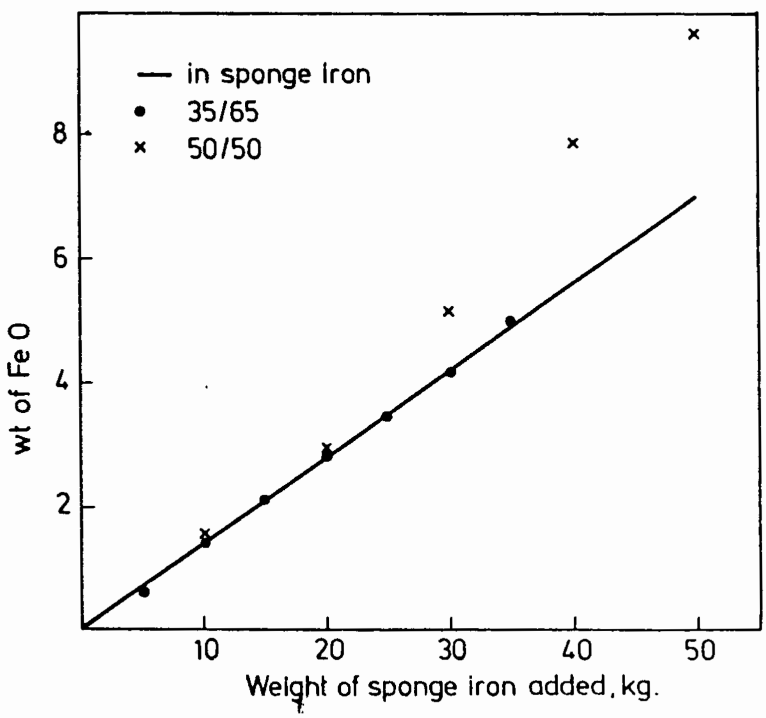


Fig. (1.24) : FeO balance in the sponge iron addition to pig iron pool metal.

Therefore, silicon is removed from the hot metal to the slag in greater proportions compared to that of manganese which in turn is removed in greater proportions than carbon.

In order to check how far reactions with FeO shares to the removal of Si, Mn and C from hot metal to slag, calculations on the availability and consumption of FeO in the system were made. The amount of FeO added to the system by sponge iron charging was calculated and given in Fig. (1.22) as a straight line. The amount of FeO that would have been consumed for reaction with Si, Mn and C to remove these elements out of the hot metal, assuming that reaction with FeO was the only way for doing that, was also calculated and given in Fig. (1.24) for charging of 35% and 50% sponge iron to the hot metal pool. The FeO weight values for the run in which sponge iron constitutes 35% of charge were very closely scattered around the straight line as shown in Fig. (1.24). This is an indication that FeO added to the system with sponge iron was all consumed in reactions with Si, Mn and C in the hot metal. On the other hand, in the runs in which 50% sponge iron was used in the charge, the FeO values were greater than the FeO weight added with sponge iron and indicated as straight line in Fig. (1.24). The excess amounts of FeO required for reactions with more Si, Mn and C in the hot metal were provided by FeO produced as a result of sponge iron oxidation during heating and melting. The oxidation process took place in runs where 50% sponge iron charge was used more than runs with 35% or 20% sponge iron. This is attributed to the greater amount of the sponge iron that should be charged to the hot metal pool at 1400°C or 50% sponge iron charge runs. Charging of sponge iron takes longer time because larger amounts of slag are formed which in turn hinder the fast melting of the sponge iron leaving it floating over the slag and allowing for considerable reoxidation of the sponge iron.

Sulphur and phosphorus contents in the hot metal decreased with the increase of the amount of sponge iron in the furnace charge as shown in Figs. (1.19) and (1.20), respectively, for 20% and 50% sponge iron in charge. Similar calculations to those performed on Si, Mn and C were done to S and P experimental data. In spite of the scattered results obtained due to the low contents of S and P which enlarged the experimental errors, it could be concluded that dilution was the main reason for decreasing the contents of these elements in the hot metal.

1.9. Metallography of Ductile Iron Produced

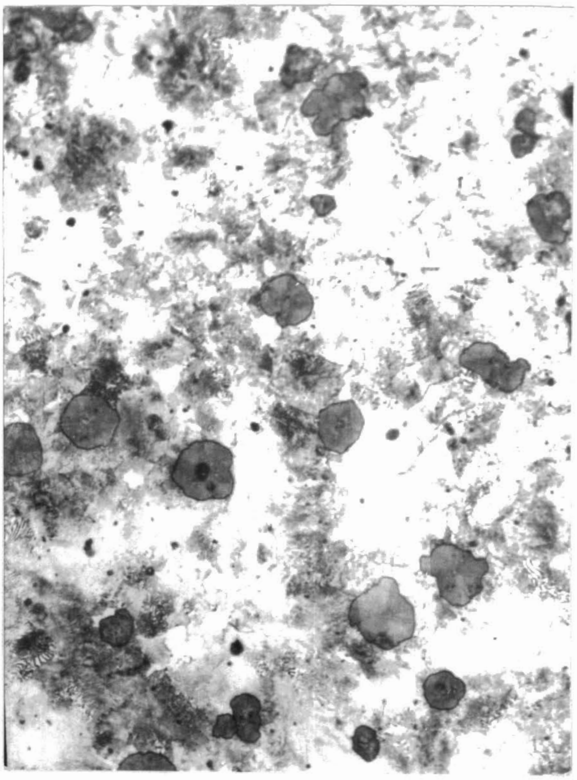
Fig. (1.25) shows that ductile iron with good structure could be produced using different sponge iron additions to the Egyptian pig iron, steel scrap as well as the imported (Russian) pig iron. By adjusting the chemical composition of the melt before pouring through controlled additions of carburizer, FeSi and FeMn it was possible to produce ductile cast iron with any predetermined matrix. Increasing the Mn-content of the melt before pouring to 0.4-0.5%, led to the formation of completely pearlitic matrix which is characterized by high strength and hardness values with lower elongation (Fig. 1.25.a). Lowering Mn-content to 0.1% and increasing Si-content to 2.0-2.5% resulted in the formation of completely ferritic structure, charactrized by high elongation (10-25%) and low tensile strength and hardness values (Fig. 1.25.b). Mixed structures of ferritic/ pearlitic matrices can be obtained by the proper combination of C, Si and Mn-contents.

Graphite incoulation

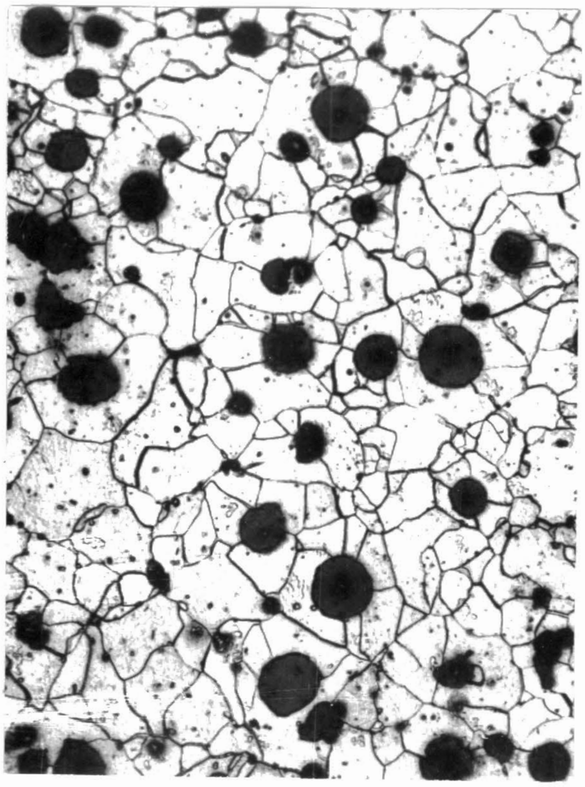
Fig. (1.26) shows that ductile iron produced from sponge iron as one of the main charge constituents responds well to inoculation by ferrosilicon. This is indicated from the large of graphite particles and the higher degree of nodularity of those particles.

It seems that sponge iron reinforces the effect of FeSi inoculant. This may be attributed to the presence of FeO; in the sponge iron. FeO - being soluble in the liquid form acts as an oxygen source causing the formation of crystalline SiO_2 and Al_2O_3 nuclei which enhance graphite nucleation.

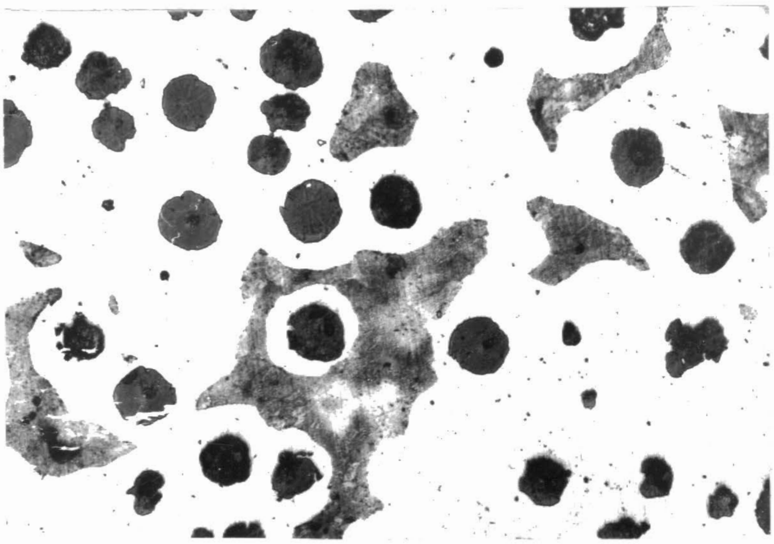
In one of our recent publications (World Foundry Congress, Dusseldorf, 1989, paper No. 21), it has been reported that, the formation of magnesium sulphide MgS due to treatment of the molten iron with MgFeSi speriodizing alloy may cause graphite to heterogeneously nucleate on MgS particles.



(a) Pearlitic Structure
20% Sponge Iron
80% Egyptian Pig Iron

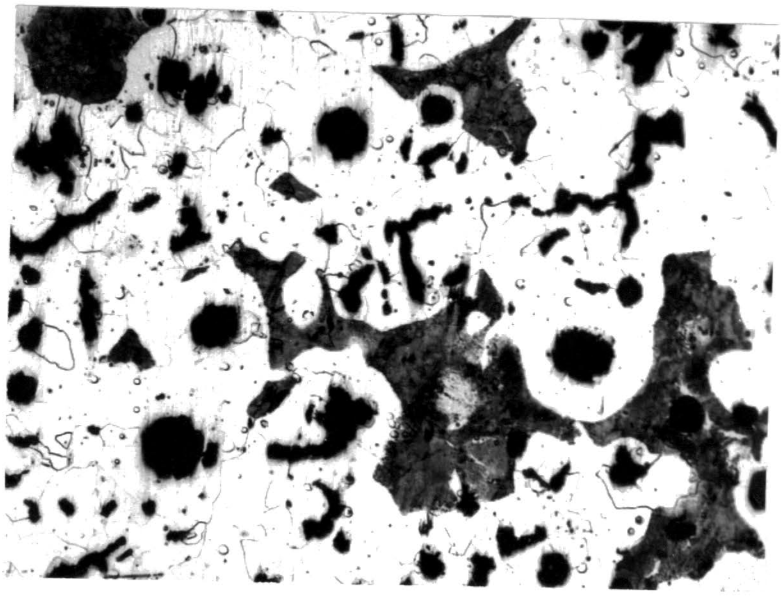


(b) Ferritic Structure
35% Sponge Iron
65% Steel Scrap

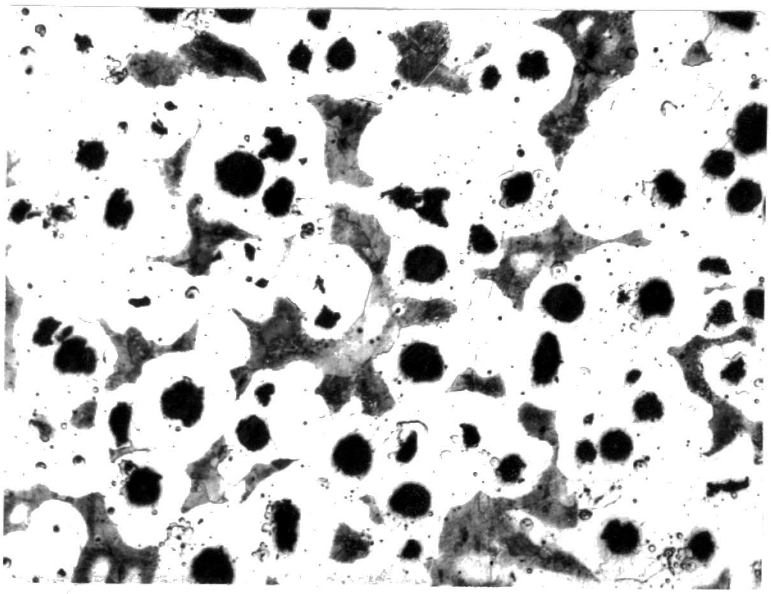


(c) Ferritic/Pearlitic Structure
50% Sponge Iron
50% Steel Scrap

Fig. (1.25) : Ductile cast irons with different matrix structures.



(a)



(b)

Fig. (1.26) : High number of graphite nodules and better graphite nodularity in ductile cast iron produced from sponge iron + steel scrap.
(a) Uninoculated. (b) FeSi inoculated.

Analysis of the heterogeneous nuclei in the centre of several graphite nodules using microprobic analysis indicated that both these two mechanisms of graphite nucleation may be active in our experiments. Fig. (1.27) shows an example of graphite nodules, where the central seed shown as a white spot was analysed. Fig. (1.28) shows that the graphite centre may contain large concentrations of Si, Al, Mg and Fe whereas Fig. (1.29) shows that oxygen is associated with these elements most probably in the form of (Fe,Mg), silicates and aluminates.

On the other hand the high peaks of Mg and S observed the centres of some other graphite nodules (Fig. 1.30) suggest that MgS plays, as well, an active role in graphite nucleation as has been reported before by the authors.

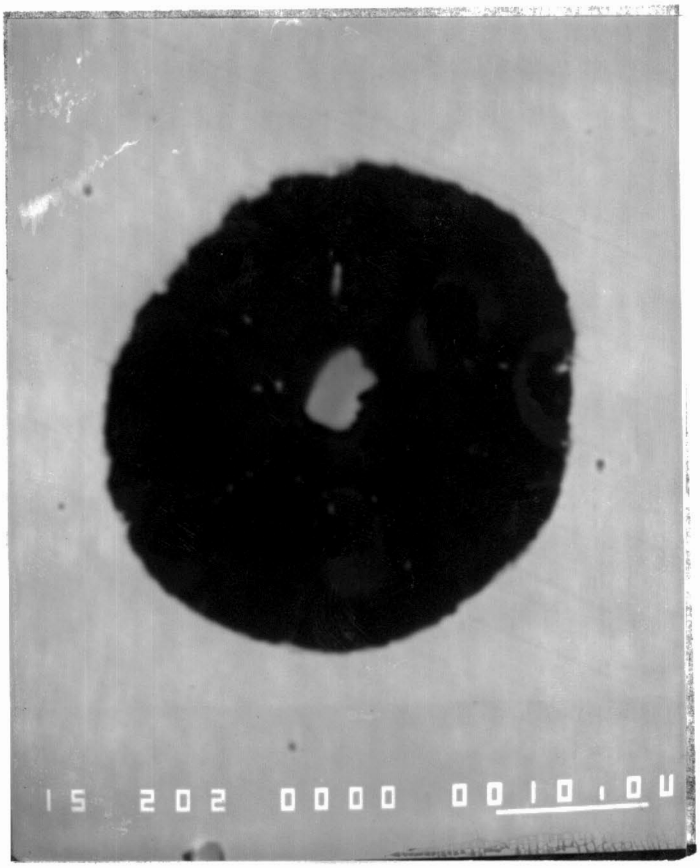


Fig. (1.27) : Central nucleus of graphite nodule.

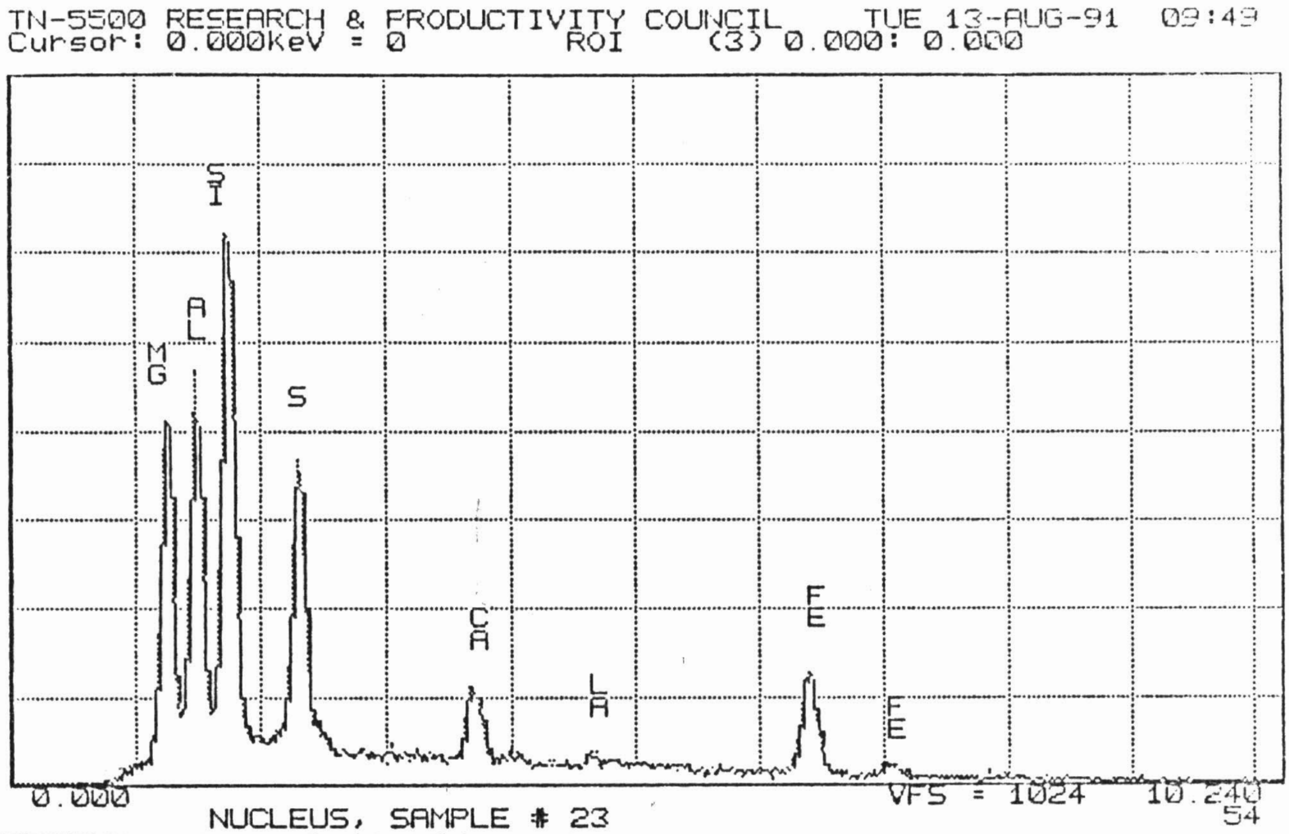


Fig. (1.28) : Higher concentrations of Si, Al, and Mg in the centre of graphite nucleus of Fig. (1.27).

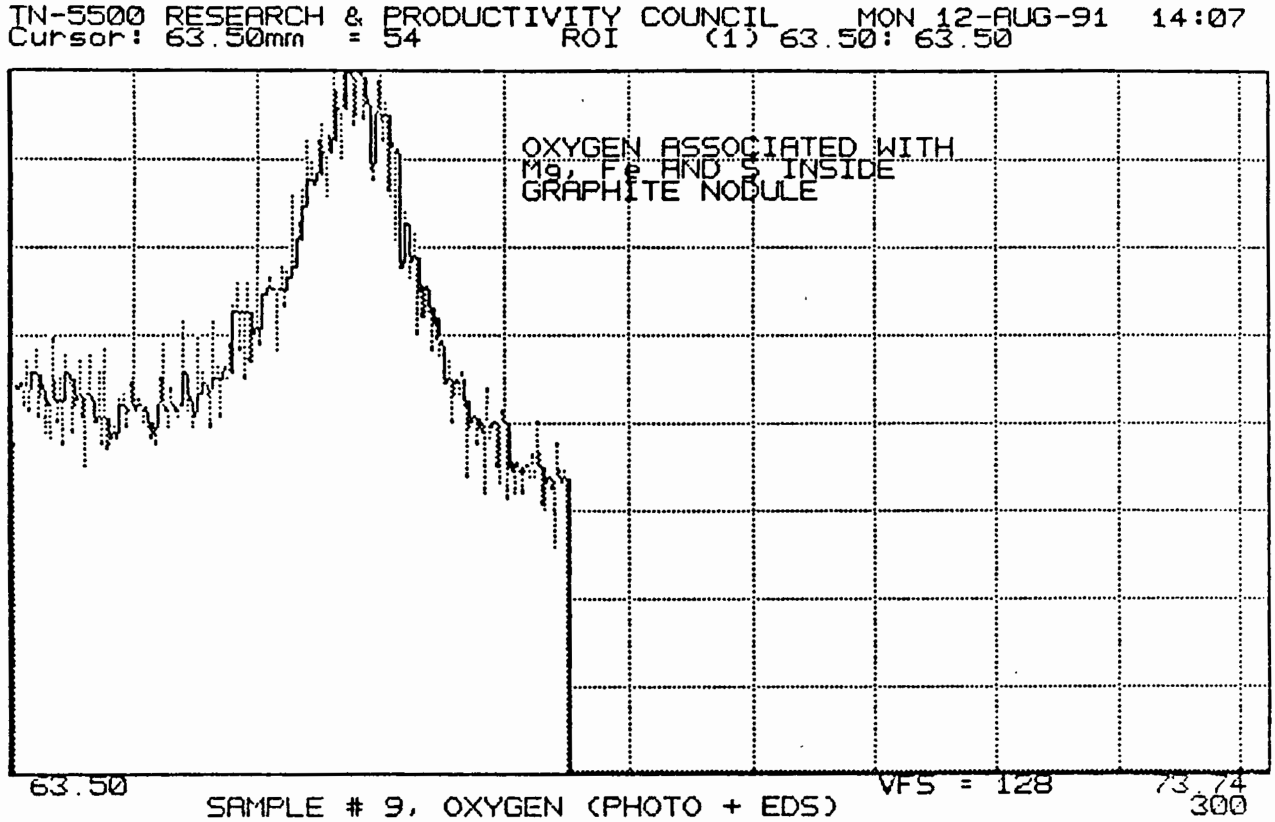


Fig. (1.29) : High oxygen concentration associated with Si, Al, Mg and Fe at the centre of graphite nodule.

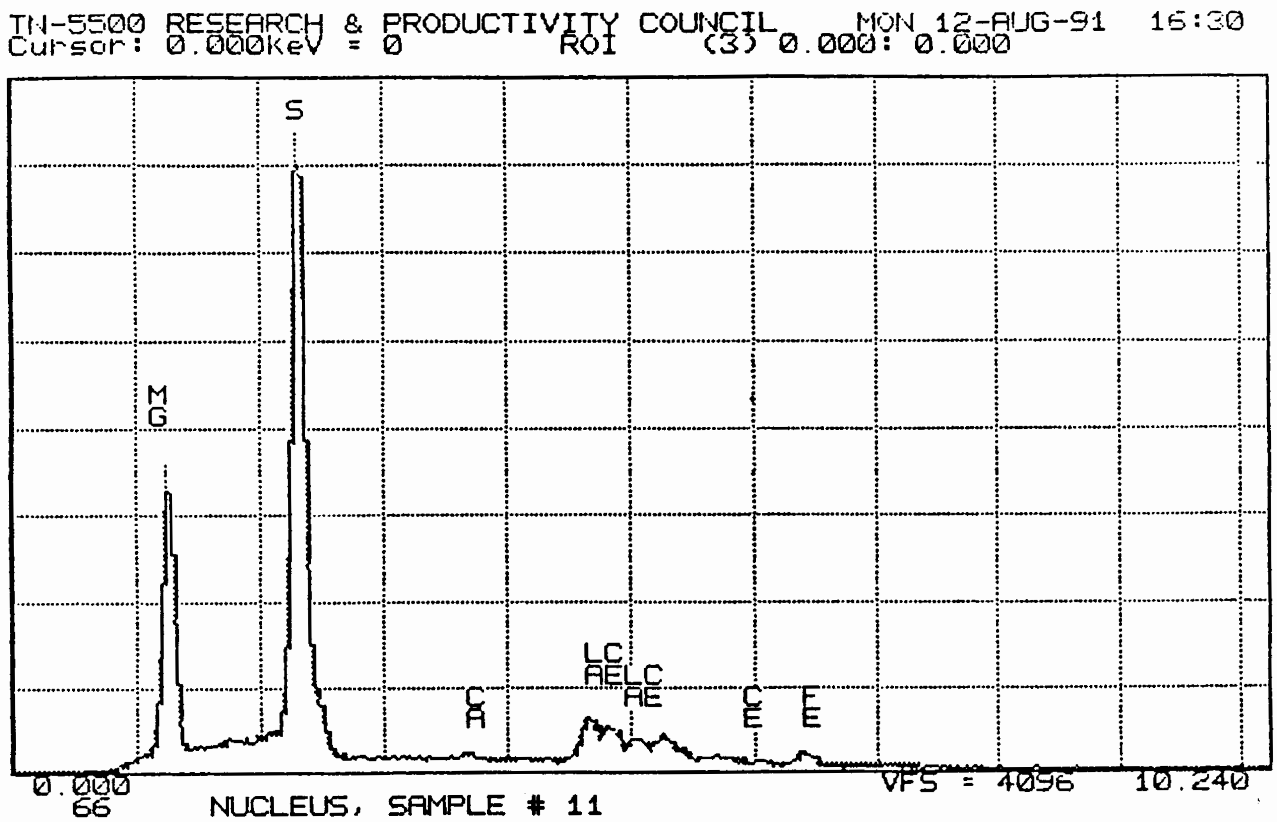


Fig. (1.30) : Graphite nucleation by MgS particles.

CHAPTER 2

FRACTURE TOUGHNESS MEASUREMENTS

2.1. Introduction

The fracture toughness of the produced ductile cast irons as well as the white alloyed cast iron was evaluated. As will be shown in the next chapter, sponge iron was utilized for production of these two alloys on both pilot as well as industrial scales.

The fracture toughness test, which measures the resistance to crack propagation, is the most extensively used test for characterizing the toughness of materials, primarily because of its excellent reproducibility and high sensitivity to small changes in the microstructure. It must be emphasized that this test has only recently been utilized to characterize white irons and, to date, has not been correlated with service performance. It should be, however, recognized that the test defines the limiting conditions under which a crack will propagate; thus, the test results may prove to be very useful in selecting alloys and treatments for new more critical applications for ductile and high-Cr white irons.

2.2. Procedure

The property K_{IC} (stress-intensity factor) determined by fracture toughness test method characterizes the resistance of a material to fracture in a neutral environment in the presence of a sharp crack under severe tensile constraint.

The greater the value of K_{IC}, the greater the stress required to produce rapid propagation and the greater the resistance of the material to brittle fracture. The critical stress-intensity factor (K_{IC}), which also is called the plane-stress fracture toughness and is expressed in unit of $MPa.m^{\frac{1}{2}}$ or $Psi.in^{\frac{1}{2}}$.

Fracture toughness measurements have been conducted in the laboratory of RPC-Fredricton under the supervision of Dr. Jiff Thornley and Mr. C. Seedman :

i) **Ductile iron :** four samples produced by melting sponge iron with steel scrap, Egyptian pig iron or imported pig iron were selected for evaluation. The chemical composition of selected irons is shown in the following table :

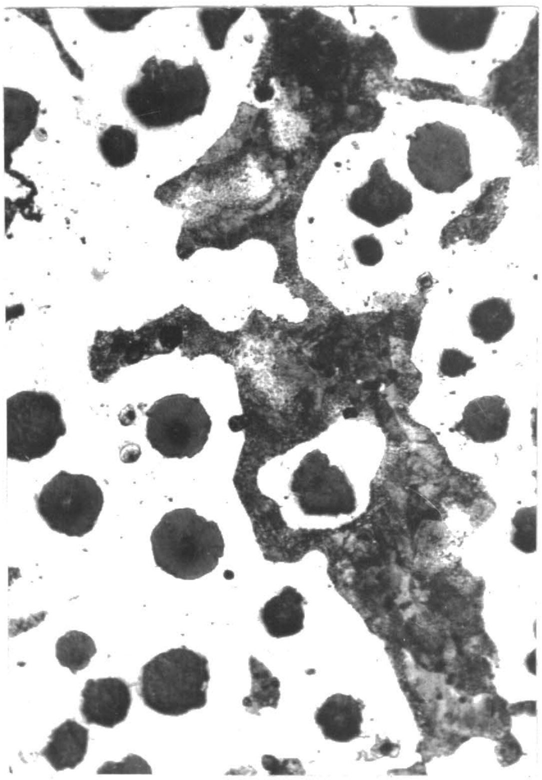
charge \ element	C	Si	Mn	S	P	Mg	CE
Sorel metal 100%	3.37	2.57	0.459	0.013	0.029	0.06	4.21
HPPI from S.I.	3.52	2.47	0.513	0.007	0.068	0.06	4.34
50% St. Sc.+50% S.I	3.31	2.67	0.469	0.008	0.030	0.06	4.20
50% EPI + 50% S.I.	3.34	2.68	0.444	0.010	0.230	0.05	4.23

The microstructures of these selected samples in the as-cast condition is shown in Fig. (2.1).

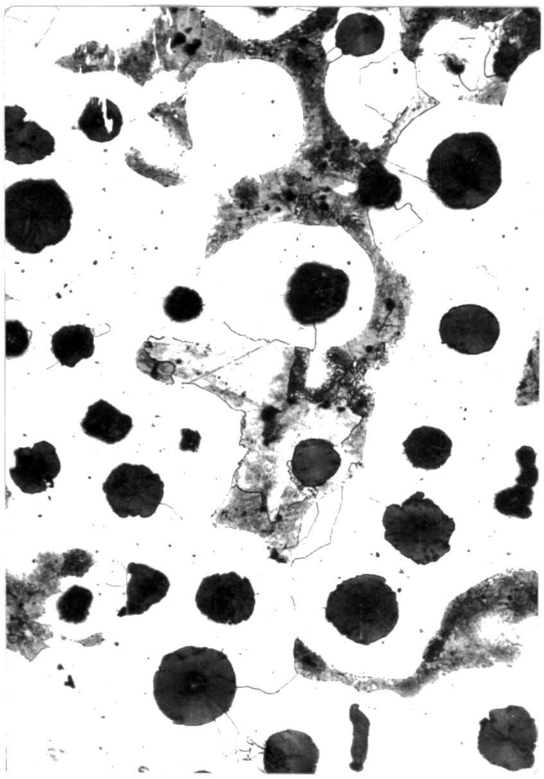
ii) Two alloys of high Cr-Mo white irons with two different C-contents (2.41 and 3.95%) were selected. The chemical composition of these alloys is shown in the following table :

sample \ element	C	Si	Mn	Cr	Mo	S	P	Ni
W2	2.41	0.48	0.45	14.65	1.71	0.04	0.06	0.1
W5	3.95	0.48	0.56	14.51	1.81	0.04	0.06	0.1

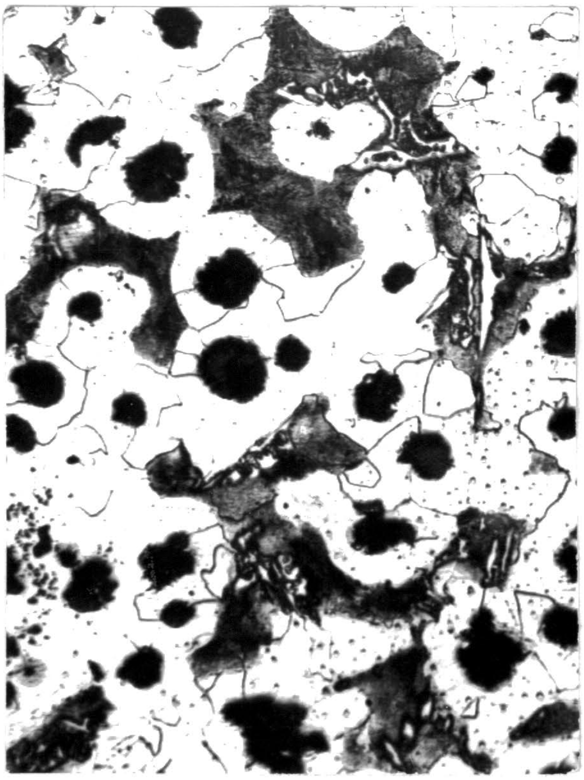
Two different levels of C-content were selected to study the effect of carbide volume fraction (CVF) on the fracture toughness of the fracture toughness of the white irons. Moreover, the two samples were subject to different heat treatment cycles to produce austenitic or martensitic matrices and hence to study the influence of the



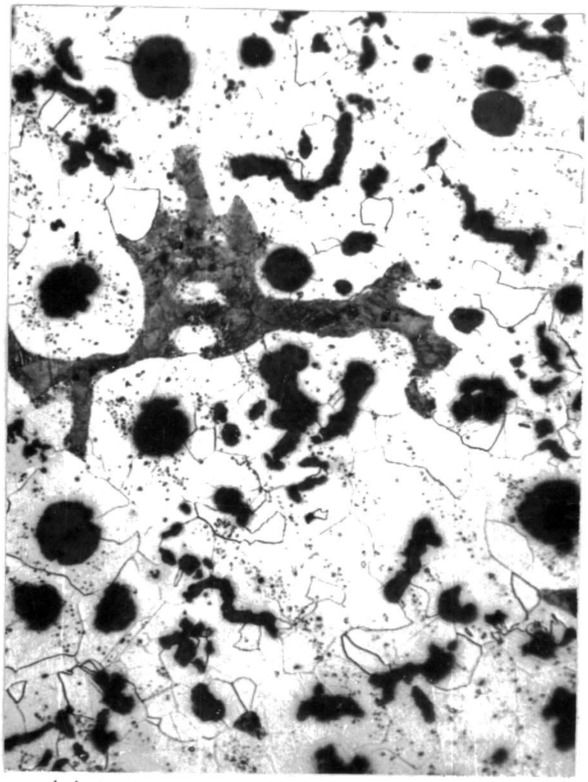
(a) 100% sorel metal.



(b) spheroidized and inoculated HPPI produced from sponge iron to EPI ratio of 3:1.



(c) 50% sponge iron and 50% steel scrap



(d) 50% sponge iron and 50% EPI

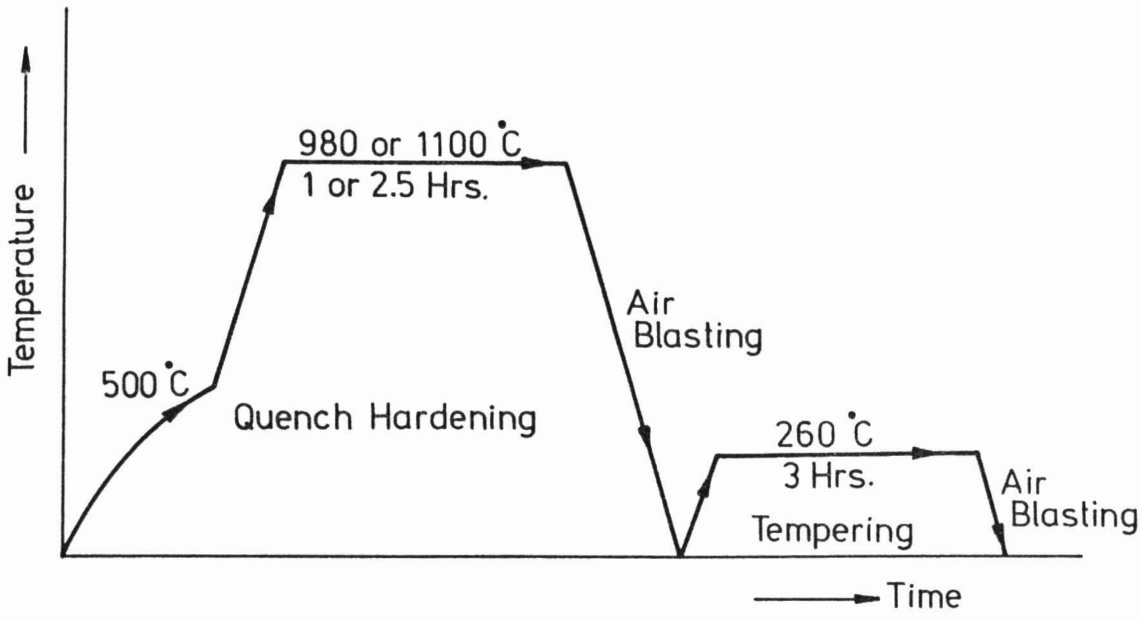
Fig. (2.1) : Microstructures of ductile cast iron specimens tested for fracture toughness and produced from different charge composition.

matrix on the fracture toughness. The heat treatment cycles adopted and the resultant microstructures are shown in Figs. (2.2) and (2.3), respectively.

2.3. Fracture Toughness Test

i) Fracture toughness tests were conducted on "INSTRON" dynamic testing system. Two machines were used to determine the material toughness. The first, was used for creating a cracking initiation in the specimens according to ASTM Designation E399-83, Fig. (2.4.a). The second machine was used for measuring the maximum load to break the specimen, Fig. (2.4.b).

ii) Compact tension test was used to determine fracture toughness properties of the studied alloys. The specimens of high Cr-Mo white cast iron were precracked with a fatigue load of 2560-3573 lbs. at 12 Hz and specimens of ductile iron were precracked with a fatigue load of 3979-4906 lbs. at 20 Hz. Before precracking, specimens were polished at the area under notch to see and measure crack length (A), as shown in Fig. (2.5). The crack length was at least 2 mm. After the specimens already precracked at a certain number of cycle, the second machine was used to break them. Before breaking the specimens, a load cell and slip gauge were used to monitor load and displacement which provided an autographic record for analysis. The slip gauge was mounted on machined knife edges and located by sticking at the specimen along loading line. Fracture toughness (K_{IC}) is calculated from the chart by using a computer program. All reported (K_{IC}) fracture toughness values are the average of at least two test values. The tests were carried out in air at 50% relative humidity and 24°C for white irons and -40°C for ductile irons as in the following table :



(a) Preheating at 500 °C.
(b) Austenitizing at 980 °C or 1100 °C.
(c) Air blasting down to room temperature.
(d) Tempering at 260 °C for 3 hrs.
(e) Air blasting down to room temperature.

Fig. (2.2) : Heat treatment cycles used to charge the matrix of high Cr-Mo white iron.

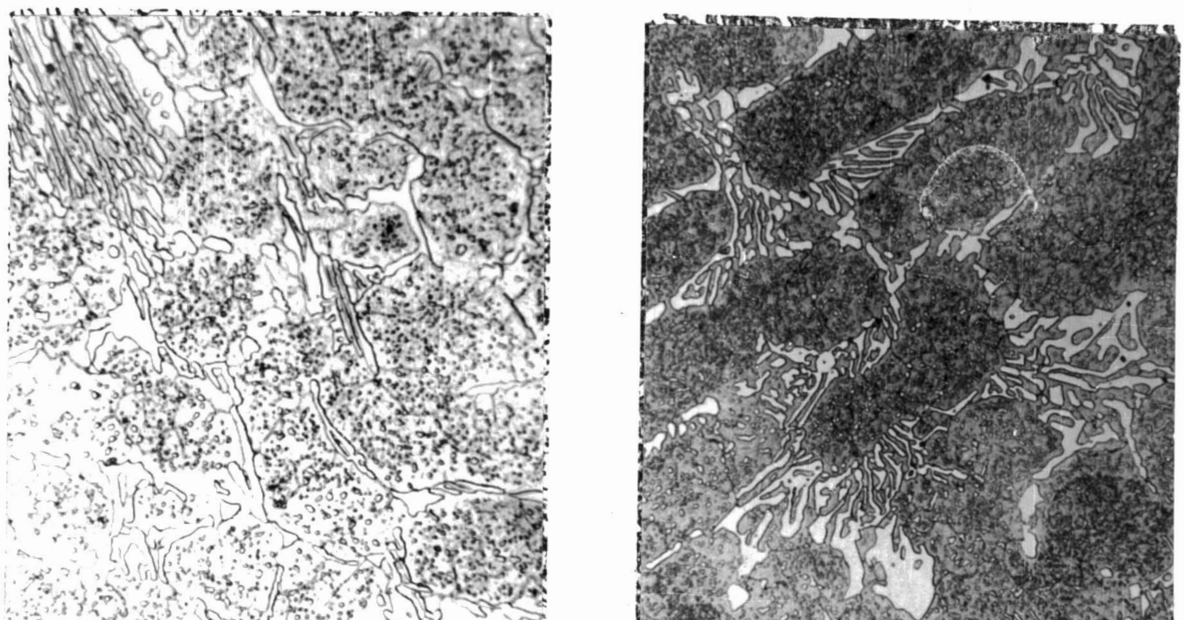
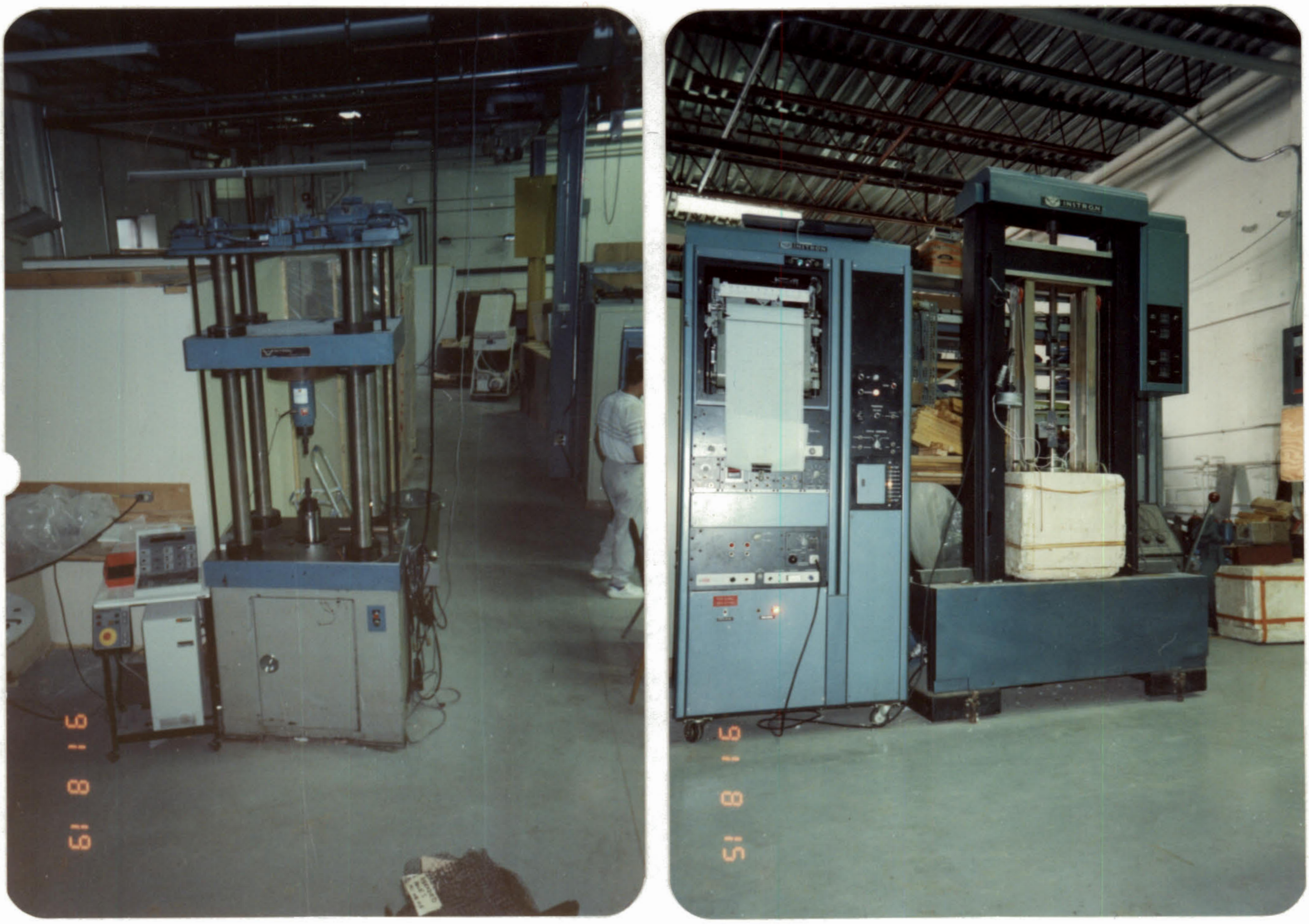


Fig. (2.3) : Microstructures of high Cr-Mo white irons. (a) Austenitic matrix. (b) Martensitic matrix.



(a) (b)

Fig. (2.4) : Fracture toughness testing machine.
(a) Precracking machine
(b) Tension machine.

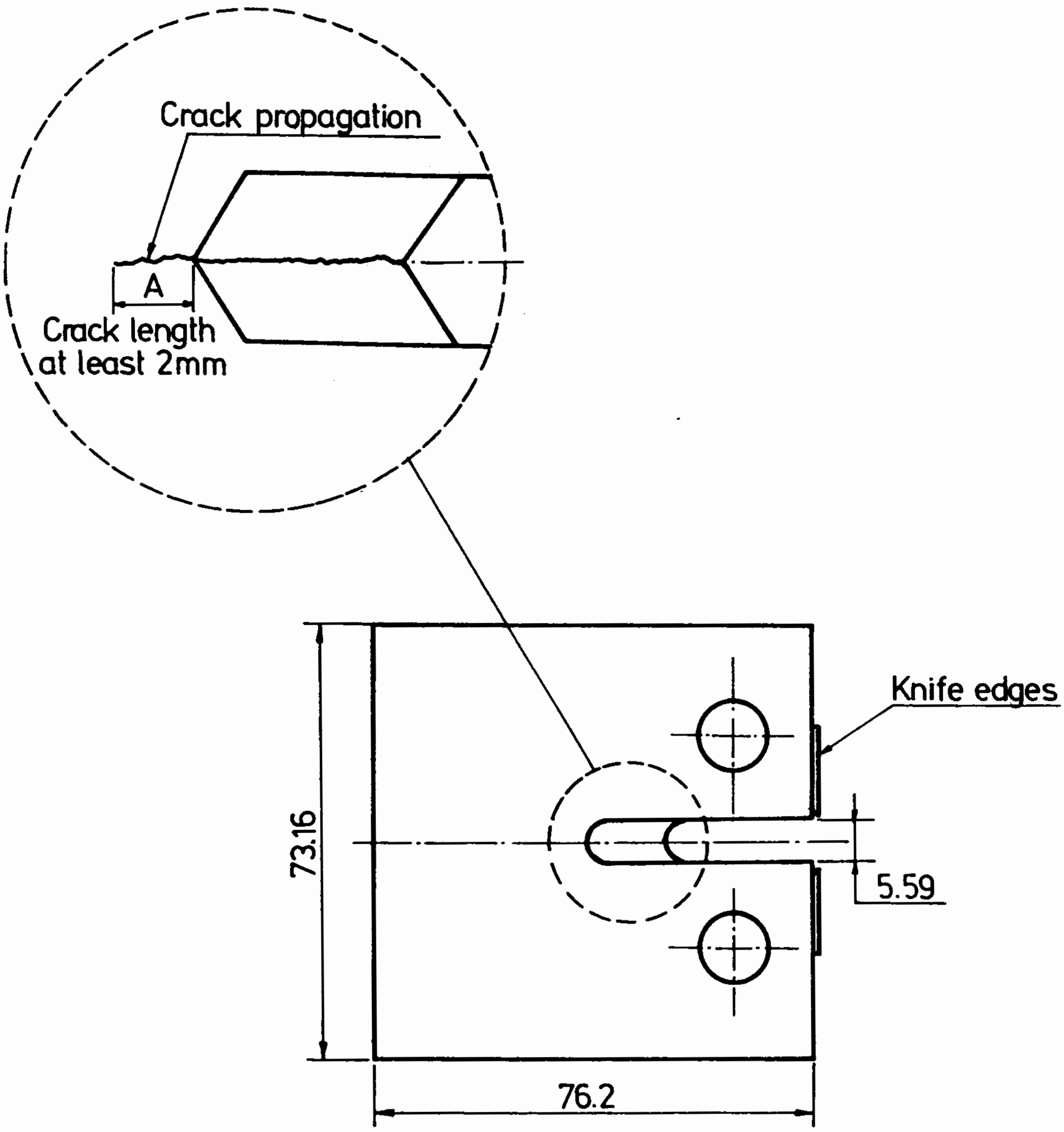


Fig. (2.5) : Cracked area of the fracture toughness specimen.

Yield and Tensile Strengths of Ductile Iron Specimens Tested at -40°C

	Yield Strength PSI	Tensile Strength PSI
(a) Sorel Metal	56000	81900
	57900	83600
	-	37400 (rejected)
(b) HPPI	59300	80000
	58700	81400
	58700	81400
	57300	81500
(c) 50% Steel scrap +	55500	79700
50% Sponge iron	58100	84300
	59900	86800
(d) 50% EPI +	66800	76000
50% Sponge iron	67000	67300
	-	64900

iii) **Test record :** A test record is made consisting of an autographic plot of the output of load-sensing transducer versus the output of the displacement gauge. Combination of load-sensing transducer and autographic a recorder is selected so that the load, P_Q, can be determined from the test record with an accuracy of $\pm$ 1. The test is continued until the specimen can sustain no further increase in load, which indicates the maximum load, $P_{max.}$.

From the output chart shown in Fig. (2.6) for white irons and Fig. (2.7) for ductile irons of the investigated specimens, K_{IC} can be calculated by using a computer program (Appendix 1) which was developed to facilitate the calculations.

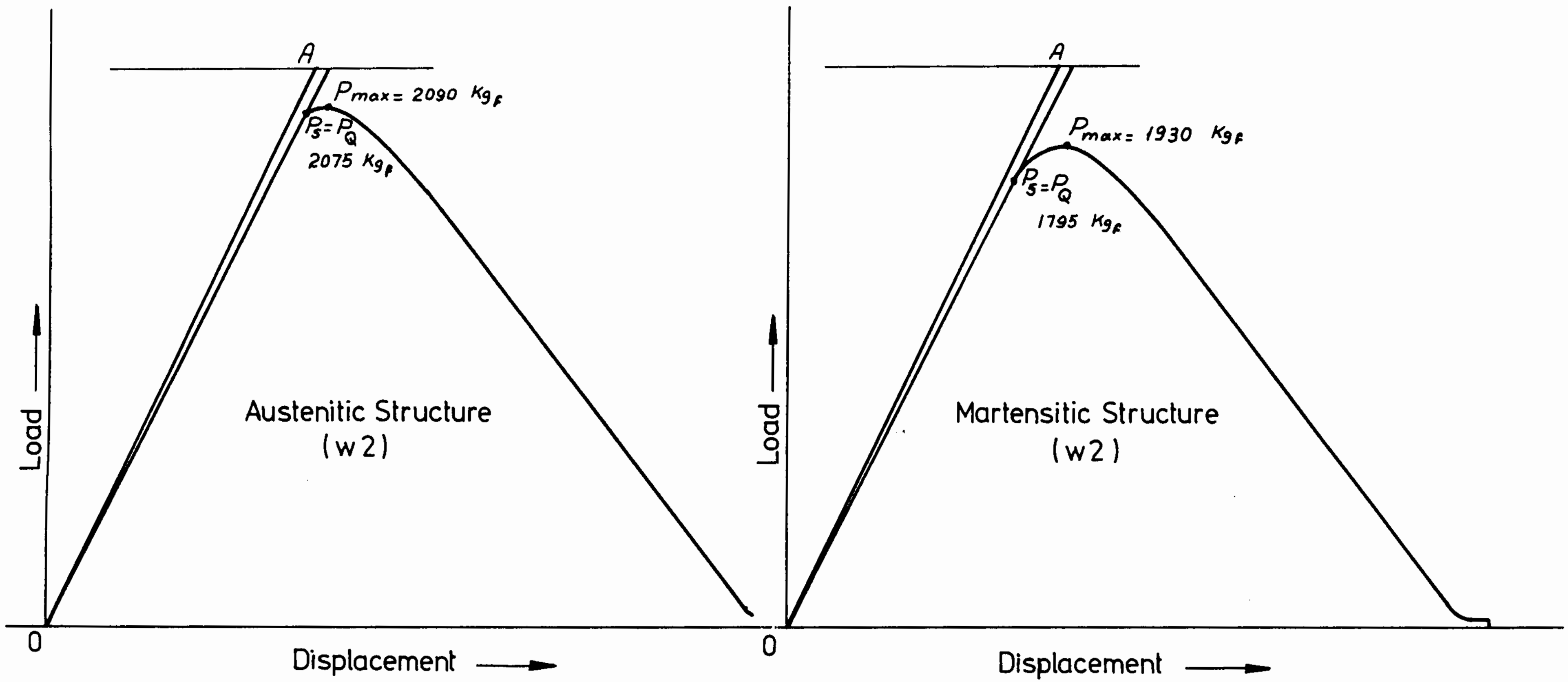


Fig. (2.6) : Output chart of the fracture toughness test of alloyed white iron specimens.

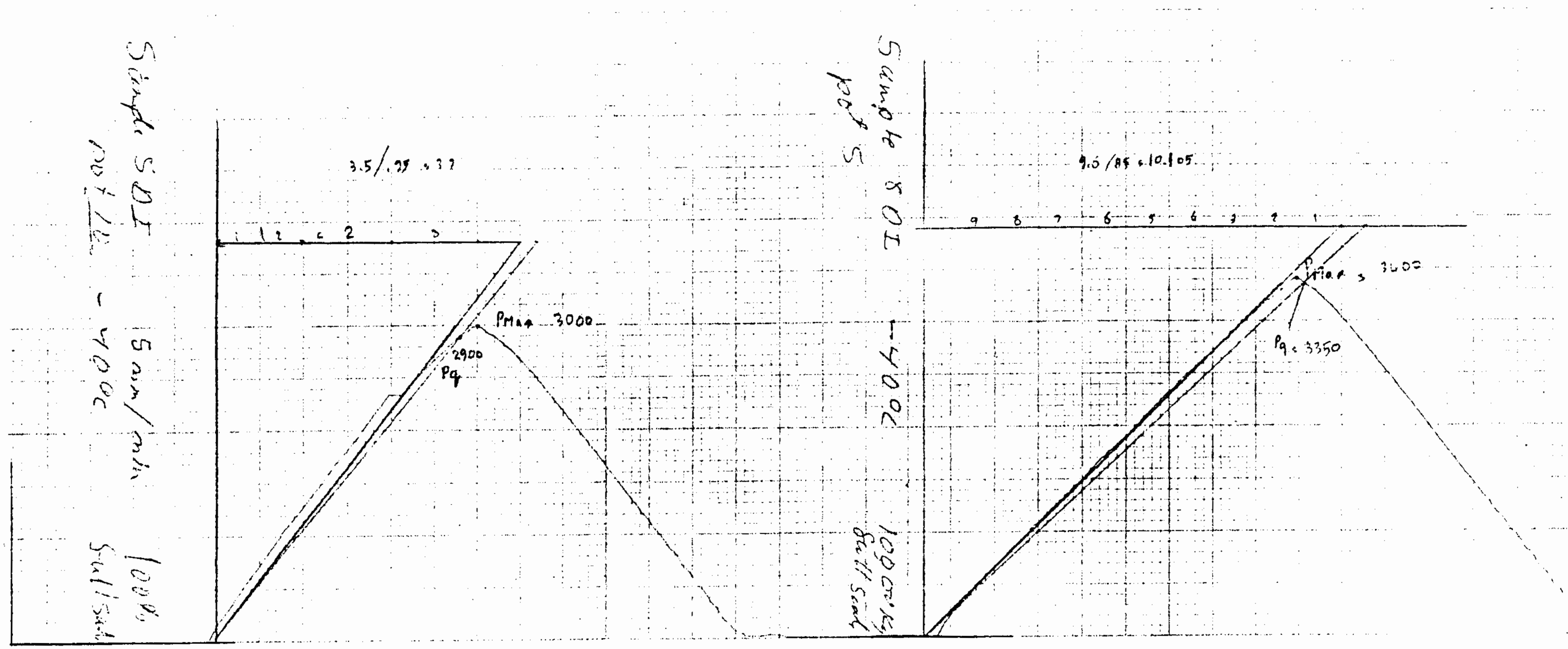


Fig. (2.7) : Output charts of fracture toughness test of ductile cast iron specimens.

2.4. Test Results

Fracture toughness measurements of the investigated alloys (K_{IC} MPa $m^{\frac{1}{2}}$) (min./max.) are shown in the following tables :

(a) Ductile Iron

Charge Composition	K_{IC} MPa $m^{\frac{1}{2}}$
Sorel metal	40.79
Sponge + Egyptian pig iron	44.68
Sponge + Sorel metal	41.69
Sponge + Steel scrap	29.75

(b) White Irons

	Annealed Pearlitic	Austenitized at 1100°C	Austenitized at 980°C
W2 C = 2.4% and CVF = 22%	28/28.4	25.5/28.9	23/27.1
W5 C = 3.95% and CVF = 36%	not measured	19/20	19.8/21.8

Fracture appearance of ductile iron samples is shown in Fig. (2.8), whereas scanning electron microscope fracture surfaces of ductile iron and white iron sampels are shown in Figs. (2.9) and (2.10), respectively.

Figure (2.10a-c) shows the fracture surfaces of K_{IC} specimens for annealed and quenched- and tempered-structures with high and low carbide volume fraction.

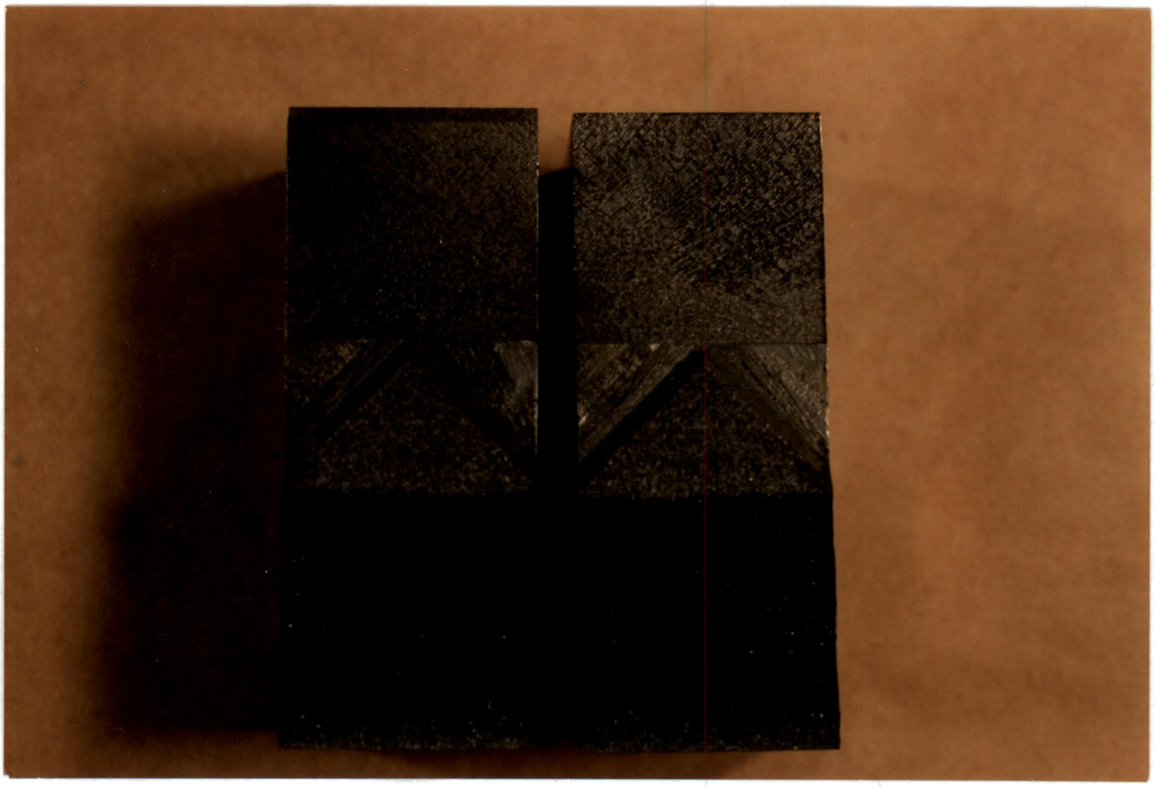
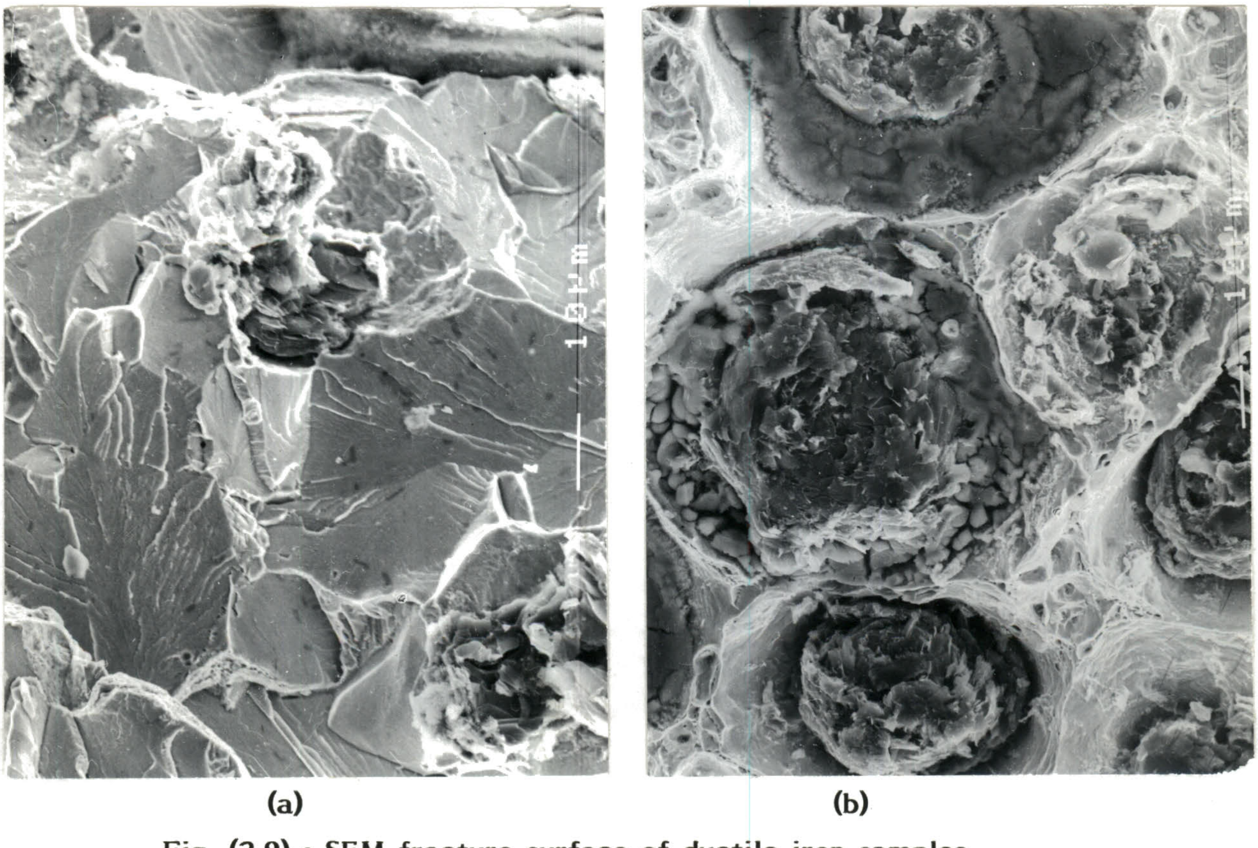
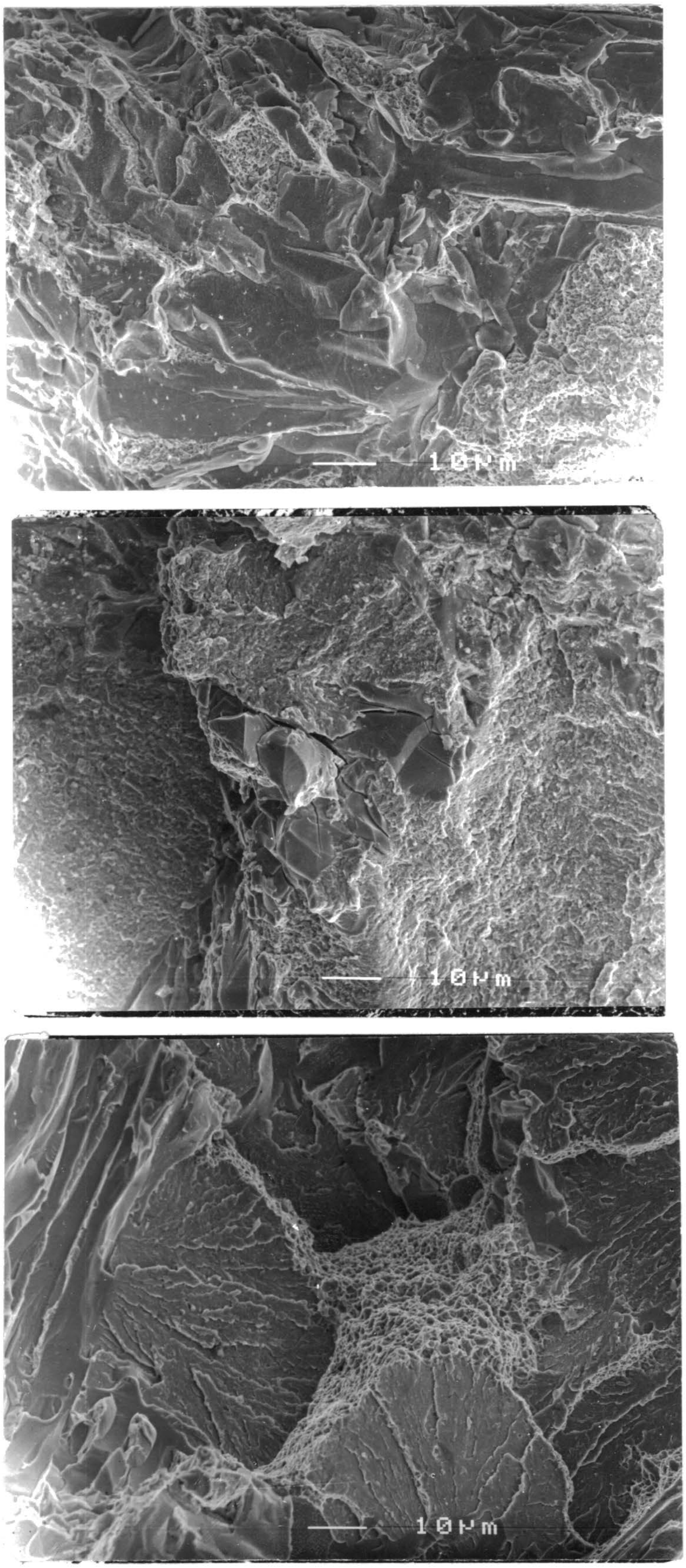


Fig. (2.8) : Fracture appearance of ductile iron specimens.



(a) (b)

Fig. (2.9) : SEM fracture surface of ductile iron samples.
(a) 50% steel scrap + 50% sponge iron.
(b) 50% EPI + 50% sponge iron.



a-

b-

c-

Fig. (2.10) : Micrographs of static fracture toughness of specimens :

(a) alloy W5 (36% CVF)
(b) alloy W2 (22% CVF)
(c) alloy W2 (pearlitic structure)

S.E. micrographs reveal the essential features of the fracture process. Figure (2.10a) represents the micrograph of alloy W5. Because of the relatively high carbide volume fraction (36% CVF), the micrograph revealed large amount of cleavage facets "A". These cleavage facets indicate that the cracks in this alloy propagated on the carbides or at carbide/matrix interface. It is clear from the micrograph (a) that there is a small amount of dimples "B" (ductile fracture). The presence of these dimples could be attributed to the presence of retained austenite phase in the microstructure.

Figure (2.10b) represents micrograph of alloy W2 which contains 22% CVF. The micrograph revealed large amount of dimples "B" (ductile fracture) and small amount of cleavage facets "A" (brittle fracture). From the micrograph (b), it noticed that the cleavage crack propagated on the carbide particles and at the carbide/austenite matrix interface "C".

Figure (2.10c) shows fractograph of the annealed alloy W2. It is clear that there is large amount of dimples "A" which reveal a ductile fracture and may be attributed to the soft pearlite matrix. The most dominating feature of the fracture is the cleavage fatigue-striation. It is noticed that cleavage facets observed with highly developed river patterns of cleavage steps "B". Those grains "river patterns" that are favorably oriented with respect to the cyclic stress axis fracture by sudden cleavage and those oriented to relax the load by cyclic plastic relaxation fracture increamently by fatigue.

CHAPTER 3

TECHNOECONOMIC EVALUATION AND INDUSTRIAL IMPLEMENTATION

This chapter deals with the comparative study of the production of high purity pig iron as well as ductile cast iron with and without utilization of sponge iron in the charge.

More detailed information about two castings selected for production with sponge iron as one of the main charge constituents :

(1) Ductile iron rolls (½ - 2 tons)

(2) Grinding segments of clay-disc mill, as an example of engineering, abrasive-resistant castings.

3.1. Production Cost of High Purity Pig Iron (HPPI)

(a) Induction Melting

The following table shows a comparative study of the production cost of one ton of HPPI compared melted in an induction furnace to the purchase price of the imported (Sorel) pig iron. It should be noticed that the prices of raw materials are updated and therefore, are higher than those mentioned in the interim report II.

Apart from the evident strategic importance of having a local source of such pig iron, the local production will result in about 30-40% savings, taking into consideration that the price of Sorel metal in Egypt is approaching 1000 L.E./ton.

Raw Material	Price per ton	Sponge Iron + Steel Scrap		Sponge Iron + Egyptian Pig Iron	
		% in Charge	Cost, L.E.	% in Charge	Cost, L.E.
Steel Scrap	450	50	225		
Egyptian P.I.	500	-	-	50	250
Sponge Iron	400	50	200	50	200
Carburizer	2000	2.5	50	2.0	40
FeSi	1800	1.5	27	1.0	18
FeMn	2000	0.3	6	0.3	6
Overheads	20%		92		92
			600		606

***N.B. :** The price of imported Sorel Metal in Egypt ranges between 950-1000 L.E./ton.*

(b) Cupola Melting

It has been illustrated that when adding sponge iron up to 50% in the cupola charge, a molten metal of an appropriate analysis for ductile iron production (low Mn- and P-content) could be produced. The only exception was the rather high S-content (0.07-0.10%). However, by using a commercial desulphurizer such as FOSECO-Sulplex, it was possible to reduce the S-content to 0.03%, and the iron produced can be used as a base metal for ductile iron production.

Without desulphurization, the molten iron produced from the cupola using 50% if sponge iron in the charge had the following analysis :

C	Si	Mn	P	S
3.3-3.4	1.5-2.0	0.1-0.3	0.03-0.05	0.07-0.10

Such analysis is suitable for production of different grades of grey and white iron castings and was used for the production of the abrasion resistant white iron castings mentioned in the following section. The following is a cost analysis of producing one ton of molten iron in the cupola.

Raw Material	Price per ton	% in the Charge	Cost, L.E.
Egyptian P.I.	500	50	250
Sponge Iron	400	50	200
Coke	450	20	90
Limestone	100	5	5
Fluorspar	600	0.5	3
Desulphurizer	3000	1	30
Overheads* (20%)			116
Total			694

***Overheads :** *Equipment depreciation + labour + electrical power + administration costs.*

Due to the relatively low C-content of the cupola iron (3.3-3.4%) related to the C-content of the imported Sorel metal (about 4%), a certain allowance corresponding to about the cost of 1% carburizer (20 L.E.) should be added for more accurate comparison. The actual cost of cupola HPPI will be 714 L.E. compared to 950-1000 L.E. of the imported HPPI (20-25% savings).

3.2. Direct Production of Ductile Iron in Induction Furnaces

The results obtained on pilot scale for melting sponge iron in induction and cupola furnaces were implemented in three foundries.

i) The iron foundry of the Aluminium Co. of Egypt (Egyptalum) (3 x 2.5 t induction furnaces).

ii) El-Nasr Castings (5 t induction furnace).

iii) Osamico Foundry (1.5 t/hr cupola).

The following is a brief description of the results obtained when introducing sponge iron to the charge used in those two foundries.

i) Induction Melting at Egyptalum and El-Nasr Castings Iron Foundries

Two hundred tons of sponge iron were melted over two months in 2.5 and 5 t medium frequency induction furnace at Egyptalum and El-Nasr Castings foundries. The product selected for these trials was ductile iron rolls weighing up to 2.5 ton. These rolls have been selected to be the objective of this research due to serious economic considerations. Production of rolls has started in three Egyptian foundries about rhee years ago with the technical assistanceof CMRDI. Before 1990 every roll used in Egypt was imported at rather high prices (one ton of ductile iron rolls costed between five and seven thousands dollars). Apart from the evident economic advantage of roll local production, there is strategic importance for such production, as rolls are vital tool for steel industry. Inavailability of hard currency needed to import rolls beside the absence of local technology for their production lead to complete stoppage of steel industry in some developing countries for some time (e.g. Nigeria and Algeria). That is why CMRDI took the initiative to develop a local technology for ductile iron roll production.

To convince the local steel industry to replace the already used rolls, that has been imported for decades from industrialized countries such as Germany, Japan and U.K., with those locally produced, the price of the latter should be very competitive. Taking into consideration that the roll consumption in the Egyptian steel rolls exceeds 5000 t/year, the importance of such technology transfer may become clear.

Sponge iron was introduced in quantities up to 50% of the charge, as a replacement of the imported special pig iron (Sorel metal). With additions up to 25%, no difficulties were encountered in manual removal of excess amounts of slag formed. Moreover, the influence of the formed slag on the wear of the acid lining was insignificant.

Increasing the sponge iron percentage in the charge to 50% (the balance is return cast iron scrap and steel scrap) resulted in some difficulties in manual slag removal which resulted in the increase of melt time by about 5-10%. Moreover, the life time of the furnace lining was reported to be decreased by 25-30%, which should be taken into account, when evaluating the economic merits of sponge iron utilization in induction furnaces. Other factors to be taken into account are increased power consumption arising from longer melt time and increased labour required for extra deslagging.

The following table gives a comparative evaluation of the cost of raw materials used to produce one ton of molten metal required for the production of one ton of ductile iron. The cost of different charges is related to the standard 50% Sorel + 50% steel scrap usually used in Egyptalum foundry. The cost of the 100% Sorel charge is given for reference and is shown to be 22% higher than the usual charge. Introduction of 50% sponge iron to the charge whether with steel scrap or Egyptian pig iron representing the balance results in 30% savings from the standard charge. Some comments on the figures mentioned in the table are listed in the followings :

- The extra expenses encountered when using sponge iron and arising from increased lining wear, increased labour cost required for deslagging as well as increased power consumption are more compensated by the differential price of the main raw materials in the charge.

- The extremely low S-contents in melts using sponge iron result in lower consumption of FeSiMg alloy needed for graphite spheroidization, which represents another saving.

- The cost of alloying elements Cr, Ni or Mo used in production is not included in the comparison as they are added in the same amounts to melts of different charge constituents.

Comparative Study of the Cost of Preparation of One Ton of Molten Metal Required for Ductile Iron Production

Raw Material	Price/ ton, L.E.	50% Sorel		50% Sorel + 50% Steel		50% Sponge + 50% Steel		50% Sponge + 50% EPI	
		%	Price, L.E.	%	Price, L.E.	%	Price, L.E.	%	Price, L.E.
Sorel metal	1000	100	1000	50	500	-	-	-	-
Egyptian P.I.	500	-	-	-	-	-	-	50	250
Steel scrap	450	-	-	50	225	50	225	-	-
Sponge iron	400	-	-	-	-	50	200	50	200
Carburizer	2000	-	-	2	40	3	60	2	40
FeSi	1800	-	-	2	36	3	54	2	36
FeSiMg	3500	1.3	45	1.5	51	1.3	45	1.3	45
Inoculant	2000	0.5	10	0.5	10	0.5	10	0.5	10
Extras for :									
Lining		-	-	-	-	-	15	-	15
Power		-	-	-	-	-	3	-	3
Labour		-	-	-	-	-	2	-	2
Total price of one ton, L.E.			1055		862		614		601
, %			122		100		71		70

ii) Cupola Melting at Osamco Foundry

The cupola furnace in this foundry is almost of the same features as the experimental foundry of CMRDI. This foundry is a jobbing one with a production of about 800 t/year. Sponge iron additions up to 25% were used in the charge with the balance consisting of return scrap 30% and Egyptian pig iron 45%. Normal grey iron castings such as pipe fittings up to 12 inch, gibaults, manhole covers, ... etc. were produced with average savings in the cost of molten metal of 10-15%.

Although the Mn- and P-contents of the molten iron were in the ranges suitable for ductile iron production (0.3 and 0.05% respectively), the S-content (0.07%) was too high for ductile iron production.

3.3. Production Technology and Performance of Selected Castings

(a) Ductile Iron Rolls

Two types of rolls, single- and double-poured are produced using charges containing up to 50% sponge iron, melted in an induction furnace 2.5-ton capacity. The following is a brief account of the production technology of both types :

i) Single-Poured Rolls

If the roll is to be single poured or straight cast (Fig. 3.1), the metal fills the mold in the shortest possible time and is allowed to cool undisturbed in the mold. All cast iron rolls are left to cool to about ambient to 100°C.

Single poured iron rolls are limited to less than 65°C Shore C hardness because to balance this barrel hardness, the core and neck structures become too weak due to the relatively white or hard microstructure which develops.

Thus, a single poured roll, that is, a single melt and composition, must provide both wear resistance for the working barrel and strength to withstand rolling loads in the necks.

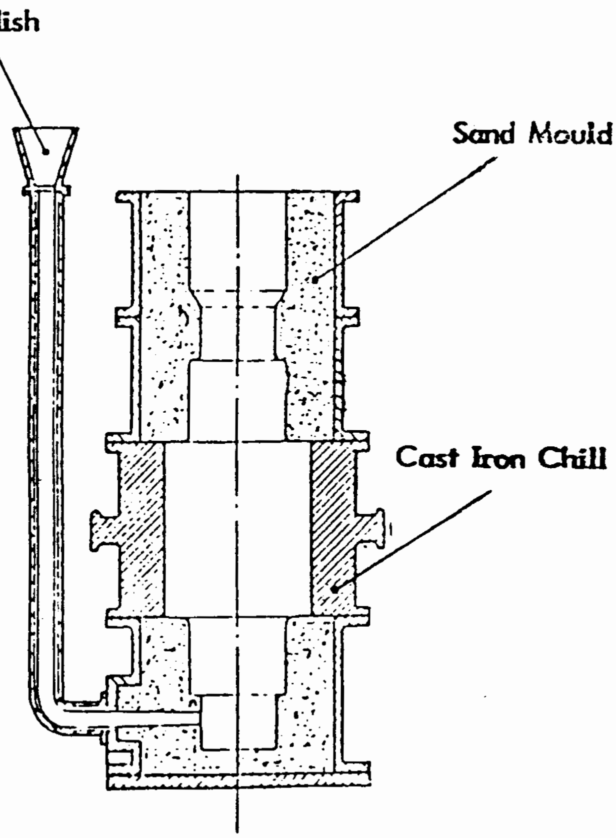


Fig. (3.1) : Simple mould assembly used for casting a single-poured roll.

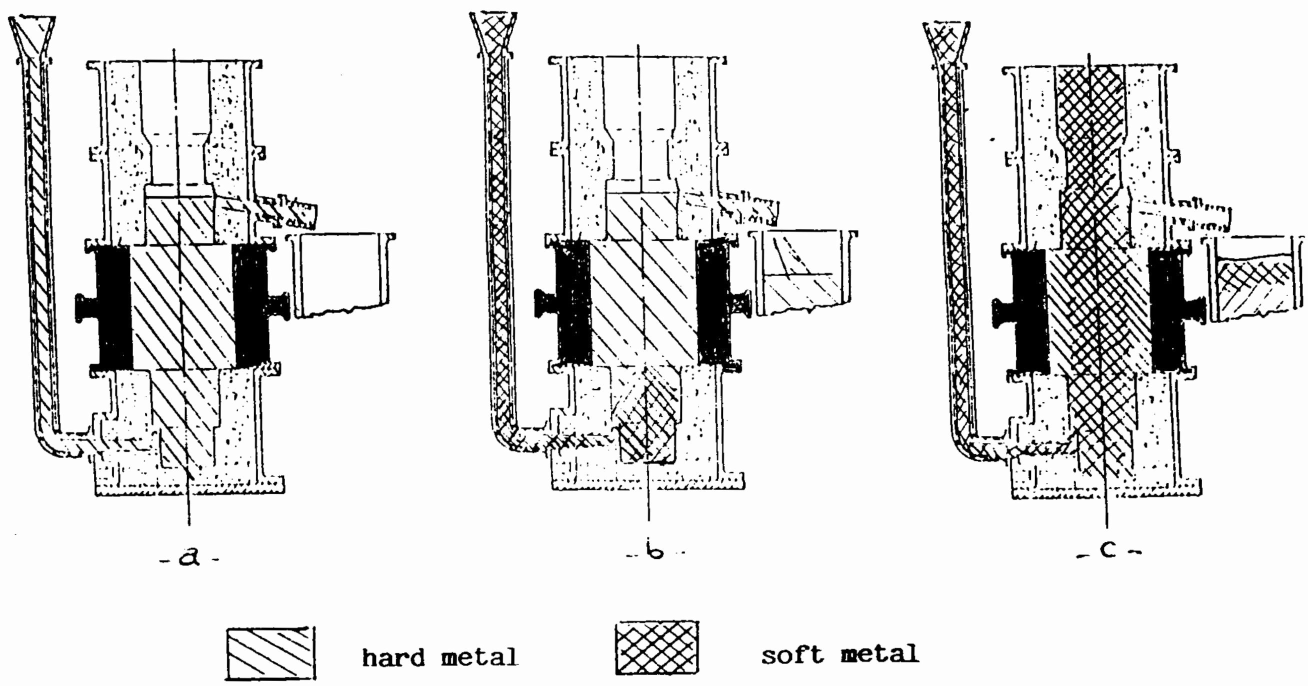


Fig. (3.2) : Sequence of operations involved in double-pouring.

This type of iron roll is characterized by the gradual change in properties through the barrel cross section due to the same composition solidifying in various microstructures under the influence of a changing rate of cooling. An exception to this characteristic is the "clear chill" roll which solidifies as a true white iron at the barrel surface, but via a narrow "mottled" or eutectic zone, suddenly solidifies as a true gray iron.

ii) Double-Poured Rolls

Static cast double poured rolls are produced by displacing and/or diluting the liquid metal inside the mold with a second liquid metal or different composition. Fig. (3.2) illustrates the sequence of operations involved in the double pouring of a 1.5 ton roll at Egyptalum foundries, whereas Fig. (3.3) schematically illustrates the flow diagram for casting such rolls from one induction furnace.

Cast iron double poured rolls are generally produced by adding the second liquid through the bottom of the mold via the same running system as the first metal. The displaced and diluted excess is collected as it pours from the mold and is then available as an alloyed raw material.

The first metal to be poured into the mold is that which will eventually form the working layers or shell or the barrel. The level to which it fills the mold is part-way up the top neck. One technique employed is to have the runner for the excess metal positioned at this point in the mold. Another technique used to double pour is to have excess metal pouring over the top of the mold.

Solidification of this first shell metal commences immediately at the casing or permanent mold chiller. Speed of solidification, hence the depth of the shell, is dependent upon time and casting size. The depth of shell solidification required is determined by the mill, that is, it is dependent upon the reject diameter of the roll under consideration.

After due time for solidification of the shell, the second liquid or core metal, is poured through the same runner system, but at a controlled

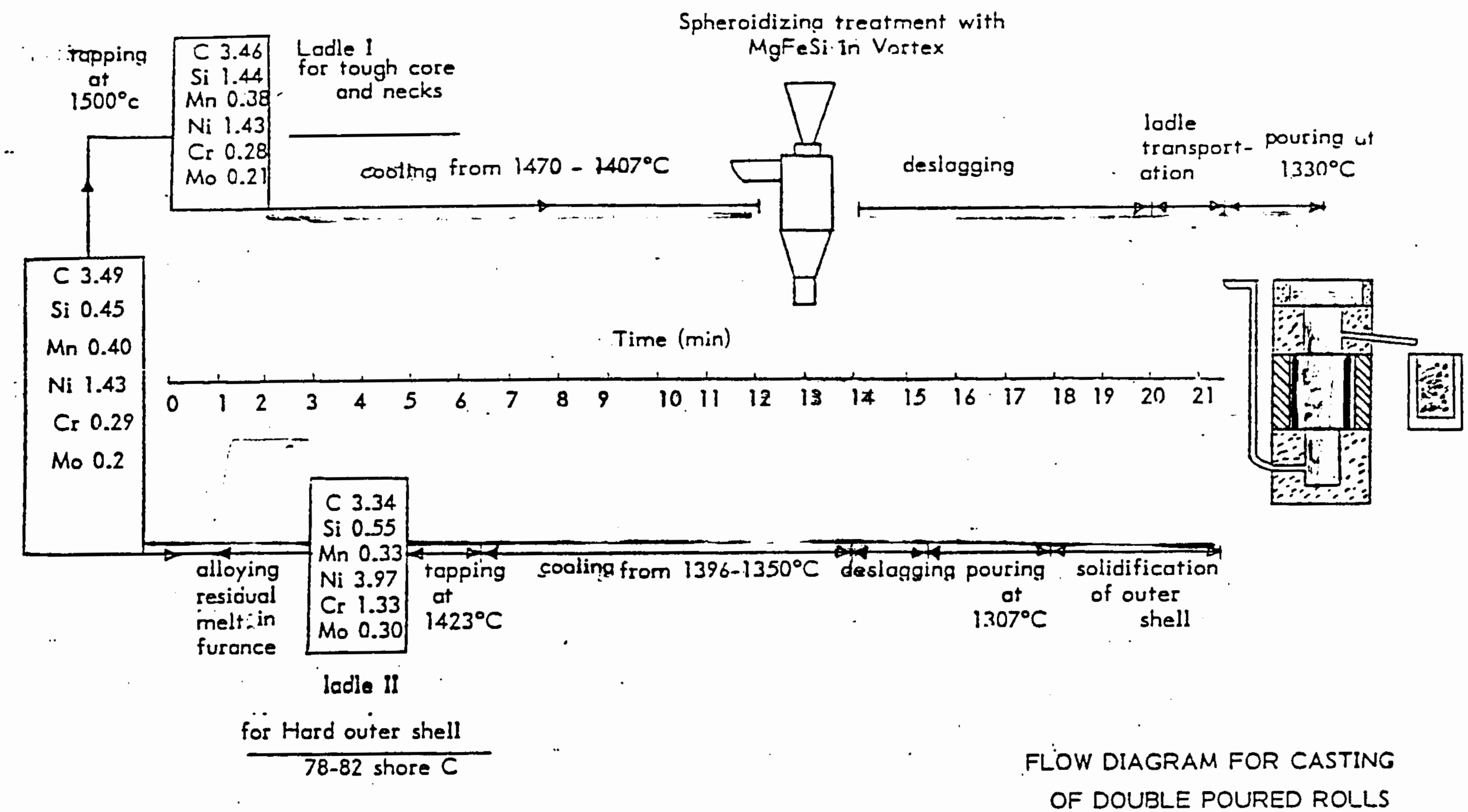


Fig. (3.3) : Flow diagram for casting of double poured rolls from one induction furnace.

and even pouring rate. The rate of pour allows mixing, dilution and displacement of the liquid shell metal with mixing and gray iron formation immediately at the solidified shell boundary (Fig. 3.4).

The interface between shell and core is very marked and readily distinguishable on a machined roll.

Liquid displaced from the mold is collected separately via the orifice in the top neck, for such a time that sufficient mixing has occurred to give the displaced liquid an overall ratio of approximately 80 percent shell and 20 percent core metals.

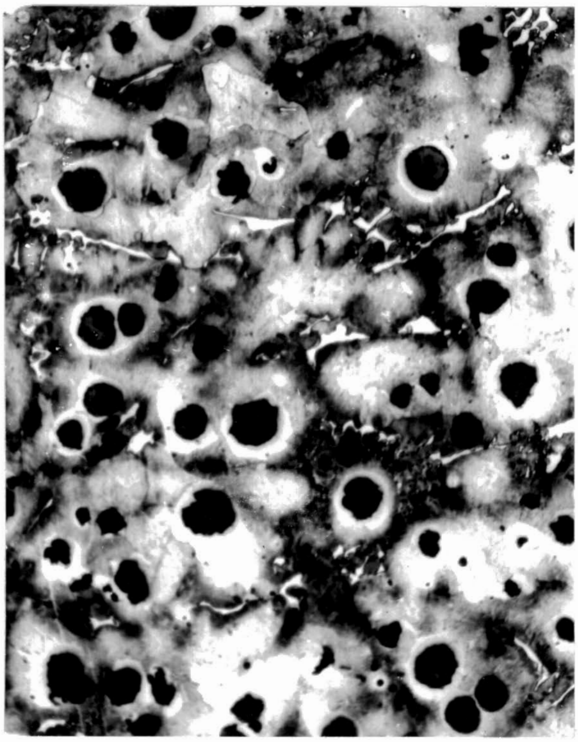
At this time, there is still core metal remaining in the ladle to complete the casting. The neck is sealed at the overflow point, then the remaining top neck and feeding head are filled using the remaining core metal.

This method of double pour casting requires a large amount of liquid metal including the highly alloyed shell metal. The degree of dissimilarity between the two liquid compositions and solidification characteristics is limited to closely related materials. The major problems are in obtaining mixing and dilution of the two liquids and also in ensuring a sound, mechanically strong interface.

Major interfacial problems can occur when either one of two conditions are satisfied within the liquid interface, that is, either graphite or carbide are caused to precipitate in a continuous form.

Fig. (3.5) shows typical performance evaluation curves of ductile iron rolls produced at Egyptalum foundries from charges containing up to 50% sponge iron as compared to that of imported rolls. It is evident that the performance of locally produced rolls is higher and that may be attributed to several factors; the extremely low sulphur and phosphurs contents of molten base metal produced from charges containing sponge iron may be two of them.

(a)



(b)

Fig. (3.4) : Microstructures of outer shell of highly alloyed ductile iron (a) and core metal of low alloyed ductile iron (b) of a double-poured rolls.

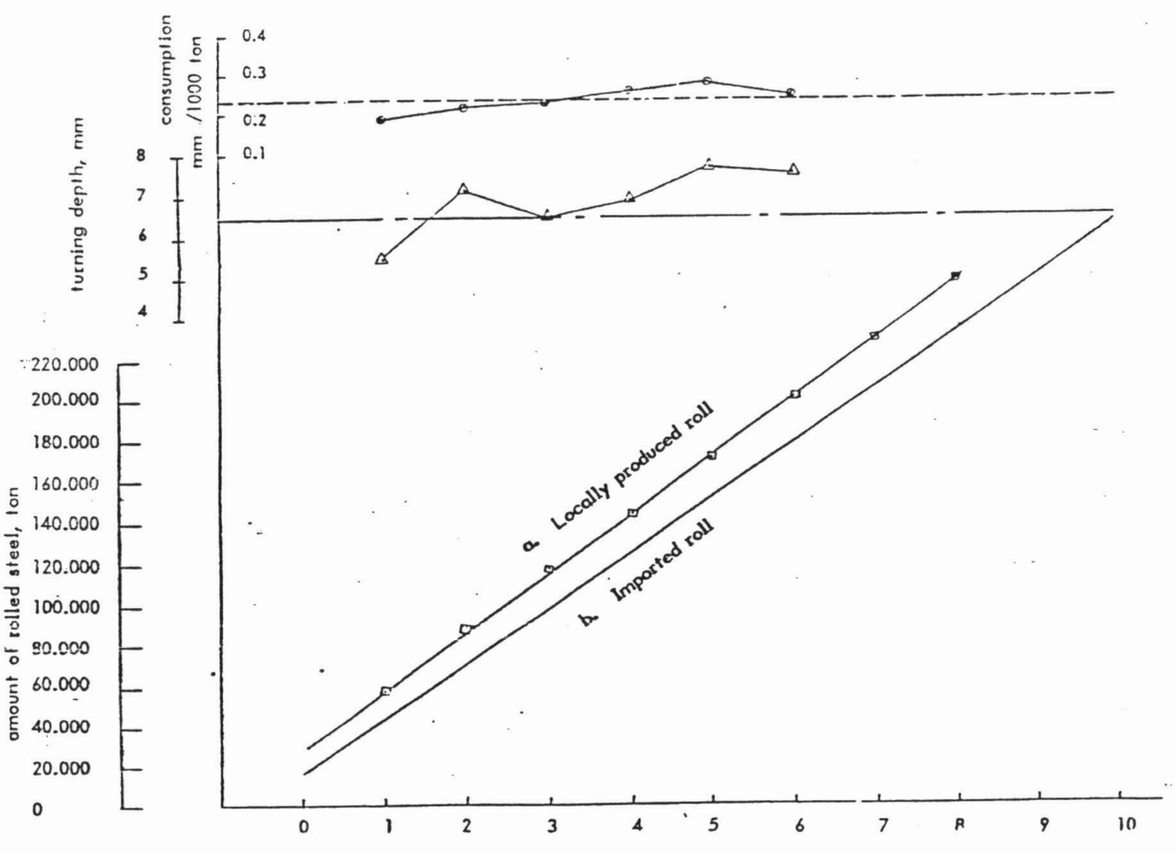


Fig. (3.5) : Performance evaluation curves of locally produced ductile iron rolls (curve a), compared to that of imported one (curve b).

Fig. (3.6) illustrates the surface quality of those rolls after machining.

(b) Grinding Segments of Clay-Disc Mills

This item is chosen as an example of abrasion resistant engineering castings. The Egyptian imports from this category of castings reached alarming figures and CMRDI has started an R&D program to develop technologies for local production of different abrasion-resistant castings.

Fig. (3.7) shows a picture of some segments used for grinding and sequeezing clays. One clay-disc mill uses about 20 sets/year (each set comprises 16 rotors and 16 stators).

These segments used to be imported from steel base and build-on teeth made from WC + CO filler wires by arc-welding (armouring operation). the segments are subject to :

- compression and shear forces
- high stress abrasion due to attribution of clay feed to about -0.1 mm size.

Armouring, although has superior hardness, has some drawbacks, such as :

- imported, very expensive material
- teeth are rather brittle

It was therefore, decided at CMRDI to develop a ledeburitic high-Cr iron to suit the complicated requirements of such segments, e.g. :

- alloy matrix must have good abrasion resistance (martensitic + carbidic matrix).
- alloy should have at least moderate toughness (fine matrix grain size + some retained austenite).
- the alloy should respond to softening annealing for adequate machinability before hardening to acceptable depth.

Fig. (3.6) : Ductile iron rolls of different types produced from charges containing up to 50% sponge iron.

stator

rotors

Fig. (3.7) : Grinding segments of clay-disc mills.

Production Technology

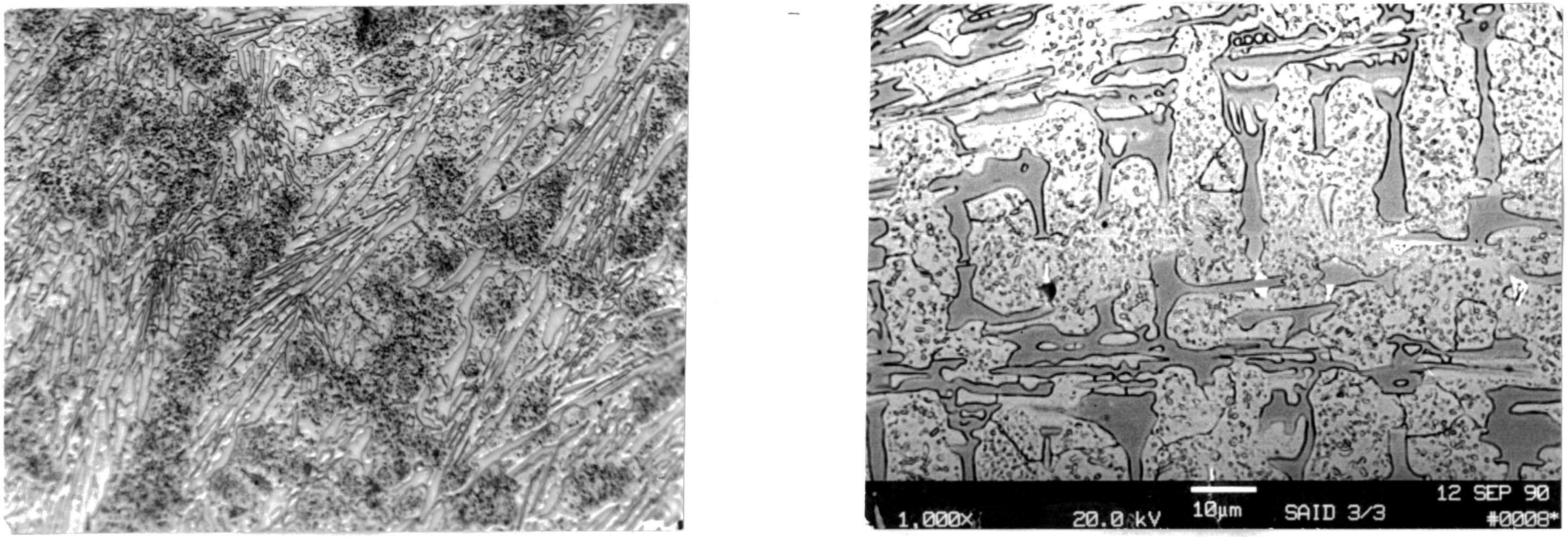
Sponge iron was used as one of the charge constituents, together with steel scrap, FeCr, FeMo, FeV and carburizer to give the following analysis :

C	Si	Mn	Cr	Mo	V	S	P
2.4/2.8	0.6/0.9	0.7/0.9	15/17	2/2.5	0.8/1.0	0.03	0.03

The segments were subject to annealing, machining and then surface hardening using induced air cooling and then tempered to hardness value of 67 HRC.

Fig. (3.8) shows the microstructure of as-cast and heat-treated conditions. The as-cast structure consists of primary and secondary carbides of type M_7C_3 impeded in pearlitic-austenitic matrix with traces of martensite. Annealing results in the formation of softer structure with pearlite and eutectic carbide matrix. Hardening and tempering give a tempered martensite with eutectic and secondary carbides matrix.

The life time of the locally produced segments was about 85-90% of that of the imported armoured segments, whereas the price did not exceed 10-15% of the import price.



(a) (b)

Fig. (3.8) : Microstructure of high Cr-Mo-V irons.
(a) as-cast. (b) hardened and temepred.

GENERAL CONCLUSIONS

- The melting of sponge iron in coreless induction furnaces is technically feasible. The pilot findings of this research gave much of the background needed to begin commercial applications.

- High purity pig iron, with chemical composition adequate for ductile iron production was produced in induction furnaces from different charge compositions, by adding up to 75% sponge iron to molten pools of Egyptian pig iron, steel scrap or foundry grade pig iron.

  The high purity pig iron produced was about 30% cheaper than the imported Sorel Metal of equivalent analysis.

- Ductile cast iron was produced from base metal, melted in induction furnace by using the high purity pig iron produced from sponge iron, or directly by adding up to 50% sponge iron to Egyptian pig iron, steel scrap or foundry grade pig iron.

- The pilot trials in induction furnaces up to 350 kg capacity did not face serious difficulties related to the increased slag formation or furnace lining wear. During commercial applications in induction furnaces of capacities up to 5 tons, the excessive slag formation decreased the lining life by about 25%.

  Taking that into consideration, the cost of molten metal production when using sponge iron on commercial scale was still cheaper as the cost difference of charge constituents was more than that required to compensate for the lining wear.

- Up to 25% sponge iron can be easily used in a cupola charge without causing any significant operational difficulties. With higher percentages of sponge iron in the charge, however, the permeability of the charge decreases, and as a result, the gas flow experiences greater resistance, leading to increased air pressure in the windbox. Care has to be taken to study this aspect before using significant percentages of sponge iron in cupolas.

- Sponge iron additions to cupola charges resulted in decreased carbon- and silicon-contents whereas sulphur-content was slightly affected. Addition of up to 50% in the charge caused significant decrease of manganese- and phosphorus-contents of the Egyptian pig iron.

- 10-20% increase of coke consumption was necessary to slag the higher gangue content of the sponge iron. Even with this increase, the cost of molten metal production was 15-20% in favour of charges containing sponge iron.

- Results obtained on the pilot scale were upscaled to commercial application in three foundries; two using 2.5 and 5 t. induction furnaces and the third using 1.5 t/hr cold-blast cupola.

- Two representative castings of special importance to the Egyptian industry were selected for production from charges containing sponge iron as one of the main charge constituents, i.e. ductile iron rolls and abrasion resistant grinding segments. The master technologies of production of those castings are given in this report. Service performance of those parts showed excellent results.

- The fracture toughness of the produced ductile iron and abrasion-resistant alloyed white irons were measured and found to be of the same level as that of irons produced from conventional raw materials.

- The results of this research were exposed to foundrymen, representing small- and medium-sized foundries in Egypt in a workshop, specially held for that purpose. Great interest was shown in this technology as result of the serious difficulties, these foundries are currently facing to secure their needs of metallic foundry materials, e.g. steel scrap and foundry grade at special pig irons.

APPENDIX I

Fracture toughness program

```
10 REM Fracture toughness ASTM E 399-83
20 REM K.M. Ibrahim  Oct. 20,1991
30 REM
40 REM
50 BEEP
60 INPUT "Enter Specimen Identification "; S1$
70 LPRINT "   COMPACT TENSION SPECIMEN:   "; S1$
80 LPRINT "   ********************************"
90 LPRINT
100 TEST$ = "YES"
110 BEEP
120 INPUT "Enter Fatigue and Fracture Test Temperature"; T1$, T2$
130 LPRINT "   Fatigue Precracking Temperature "; T1$
140 LPRINT "   Fracture Toughness Test Temperature "; T2$
150 BEEP
160 INPUT " Enter Specimen Dimensions B and W"; B, W
170 BEEP
180 INPUT " Enter Crack Lengths, A1 to A5"; A1, A2, A3, A4, A5
190 BEEP
200 INPUT "If Dimensions are entered in mm type 1,type 0 if inches"; U
210 IF U = 1 GOTO 240
220 W=W*25.4;B=B*25.4;A1=A1*25.4;A2=A2*25.4;A3=A3*25.4;A4=A4*25.4
230 A5 = A5 * 25.4
240 LPRINT
250 LPRINT "  Specimen Dimensions, inches (mm)"
260 A11 = A1: A22 = A2: A33 = A3: A44 = A4: A55 = A5: W4 = W: B1 = B
270 A1 = A1 / 25.4
280 A2 = A2 / 25.4
290 A3 = A3 / 25.4
300 A4 = A4 / 25.4
310 A5 = A5 / 25.4
320 B = B / 25.4
330 W = W / 25.4
340 LPRINT "  B= "; B; " ("; B1; ")"
350 LPRINT "  W= "; W; " ("; W4; ")"
360 LPRINT "  A1="; A1; " ("; A11; ")"
370 LPRINT "  A2="; A2; " ("; A22; ")"
380 LPRINT "  A3="; A3; " ("; A33; ")"
390 LPRINT "  A4="; A4; " ("; A44; ")"
400 LPRINT "  A5="; A5; " ("; A55; ")"
410 A = ((A2 + A3) + A4) / 3
420 LPRINT "  Average crack length = "; A
430 W1 = .45 * W
440 W2 = .55 * W
450 LPRINT
460 LPRINT "  B and A must be between 45% and 55% of W"
470 IF B < W1 GOTO 500
480 IF B > W2 GOTO 500
490 GOTO 510
500 LPRINT "  ** B violates this requirement **"
510 IF A < W1 GOTO 540
520 IF A > W2 GOTO 540
530 GOTO 560
540 LPRINT "  ** A violates this requirement ** "
550 TEST$ = " NO "
560 LPRINT
570 P1 = .1 * A
580 D1 = ABS(A2 - A3)
590 D2 = ABS(A2 - A4)
600 D3 = ABS(A3 - A4)
610 IF D1 > D2 THEN D2 = D1
620 IF D3 > D2 THEN D2 = D3
630 IF D2 > D1 THEN GOTO 660
640 LPRINT "   Central crack front is valid   "
```

```
650 GOTO 680
660 LPRINT "   Central crack front is invalid   "
670 TEST$ = "  NO "
680 LPRINT
690 D4 = ABS(A1 - A)
700 D5 = ABS(A5 - A)
710 D6 = ABS(A1 - A5)
720 IF D4 > D5 THEN D5 = D4
730 IF D6 > D5 THEN D5 = D6
740 IF D5 > P1 THEN GOTO 770
750 LPRINT "   Crack edge is valid "
760 GOTO 790
770 LPRINT "   Crack edge is invalid "
780 TEST$ = " NO "
790 BEEP
800 INPUT " Enter the max. load sustained ( Pmax. ) ,in Kgs. "; L1
810 INPUT " Enter load Pq , in Kgs. "; L2
820 L3 = L1 / L2
830 L1 = L1 * 2.2046
840 L2 = L2 * 2.2046
850 LPRINT
860 LPRINT "   Pmax. = "; L1; " Lbs "
870 LPRINT "   Pq = "; L2; " Lbs "
880 LPRINT
890 IF L3 <= 1.1 GOTO 930
900 LPRINT "   Pmax / Pq > 1.1 , invalid K1c "
910 TEST$ = " NO "
920 GOTO 940
930 LPRINT "   Pmax / Pq < 1.1 , valid K1c test "
940 A6 = A / W
950 F = (2 + A6) * (.886 + 4.64 * A6 - 13.32 * A6 ^ 2 + 14.72 * A6 ^ 3 - 5.6 * A6 ^ 4) / (1
 A6) ^ 1.5
960 LPRINT
970 LPRINT "   f ( A / w ) = "; F
980 LPRINT
990 K1 = (F * L2) / (B * (W ^ .5)) / 1000
1000 LPRINT "  Kq = "; K1; " Ksi square inch "
1010 K2 = K1 / .91005
1020 LPRINT "  Kq = "; K2; " MPa m^0.5"
1030 LPRINT
1040 BEEP
1050 REM Enter 0 if yield stregth is not known
1060    INPUT " Enter  yield stregth at Fatigue Test Temperature, Ksi"; Y1
1070 IF Y1 = 0 GOTO 1240
1080 BEEP
1090    INPUT " Enter  yield stregth at K1c Test Temperature, Ksi"; Y2
1100 LPRINT "  Test Yield Stegths"
1110 LPRINT "At "; T1$; "= "; Y1; "Ksi"
1120 LPRINT "At "; T2$; "= "; Y2; "Ksi"
1130 LPRINT
1140 Z = 2.5 * (K1 / Y2) ^ 2
1150 IF A > B THEN M4 = B
1160 IF B > A THEN M4 = A
1170 LPRINT "  Is2.5*(K1/Y2)^2<Both A and B?"
1180 IF Z > M4 GOTO 1210
1190 LPRINT " Yes It Is, Therfore Kq= K1c"
1200 GOTO 1240
1210 LPRINT "  No, Larger Specimen Size is Required"
1220 TEST$ = "No"
1230 LPRINT
1240 BEEP
1250 INPUT " Enter Young's Modulus, In Ksi"; YM
1260 IF YM = 0 GOTO 1460
1270 INPUT "Enter the Maximum Fatigue Load , In Ibs"; ML
```

```
1280 LPRINT " Young's Modulus, Ksi, E = "; YM
1290 LPRINT
1300 LPRINT " Maximum Fatigue Load , Ibs = "; ML
1310 K3 = (ML * F) / (B * (W ^ .5)) / 1000
1320 K4 = K3 / .91005
1330 LPRINT
1340 LPRINT " Kf(Max) ="; K3; "Ksi inch ^.5"
1360 LPRINT
1370 Z1 = K3 / YM
1380 LPRINT
1390 LPRINT "Kf(max)/E="; Z1; "inch^.5"
1400 IF Z1 < .002 GOTO 1440
1410 LPRINT " Which is >0.002 inch^0.5, and **Invalid**"
1420 TEST$ = "NO"
1430 GOTO 1450
1440 LPRINT " Which is <0.002 inch^0.5, and **valid**"
1450 LPRINT
1460 Z2 = .6 * K1
1470 LPRINT "60% OF Kq="; "Ksi inch ^0.5"
1480 IF K3 > Z2 GOTO 1510
1490 LPRINT " Valid Fatigue : Kf (max) <60% Kq"
1500 GOTO 1530
1510 LPRINT " Invalid Fatigue: Kf (max) >60% Kq"
1520 TEST$ = "No"
1530 IF Y1 = 0 GOTO 1630
1540 IF Y2 = 0 GOTO 1630
1550 Z3 = (Z2 * Y1) / Y2
1560 LPRINT
1570 LPRINT " 60% of Kq (Y1/Y2)= "; Z3; "Ksi inch ^0.5 which is "
1580 IF K3 > Z3 GOTO 1610
1590 LPRINT "  >Kf(max), Valid Fatigue Precracking Test"
1600 GOTO 1630
1610 LPRINT "  >Kf(max),** Invalid Fatigue Precracking Test**"
1630 LPRINT
1640 RSC = (2 * L1 * (2 * W + A)) / (B * Y1 * (W - A) ^ 2) / 1000
1650 LPRINT " Rsc = "; RSC
1660 LPRINT
1670 LPRINT "  All of the requirements were met ? "; TEST$
1690 LPRINT
1700 LPRINT
1710 LPRINT
1720 LPRINT
1730 LPRINT
1740 LPRINT
1750 BEEP
1760 PRINT
1770 PRINT "Adjust printer to a new page if required"
1780 PRINT "*****************************************"
1790 PRINT
1800 BEEP
1810 BEEP
1820 INPUT " To continue enter 1, to stop enter 2"; S
1830 IF S = 1 GOTO 60
1840 PRINT
1850 PRINT "End of calculation program tough"
1860 PRINT " Please review your entered values"
1870 PRINT "***********************************"
```