PRODUCTION AND STUDY OF DUCTILE IRON FROM HOT BLAST CUPOLA

By

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A thesis submitted to the department of Metallurgical Engineering, Bangladesh University of Engineering and Technology, Dhaka, in partial fulfilment of the requirements for the degree of Master of Science in Engineering (Metallurgical).

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DECLARATION

This is to assert that this research work has been carried out by the author under the supervision of Dr. Ehsanul Haque Professor, Department of Metallurgical Engineering, BUET, Dhaka, and co-supervision of Mr. Maksudur Rahman, Genenral Manager of Galfra Habib Ltd Barabkunda, Chittagong and it has not been submitted elsewhere for the award of any other degree or diploma

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ABSTRACT

Molten iron used to produce ductile iron has some requirements more stringent than those for other cast irons. High pouring temperature and control of chemical composition are vitally important for the production of ductile cast iron. Essentially, the metal should be low in sulphur and phosphorus content, relatively high in C content with Si controlled within established limits for the properties required. Many methods of melting are capable of producing such an iron. High temperature required for the production of ductile cast iron is generally achieved by using induction furnaces. Cold blast cupola is almost the only furnace generally available to the foundries in Bangladesh. The molten metal temperature of these cupola furnaces is around 1350°C and is not therefore, considered suitable for the production of ductile cast iron.

A cold-blast cupola furnace was converted into a hot-blast cupola furnace by heating the cold blast of air to about 300°C in a heat exchanger, heated by hot gases produced by the combustion of natural gas. This hot blast entering into the cupola raised the temperature of the molten metal to about 1450°C. The required

chemical composition was obtained by adjustment of the charge materials and the percentage of sulphur in the base iron used in the production of the ductile iron was lowered from 0.07 percent to 0.023 percent by prior desulphurizing with desulfex-150. This base metal was treated with FeMgSi for the purpose and inoculated with FeSi to produce the ductile iron.

A number of castings were made for producing the ductile cast iron. The properties of the ductile cast iron were determined and it was found to be satisfactory.

In the first heat, a mixture of nodular, vermicular and flake graphite was found in the matrix. This result indicates that the addition of the alloying elements must be done at a higher temperature i.e. above 1400°C.

The melting processes that has been used for this purpose are given, and the compositional restrictions which must be considered for the highest quality ductile iron have been discussed.

DECLARATION

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ABSTRACT

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1. INTRODUCTION

Cast iron has been used for the manufacture of castings for many centuries. In order to improve the mechanical and other properties of cast iron various methods have been suggested.

Ductile cast iron is defined as a high carbon, iron base alloy in which the graphite is present in compact, spheriodal shapes rather than in the shape of flakes, the Latter being typical of gray cast iron.

In the ordinary grey iron, the cavities occupied by the graphite flakes have sharp edges and tend to act as stress raisers from which cracks can emanate. This tendency is eliminited in the ductile cast iron by obtaining the graphite in a nodular or spherical form Ductile cast iron are also known as nodular cast iron or spheroidal graphite cast iron.

Modern ductile iron was first announced to the foundry industry as a new engineering material by Morrogh[1] in 1948 at the annual meeting of BCIRA-England and by Ganebin[2] of INCO of the USA. However, according to Hanchang and Xiaodong[3] iron castings with typical spheroidal graphite had been produced in ancient China about 2200 years ago.

The BCIRA Process consisted of an addition of cerium to molten iron. In the INCO process, magnesium was added to molten iron. The magnesium was soon widely used by foundries all over the world and it was a great achievement in the metallurgy of cast iron and materials engineering.

The matrix of ductile iron can be controlled by proper selection of the base composition, by suitable foundry practice and by heat treatment.

Ductile cast iron has special advantages such as low melting point, good fluidity and castability, excellent machinability and good wear resistance like gray cast iron as well as engineering advantages such as high strength, toughness, ductility, hot workability and hardenability like steel. The nearest competitors to ductile iron are steel and malleable iron.

The one property which is valued the most in the majority of designs is strength. As a rule, not ultimate but yield strength with a safety factor, will enter into engineering calculations. Thus ductile irons are generally superior[4] to both gray and malleable irons as well as to unalloyed steel, regarding their yield strength and consequently finds widespread applications.

It is true that the relationship between yield strength and toughness is inverse. Chemical and metallurgical influences which increase yield strength, usually reduce impact resistance.

A true evaluation of the importance of the latter must consider the permissibility of plastic deformation. In figure1. the impact modulii (which are indicators of reliability in service) of four materials are compared. At high elongation values the greatest impact resistance is, of course, exhibited by cast steel followed by ferritic, then pearlitic ductile iron, while the impact resistence of gray iron is nil (it fails with low elongation). Up to about 3% elongation, however, pearlitic ductile iron is more reliable under impact load than either ferritic ductile iron or cast steel. If, as is customary, plastic deformation must not exceed 0.2%, the order of reliability is

1. Pearlitic ductile iron (best).
2. Ferritic ductile iron
3. Steel and then
4. Gray cast iron .(least reliable).

Ductile iron is an important material for cast iron foundry. Heavy duty machineries, dies, wear resistant rolls, valve & pump bodies, pinions, gears, crank shafts, cams, guides, track rollers, spare parts of agricultural machineries, paper mills, construction and earth moving machineries, I.C. engines and different types of pipe fittings are manufactured by means of ductile iron

A large amount of spare parts and machineries of ductile iron required by Bangladesh for its different industries and organizations are now met through import. It is possible to reduce the import volume by manufacturing this type of ductile iron having special characteristics. However, foundries in our country, are not producing ductile iron because of lack of technical know how and suitable facilities to produce this special type of material.

The production of ductile cast iron requires low sulphur and high temperature and therefore, induction melting is usually used for production of ductile iron Direct arc and induction furnace melting practices are very satisfactory methods of producing quality base material for ductile iron. Compositional and temperature controls can be quite exact Recently, Mogni[5] has successfully produced ductile iron in Bangladesh by using an induction furnace .

Unfortunately, induction melting facilities are not generally available in Bangladesh and the foundries use conventional cold-blast cupola furnaces for making gray cast iron castings These furnaces are not suitable for the compositional control required for the production of ductile cast iron and cannot provide enough temperature for further treatments.

If the conventional cupola furnace be converted into a hot-blast cupola furnace to achieve the necessary high temperature for molten metal the foundries in Bangladesh may be able to go for the production of high grade castings of ductile cast iron.

This study was undertaken to convert a cold blast cupola furnace to a hot blast one and to study its suitability for the production of ductile cast iron. Once this process is established this may be applied commercially to industries in Bangladesh This will help to reduce the import of ductile iron machinery parts and thus will save hard - earned foreign exchange Moreover, since hot-blast cupola furnaces consume less fuel, this conversion will enable the foundrymen to produce gray iron castings at a lower cost .

2. METALLURGY OF DUCTILE IRON

The production of ductile iron is very much dependent on the process variables. An overall view of the entire process will be helpfull in explaining the type of process control needed to achieve a consistent product of ductile iron. The production of ductile iron involves the following steps.

(i). Melting a suitable base iron,

(ii) Desulphurisation (if necessary),

(iii) Spheroidizing treatment,

(iv). Inoculation,

(v). Pouring and

(vi). Cooling and Solidification

These steps are well recognized, and regarded as fundamental to obtaining a good ductile iron. A common feature of these steps which connects them into a whole unit is the temperature-time sequence over which each is practiced. True control of the process then requires a temperature-time schedule that coordinates the events of steps 1-6 into a unified system.

Before going to the production of ductile iron it is absolutely necessary to obtaine a required base metal Again the production of the base metal and its consistency involves careful control of the following essential factors:

(a) Metal of controlled composition and particularly of low sulphur control.

(b) Optimum metal temperature.

2.1. Charging Materials

Pig iron, cast iron scrap and steel scrap are the main charging materials used for the manufacture of ductile base iron.

2.1.1.Charge composition.

The selection of raw materials and the mode of melting are very important factors, in the production of a suitable base iron for the production of good quality ductile iron. The majority of ductile base irons are produced in the following range of composition:

C	3.4-3.8%
Si	2.4-2 6%
Mn	0.20%max
P	0.05%max
S	0.02%max

Alloy additions are made to modify the matrix structure. The properties of ductile iron are largely determined by the matrix structure and this is very much dependent on the chemical composition of the iron, which is in turn governed by the composition of the charge materials.

In addition to the metallic materials charged directly into the furnace, there are other very important additions. The following is a list of all the materials normally employed to obtain nodularizig and the desired matrix structure:

Foundry return scrap
Pig iron
Steel scrap
Bought-in scrap
Carburisers
Ferroalloys
Alloying materials
Desulphurisers
Nodularizing agents
Inoculating agents

2.1.2. Effect of Different Elements.

A range of defects common to ductile cast iron is related to the composition of the iron and in particular to the trace element content Therefore a precise knowledge of the metal charged and other additions made is very important. Great care is needed in the selection of materials in the production of ductile cast iron.

2.1 2.1. Effect of Main Elements

a). Carbon and carbon equivalent

Unlike grey irons, the carbon equivalent has little effect on mechanical properties of ductile cast iron. Because of this there is a tendency to use high carboon equivalent irons, since this maximises fluidity and minimises shrinkage tendency. Howerver if the C. E. is excessively high flotation of hyper-eutectic graphite nodules can occur, which can adversely affect mechanical properties and also increases the risk of dross related defects. In order to avoid problems of graphite flotation it is recommended that the C E. should not exceed the following values:

Section size, mm	CEV.
>50	4.3
12 to 50	4.5
<12	4.7

Reducing C content improves the impact properties of ferritic irons and in order to ensure good impact properties it is advisable that the C content should not exceed 3.5%

b) Silicon

Silicon promotes ferrite and suppresses carbide formation and there is an improvement in ductility but this causes reduction in strength and hardness. However, in ferritic irons, increasing Si increases tensile strength and hardness whilst reducing elongation. In ferritic ductile irons the most important effect of Si is possibly that it reduces the ductile-brittle transition temperature.

c) Manganese

Manganese is a pearlite promoting element and it also has a carbide stabilising effect, promoting a general chill in thin sections and intercellular carbides in heavy sections. The latter is particularly problematic since they are very difficult to remove by annealing. It is preferable to maintain the level of Mn in as cast ferritic iron below about 0.2% and upto 0.5% may be tolerated in pearlitic grades.

d) Phosphorus

Phosphorus must be cosidered as an undesirable element in ductile iron and its level should not exceed 0.05% in ferritic irons since its presence in levels in excess of this promotes the formation of intercellular phosphide/carbide complex which result in a deterioration in elongation and impact properties

e) Sulphur and Magnesium

Excessively high Mg contents promote carbide but otherwise has no effect on the matrix structure. Similarly S has no significance on the matrix structure but since S readily combines with Mg, high levels of S in the base iron are undesirable. High S reduces Mg yield and there is an increased risk of dross related defects.

2.1.2.2. Effect of Trace Elements

Trace elements can be classified, according to their effect on the matrix structure into two groups; Carbide stabilizing elements and parlite promoting elements.

i) Carbide-promoting elements

Obviously carbide must be avoided in as cast production and for such irons it is recommended that the Cr and V levels should be maintained below 0.05% and boron below 0.003%. Slightly higher level of Cr and V can be tolerated in irons which are to be heat treated. Molybdenum strongly promotes intercellular carbides but is generally below 0.01% unless deliberately added and consequently seldom causes any trouble.

ii) Pearlitie-promoting elements

Most of the trace elements have a pearlite promoting effect and in terms of potency they may be ranked as follows.

Elements	Relative pearlite promoting Effect
Antimony	50
Tin	39
Arsenic	28
Molybdenum	7 9
Phosphorus	5.6
Copper	4.9
Titanium	4.4
Manganese	0.44
Nickel and chromium	0.37

For the production of as-cast ferritic irons, arsenic, antimony and tin should be maintained to below 0.02%. Antimony is not found in cast iron except where added deliberately. Some heavy steel scraps may contain upto 0.04% arsenic, similarly coated scrap may contain a high level of tin and as such could cause problems in as cast ferritic irons. Upto 0.15 % Cu can be tolerated when the Mn content is below 0.2% and the level of other pearlite promoters are low. This high lights the point that the effects of trace-elements are cumulative.

Because of these interactions it is difficult to select raw materials solely based on their analysis, and in fact the only totally reliable assessment is to carry out a trial run.

Molybdenum , phosphurus and titanium can not be used to promote pearlitic structures since they also promote undesirable graphite structure and intercellular carbides

Tin and Copper are most commonly used to promote pearlite in ductile iron. However, tin contents above 0.1% provide no further improvements and the iron is embrittled when tin exceeds this level due to the precipitation of tin at the grain boundries.

Copper is widely used in varying amounts from around 0.2% to 2.0% to control the amounts of pearlite present.

In heavy sections it is more effective to make a combined addition of Cu and Sn to produce fully pearlitic structure.

Arsenic and antimony have undesirable effects on graphite morphology unless cerium is present. Because of this and also due to their toxicity they are not widely used to promote pearlitic structure However, antimony may be used in heavy sections when 100% pearlitic structures are required, which can not be attained by the addition of tin and copper.

2.2 Melting

The following effects are very important for the production of ductile cast iron

2.2.1. Effect of Temperature

Metal temperature determines to a major extent the results obtained from treating the base iron with nodularizing elements and inoculants. The effect of temperature on the nucleation and growth of graphite in cast irons is summarized in Fig.2. An addition agent such as magnesium or mischmetal is effective in producing the desired graphite type only if it is added in such a way that the metal temperature after addition is in the temperature range where that type of graphite is nucleated. Vermicular and/or flake forms of graphite develop in increasing percentages as the temperature decreases[6] below the optimum of about 1482°C.

As cited, additions made at 1260-1371°C generally produce mixtures of nodular, vermicular and flake types of graphite with the vermicular and flake types predominating. The same results are obtained from inoculants following or accompanying the nodularizing treatment. For example, ferrosilicon added at too low a temperature will promote vermicular or flake types of graphite. The size of the batch being treated, naturally, has an important bearing on the initial and final temperature. With small batches it is generally necessary to start at much higher temperatures in order to end up the proper nucleation temperature. The reverse is true with larger batches.

It has been suggested[7] that prior to treatment, the melt should be superheated to about 1565°C, and then treated and inoculated at the optimum temperature of about 1482°C.

Regardless of the superheating effect, there is no question that there is an optimum temperature for the metallurgical additions.

The dominating influence of temperature of metal treatment and nucleation and growth of the various graphite shapes (and carbides) emphasizes the problem of obtaining only spheroidal graphite in the structure. Fig. 2 points out that many types of graphite are capable of nucleating or none may nucleate and carbides develop instead. Unless the proper temperature range of addition is practiced, mixed structures are likely to be the rule rather than the exception

2.2.2. Effects of Time

Total duration of the processing cycle determines the time spent by the iron in the various temperature ranges of graphite nucleation and growth. An example of typical time-temperature cycles in metal handling is shown in Fig.4. A progressive decrease in temperature through the range of spheroidal graphite nucleation is observed in Fig.4. In connection with nucleation of spheroidal graphite, it should be recognized [8,9] that the number of spheroids at first increases and then decreases as temperature decreases in the range of 1427-1149°C.

Furthermore, other types of graphite may be nucleated in the lower end of this temperature range. Time at each level of temperature determines the nucleation product that will be continued down to lower temperatures. Increasing time favors dissolving of graphite spheroids or rendering them dormant [9] at lower temperatures. Thus, increasing time favors the nucleation of vermicular graphite, or flake types.

Failure of graphite to nucleate and grow may also result from increasing time and lower temperature, and then the carbide stabilizing effects of magnesium (or rare earths) function to cause eutectic carbides to freeze at the end of the solidification process.

2.2.3. Dross Formation

The present progress on the AFS-supported research has centered [11] around the content that dross as it occurs in castings need not represent equilibrium. Due to the recurrence of MgO and Si compounds in dross, the kinetics of compound formation in the $MgO-SiO_2$ system has been studied and related to the surface dross and Mg loss rate which occurs in melts as a function of environment. Although the study requires further investigation in several areas, the following major conclusions may still be reached:

1. MgO makes up a major portion of casting dross and melt surface dross. Given a sufficient length of time. Mg_2SiO_4 (forsterite) will form on the melt surface. Forsterite indicates driving from the MgO side of the $MgO-SiO_2$ phase diagram.

2. The rate of forsterite formation can be decreased by the presence of O_2, lower temperatures and the presence of other oxides.

3. Of the different techniques for forsterite occurrence, the direct combination of MgO and SiO_2 appears to be most operative. Magnesium reduction of SiO_2 with reoxidation of a metallic Si offers one source of the MgO-SiO_2 necessary to form forsterite

4. Magnesium loss rates from the melt can be represented by first order kinetic reaction rate theory

$$\text{Log}\ \frac{\%\text{Mg (time = 0)}}{\%\text{ mg (time=t)}}\ \text{vs time}$$

5. The Mg loss rate undergoes a maximum at approximately 1375^{0}C and may be related to the CO-SiO_2 equilibrium inversion.

6. In general, Mg loss rates are higher in an air atmosphere for MgO and Al_2O_3 crucibles The thermodynamically unstable SiO_2 crucible has a higher loss rate in Ar, possibly due to its inability to form a protective forsterite layer.

2.3. Melting Equipments

Thus furnaces devised for melting cast iron or steel can also be used for melting ductile iron base. However, the foundryman will have to choose the melting process considering both economy and quality. More often, however, he must accept the existing melting device.

The choice and performence of the melting plant will have a major influence on the ability to meet the compositional and temperature requirements for the production of ductile base iron. There is now a considerable range of melting furnaces available for preparing base irons for ductile iron. It is imortant to mention that the dicision on which unit to employ should be based on a comprehensive technical and economic evaluation of all the alternative options and there is no universal one best choice of melting plant. It should be remembered that other than the cupolas where S is picked up from the coke, the melting unit will not result in a rise in S level in melting. The base irons generally fall into two categories:

1. Iron suitable for direct nodularisation, having a desirably low S content.

2. Iron of high S content which requires desulphurizing.

So it is necessary to have a detailed look at the advantages and disadvantages of the various melting systems as the possible processes are dependent on whether desulphurization is employed or low S is attained by the use of low S charge materials

2.3.1. Induction Furnace

Coreless induction furnaces are ideal for melting ductile base iron. Medium frequency furnaces are particularly suitable as they give better stirring action. So addition of C and S are easily assimilated homogenijation. They are easy to charge and operate, provide few refractory problems and capable of superheating to temperatures in excess of 1500° C thus eliminating the problems that can sometimes occur owing to temperature loss during treatment and inoculation.

There is no increase in the level of S during melting, This does not, however, mean that the S level will always be satisfactory. The main source of sulphur in electrically melted iron are from low-purity carburisers and poor-quality steels. If significant amounts of these materials are charged then S can be above 0.02% with consequential effects on metal structure or treatment costs.

2.3.2 Arc Furnace

Arc furnaces are extremly robust and designed principally to melt steel. They are by far less popular than induction furnace in a ductile iron foundry although existing installations in steel foundries are sometimes used for ductile iron production. Charges can consist of pig iron, foundry returns and steel there are no technical difficulties associated with melting of the base iron, however, the problem is the lack of turbulence in the bath. This may result in compositional layering especially when alloys are added

2.3.3 ROtary Furnace

A rotary furnace consists of a cylindrical body with open conical ends. The furnace is fired with an oil ,or gas burner situated at one of the conical ends and the hot gases are exhusted through the opposite end. The exhust ducting includes recuperator which preheats the combustion air for the burner, thus providing a higher flame temperature and improved economy. The furnace body is continuously rotated. Melting is helped by the heat transfer from the hot lining material along with the burner flame.

Rotary furnaces are suitable for a small foundry where continuous supply is not required and where individual casting weights may be upto 5 tonnes. Commercially rotary furnaces offer advantages because they are a fairly low capital cost item, in comparison for example with an electric induction furnace. They can also be economic to operate in areas where electricity costs are high, coke is difficult to obtaine or where oil/gas prices are low. The do not increase the S content and oxy-assisted melting developments offer increased potential for their application

Rotary furnaces, however have some disadvantages. There is loss of elements due to oxidation by the flame. Losses of C and Si result in the need for large amounts of pig iron which has economic implication. Si losses can be overcome by the choice of pig iron and additions of Fe-Si, based on operating experience.

Injection of graphite by lancing may compensate the loss of carbon. However, in order to use an injection lance, the burner has to be turned off and swung back to allow access. Besides, the solution of C in iron is endothermic Both these aspects of operation combine to produce a significant temperature loss in the bath and refining for superheating results in further C loss So the technical difficulties and the economics of melting must be carefully considered before using rotary furnace for the production of ductile cast iron base metal.

2.3.4 Cupola Furnace

Cupola furnace is a shaft furnace of very easy construction. They are very simple to operate and are most common and time-proven melting equipment for melting cast iron. They also offer advantages regarding both quality and melting economy.

2.3.4.1 Basic Cupola

Cupola melted base iron for the ductile cast iron can be prepared in a basic cupola, since it can provide a continuous sypply of low S iron The important feature of basic cupola operation is that some desulphurisation of the metal charge or at least prevention of resulphurisation is achieved by the basic slag.

However basic cupola has a higher Si loss and difficulty in having a consistent C control. The basic cupola may be operated in almost a liningless condition by water cooling system to avoid refractory cost. However, the cost of cooling water is not significantly different from that of refractories besides a fall in metal temperature. Basic cupola operation is rarely used now a days owing to high refractory and operating costs.

2.3.4.2.Cokeless Cupola

To overcome the disadvantages of the basic cupola and yet to achieve low S iron, cokeless cupola can be used. The cupola consists of a refractory- lined stack similar to a conventional cupola but with the replacement of coke as a fuel, by oil or gas, fired through burners in the side of the stack. The coke bed is replaced with a series of refractory spheres supported on a water-cooled grate, beneath which is the well,containing only metal and slag. It is usual to preheat the refractory bed prior to charging The charges comprise metallics and only a small amount of limestone because there is no coke ash to flux. The charge also contains small amounts of refractory spheres to replace that consumed amounting 2.0-2 5%. of metal through put.

Since the cokeless cupola contains no coke, there is no S pick up. However, to maintain the required level of C injection of graphite into the well is carried out.

The cokeless cupola can therefore be of advantage but it should be stated that adequate metal temperature attainment is dependent on both fuel and refractory spheres usage and can be costly if the metal is not dispensed very quickly. An ideal application could be to employ the cokeless cupola as a prime melter followed by an electric furnace treatment.

2.3.4.3. Acid Cupola

Acid cupola is the most economic and easy way of continuous production of molten metal. However, the requirements of composition and temperature control for ductile base iron are unlikely to be met by an intermittently tapped and slagged cold blast cupola. Even when melting low S pig iron, steel and returns; pick up of S is inevitable and it is usually impossible to produce a melt having a S content less then 0.05%. This means that some form of desulphurising treatment is required in order to reduce the level of S present. The desulphurizing treatment has to be carried out after tapping and during this period temperature is lost. If the melt is not hot enough as in the case of hot blast cupola melting an intermediate process is required to facilitate reheating. So desulfexing with electric furnaces are often used

2.3.4.4. Duplex Process

The thermal efficiency and economy of the cupola furnace is exceptionally good up to the point when the charge is molten.

However, temperature and composition control is not upto the mark Cupola melting followed by treatment in an induction or arc furnace allows superheating and compositional adjustments of the melt. Thus utilizing the advantages of different types of furnaces in a duplex process the exacting demands for both chemical composition and tapping temperature for the production of ductile base iron are met. However, for the duplex process the total plant cost are high and this restricts the use of duplexing combinations.

2.3.4.5 Hot Blast Cupola Furnace

It has already been mentioned that the problem with cupola furnace in the production of ductile base iron is that the melt picks up S from the coke. Naturally desulphurisation is necessary and this has to be performed outside the cupola. This result in severe loss of temperature. Still further heat will be lost during spheroidizing and inoculation treatment. However, after desulphurisation the melt can not be returned to the cupola for reheating, as is possible with an induction furnace So duplexing with electric furnace is a common practice. However, electric furnaces are costly and are not always available.

If preheating of the blast is adopted the initial tapping temperature can be raised and reheating after desulphurization can be avoided However in that case a very good preheating of metal treatment and casting ladles can be of additional advantage. This superheating has twofold advantage. Firstly, it allows more steel scrap to be charged, which also lowers the S content and secondly the high tapping temperature takes care of the fall of temperature during the necessary treatments.

2.4. Desulphurization

Sulphur content in base iron should be held as low as possible for best efficiency in the nodularizing treatment. Therefore desulphurization is often necessary. Nodularizing elements such as Mg and rare earths also act as desulphurizers. They react first with sulphur in the iron and until all the sulphur is combined the nodularizing action cannot take place. The cost of desulphurization with MgFeSi alloy is approximately double of that with calcium carbide which is commonly used However, the difference is only about 0.15% Of the cost of the molten base iron per 0.01% sulphur removal. For this reason, it is believed [4] that desulphurization prior to treatment is justified only when the sulphur content of the base liquid iron exceeds 0.04%.

For the sake of both economy and cleanliness iron from acid slag cupola should always be desulphurized prior to spheroidizing treatment.

A variety of compounds are used to remove sulphur from molten iron, More practical desulphurizing agents are as follows. Caustic soda (NaOH), soda ash (Na_2CO_3), burnt lime (CaO), lime stone ($CaCO_3$) calcium carbide (CaC_2) and calcium cyanamide ($CaCN_2$) Of these, caustic soda is rarely used because of the health hazard it presents, limestone is first reduced to CaO before it desulphurises and $CaCN_2$ should be ruled out because it increases base iron nitrogen content with the resultant danger of nitrogen gas defects in the castings.

Traditionally CaO is the most widely used desulphurizing compound. In ductile iron practice it is used in basic cupola and basic electric arc melting. On rare occasions $CaCO_3$ (Limestone) is injected into large ladles resulting in both economical and excellent desulphurization, According to one report[4], the injection of 0.5% $CaCO_3$ at a rate of 14-16 Kg/min. reduced S-content of 60 tons of molten iron from 0.06 to 0.008% The method is limited to large iron quantities because to the large temperature loss.

It has been observed that the efficiency of desulphurization with the injection method consistently increased with decreasing CaC_2 particle size.

According to the report[4], the efficiency of desulphurization is dependent not only on the total CaC_2 surface area presented to the liquid iron but also on the rate of sulphur transport to these surfaces. Since the latter is dependent on the S-content of the iron. Three basic variables influencing desulphurizing efficiency are:

Degree of stirring and dwelling time

injection rate, and

CaC_2 particle size

As a general rule, 1% CaC_2 or Na_2CO_3 is needed to reduce base iron S-content from 0.1 to 0.01%. It can be either more or less depending on desulphurizing efficiency. Soda ash is seldom used because of its harmful environmental effects. Care should also be exercised with the spent CaC_2 slag since it invariably contains some active CaC_2. This reacts with water producing acethylene gas and constitutes a fire hazard The spent slag should be carried outdoors frequently and soaked in water there

2.5. Spheroidization

Ductile cast iron has a spheroidal graphite structure which is produced by the incorporation of spheroidizing elements in the molten metal just before casting. So spheroidizing treatment is used to transform the usual flake graphite of the base iron to nodular form in the production of ductile iron.

Although a number of elements are capable of spheroidizing the graphite, only magnesium usually together with some calcium, cerium and some other rare earth elements are commonly used for this purpose. Magnesium is usually alloyed with other elements in order to reduce the volatility of the spheroidizing reaction. Gries & maushake[13] have summarized the work of many other investigators and the following list contains the more popular views of the role of magnesium in ductile irons:

i) The nucleus of spheroidal graphite is a compound of magnesium,

ii) Magnesium 'poisons' the nucleus for flake graphite, thus causing spheroidal graphite,

iii) Cerium and magnesium retard or prevent the nucleation of graphite until late in the freezing process, and

iv) Cerium and magnesium forms sulphides which then promote the formation of spheroidal graphite

2.5.1 Spheroidizing elements

Nodular cast iron is commonly produced by treating molten metal with magnesium. Small amount of rare earthsand elements such as calcium,, aluminium, zirconium, strontium, barium,etc. are often added in combination with magnesium.

Usually the treatment agent will contain not more than 1.5% by weight rare earth, less than 1% by weight calcium and aluminium, not more than 2% by weight zirconium or barium and not more than 0.3% by weight strontium.

The magnesium content of the treatment agent used will depend on the size of the casting but should normally be not less than about 2.5% by Weight and no more than about 8% by weight. Below about 2.5% by weight magnesiun the treatment agent is not cost effective and above about 8% by weight magnesium the treatment agent is too violent. For the production of small nodular iron casting the preferred magnesium content is 3-5% by weight and for the production of relatively large castings a higher magnesium content treatment agent containing 5-8% by weight magnesium may be used

2.5.1.1. Size of the Spheroidizer.

The particle size[14] of the treatment agent is preferably 0.4 mm to 2 mm.

The most commonly used particle size range for MgFeSi alloys is 50 mm maximum and 3 mm minimum[5].

2.5.1.2 Requirement of Spheroidizing Elements

The minimum magnesium content[5] required in the casting to spheroidize the graphite may be as little as 0.01%. If magnesium is the only spherodizer added, its concentration must not be less than 0.02% Additions of cerium, other rare earths and calcium reduce the minimum Mg level down to but not below 0.01%. Less amount of Mg than the desired level causes difficulty in the production of ductile iron where as large amount of Mg results MgS inclusions For this reason, foundries which treat relatively high sulphur containing base irons often specify high minimum magnesium contents upto 0.05%. There exists numerous formula for the calculation of the quantity of magnesium to be added. Of all these the simplest and safest is presented below.

$$\text{Mg to add (\%)} = \frac{\text{Mg content desired (\%)}}{\text{Mg recover (\%)} \times 0.01} + \text{Base S (\%)}$$

Since the recovery of magnesium varies within a very wide range (10 to 90%), the necessary quantity must be established on home grounds. Excessive Mg-contents are detrimental by causing carbides as-cast and increasing shrinking tendency. The retained magnesium content to aim for is about 0.015% higher than the minimum requirement.

The quantity of treatment agent[14] used to produce nodular iron castings will usually be in the range from 0.8% to 2.0% of the weight of iron to be treated.

2.5.2. Fading Effect of Spheroidizing

The fading of the spheroidizing effect[4] is a very complicated phenomenon and produces a quasi-flake graphite. The reason behind this phenomenon is loss of magnesium content through oxidation or combination with S. The reaction may be as follows:

$$Mg + O = MgO$$

$$Mg + S = MgS$$

Considering the relative stabilities of the above two compounds, a more likely reaction is as follows :

$Mg + S + O = MgO + S$

If the source of oxygen is an oxide, silica, for example, the corresponding reactions are :

$2\ Mg + SiO_2 = Si + 2\ MgO$, and

$2\ MgS + SiO_2 = Si + 2\ MgO + 2S$

The fading rate is influenced by the following factors:

1) Initial Mg content; the higher content the faster the fading

2) Temperature; the higher the temperature the faster the fading.

3) Slag handling; the faster the slag is removed, the better.

4) Furnace lining; the worst is silica, the best is magnesia.

Additional fading is manifested in decreasing nodule count and deterioration of graphite shape.

2.5.3. Spheroidizing Methods

There are many different spheroidizing methods along with some variations Ladle Transfer Method is one of them and by far the largest volume of ductile iron is being produced by this method. Its main virtue is simplicity.

The magnesium master alloy is placed at the bottom of the empty ladle and liquid base iron is poured over it. The technique of ladle filling is somewhat critical. It is believed that the stream of the liquid iron must be directed away from the location of the alloy and also, Ladle filling must be very fast. Both of these are believed to increase efficiency by preventing the alloy from floating to the surface and burning. However, the Mg reaction is always very vigorous and every precaution should be taken.

A very popular variation is the "sandwich" method in which the master alloy is covered with small pieces of steel or Ferro silicon or resin bonded sand. The steel cover is supposed to delay the reaction with the Mg and it occurs only when the spheroidizer is well covered with the molten metal so that there is a good recovery. The use of ferrosilicon on the other hand is strongly advised against with no qualification. Both base iron silicon and silicon as part of the inoculant are much more effective in preventing as-cast carbides than silicon added with the master alloy. When resin bonded sand is used over the alloy it generally forms a hard shell and delays the reaction until it is broken with a plunger rod. This gives a good Mg recovery with very little temperature loss. Covered laddle treatment much improves Mg recovery and also minimises reaction violence.

2.6 Inoculation

The metallurgical meaning of the word: inoculation is to provide the melt with seeds or "nuclei" onto which the solid phases grow during freezing. The inoculation of ductile irons produces heterogeneous nuclei for the graphite spheroids.

When treated with the spheroidizer, ductile iron is in a semi-inoculated condition to a larger or lesser degree. A separate inoculation invariably improves structures by increasing nodule count and preventing carbide formation.

2.6.1 Inoculants

Almost every material inoculates to some degree. Active inoculating agents are Ca, Al, Ba, Sr, etc. For effective and well controlled inoculation ferrosilicon of controlled chemical compositions are utilized. These alloys are produced in a variety of grades, the most common, however, are the 50, 65, 75, 85 and 90% Si grades. All these grades can also be obtained with or without calcium addition. New and significant entries into the inoculant market are those containing a small amount (1-2%) of magnesium. All inoculants contain relatively little aluminium because aluminium promotes subsurface hydrogen pinhole defects, particularly in thin sections. Efficient mold inoculation has been reported with a mechanical mixture of ferro-silicon fines and barium salts.

2.6.1.1 Size of Inoculant

The sizing of the inoculant is usually 13 mm maximum. Since fine particles do not inoculate effectively, a minimum size limit of 1.5 mm is advisable.

2.6.1.2. Amount of Inoculant

Trojan[18] at al. reported that increased post inoculation amount in hypereutectic irons does not affect percentage nodularity, has little effect on nodule count, decreases ultimate tensile strength, while increasing elongation (ferritizing effect) and reduces carbide formation in thin section. On the other hand Dawson[19] reported that increased amount of post inoculant in hypoeutectic irons produce higher nodule counts. Saw and Watmough [20] stated that 0.55% silicon addition as the post inoculant will be optimum when high nodule counts, good nodule distribution and nodule sizes are considered.

2.6.2. Components of Inoculation

The response[4] to inoculation is dependent on (a) the melt and (b) the quality and quantity of inoculant added; these two being the "components" of inoculation.

The ratio between silicon content of the untreated base ductile iron and silicon added with the inoculant exerts a considerable effect on the structure. If this ratio is infinitely large i.e. the iron is not inoculated at all, the mtallurgical quality is poor. Similarly, poor quality (low nodule count, as-cast carbides, etc) results if the same ratio is zero, meaning no silicon in the base iron.

This ratio is definitely worth establishing for each operation by increasing or decreasing base iron Si-content with corresponding decrease or increase in the quantity of inoculant so that the final Si-content remains unchanged. When calculating the ratio, silicon introduced with the treatment alloy is to be disregarded. A good starting point: 2 parts of Si in base iron/1 part Si with the inoculant. (e.g 1% base iron Si-content and inoculation with 0.67% $Fe_{75}Si$).

2.6.3 Inoculating Methods

The traditional and still most common method is to add the inoculant into the stream as the pouring ladle is being filled from the treatment ladle.

The effectiveness of inoculation sharply decreases with increasing inoculating temperature Fig 5. This finding gave rise to the possibility that "post" inoculation is more effective simply because it is done at a temperature lowered by the cooling effect of the treatment.

Dell and Christ[15] investigated and reported that mold inoculation is more effective than the usual ladle addition method. They reported that post inoculation directly into the mold with as little as one gram of calcium bearing regular grade 85% ferrosilicon drastically reduces both general and inverse chill in S.G. iron. Mold inoculation also increases the number of nodules in the structure. Dell and Christ[15] also reported that direct mold inoculation could produce numerous tiny concentration cells of graphitizers promoting graphite nucleation.

Toggle and Carlson[16] found that the optimum nucleation for carbide elimination from minimum additions of ferrosilicon was dependent on the following factors:

a. Mechanics of inoculation
b. Carbon equivalent of S.G.iron.
c. Melting method
d. Magnesium level of S.G. iron.
e Sizing of inoculants
f Calcium and aluminium content of inoculants.
g. Aging of inoculants
h. Forms of Ca present.
i. other elements alloyed with FeSi and.
j. Solidification patterns,

Kust and Loper[17] stated that S.G. iron structures are considerably improved if a practice of post inoculation with ferrosilicon is followed after magnesium treatment has taken place.

When comparing nodule count between the "one-step" and traditional inoculation methods at identical inoculation temperatures, these were found to be nearly identical Fig. 3.

2.7 Pouring and Solidification

During pouring of molten metal into the mold the temperature, time and freezing of ductile base iron are very important for the production of required qualities of ductile iron. These are discussed in the following sections.

2.7.1. Process temperature and time

Temperature and time act concurrently in metal handling and solidification after pouring. Fig. 6 shows schematically the relative time-temperature cycle for treating and pouring and for cooling and solidification. Based on the results of this study[21] and other work, it appears that the total time for treating and pouring should be definitely less than 10 min and probably less than 6 min. This, of course, does not include cooling and solidification time after pouring. In Fig. 6, time prior to entry of metal into the mold is given a negative value, while time after pouring and for cooling and solidification is given a positive value.

Magnesium treatment and inoculation at an optimum temperature of about1482-15.10°C combined with rapid handing and pouring, retains the largest, number of graphite spheroids from the nucleation stage for growth during solidification. After pouring, cooling and solidification are primarily dependent on section size in a given mold . For green sand solidification times are indicated in Fig. 6 for a pouring temperature of 1426°C for bars from 2 to 100 mm. in diameter

The metallurgical effect of rate of temperature decrease, shown in Fig. 6, is to cause changes in graphite type and carbides in accordance with the principles previously descrived. Higher cooling rates will retain more spheroids and permit fewer nonspheroidal graphite particles to develop. At high rates, in sections of 25 mm. bar dia. or less, chilling occurs and carbides result. This should be récognized as carbide formation due to chilling and not due to lack of graphite nuclei or to chemical carbide stability.

Slow cooling rates occur as sections increase beyond the 50mm. diameter size. The Slow rates may permit resolution of spheroids and the nucleation of vermicular graphite as temperature decrease. Finally, increasing time at decreasing temperatures permits the chemical factor which stabilizes carbides to operate. Magnesium and rare earth elements function strongly as stabilizers. Center line carbides alone are simply a special case of slow cooling and solidification rate occurring in the most likely place, the center of the section.

Eutectic carbides, with vermicular graphite, are the result of the long temperature-time cycle cooling conditions. Here the cause of the carbides is not a chilling effect. Instead, it is an increase in carbide stability from alloying, and, in part, inadequate retention of graphite spheroids by more rapid cooling from the nucleation temperature range of the spheroids to the range where their growth is rapid. From the experiments it appears that a minimum of about 100-120 nodules/sq mm must be retained to assure growth of good spheroids.

To summarize, the quality of graphite in ductile iron deteriorates, and the amount of carbides increases if the duration of the temperature-time cycle is excessively extended. This is true whether the cycle is extended in the ladle or in the mold. Changes in the cycle for improving the results can be readily visualized once the principle is accepted.

2.7.2. Freezing of Ductile Iron

The freezing of ductile iron[4] is by and large an eutectic transformation and is a function of composition, temperature and cooling rate.Fig 7 shows that the liquidus temperature at the beginning of freezing decreases with increasing carbon content to approximately 1,150°C at 4.30% carbon at the eutectic point. Further increase in carbon content increases the same (liquidus) temperature. The influence of carbon content on the freezing is also shown with the solidus line in the diagram. Initially, increasing carbon content decreases this (solidus) temperature. Above approximately 1.75% carbon content, however, no further decrease is experienced, the line becomes horizontal.

Of all the elements (other than carbon) present in ductile iron, silicon has the greatest influence on the carbon content of the eutectic. Its effect is to move the eutectic to lower carbon content. According to the most accurate measurements, 1% silicon lowers the carbon content of the eutectic by 0.31%. The carbon equivalent is therefore expressed as,

$$C.E. = TC(\%) + 0.31Si(\%)$$

Silicon also changes the temperature of the eutectic freezing which will occur over a temperature-interval rather than isothermally.

The freezing of ductile iron is "by and large" an eutectic transformation. Even if it is of eutectic composition some slight under-cooling is unavoidable and this causes both eutectic and slightly hypereutectic alloys to start their freezing as if they were hypoeutectic. In the practical sense, then, the freezing mechanism is never eutectic but either hypo-or hyper eutectic.

The freezing rate of silica-sand molded 50mm and heavier sections are sufficiently slow to approximate equilibrium. However, in the vicinity of the cold mold wall, freezing always deviates from equilibrium. The bulk of the liquid will proceed to cool at a rate determined by the alloy property . Freezing usually does not start at the equilibrium freezing temperatures Fig.8, once the temperature of the liquid decreases sufficiently below that of the equilibrium, enough driving force is created to initiate the freezing of the first (primary) solid phase which for example in the case of hypoeutectic ductile iron, is solid iron. As soon as this phase appears, the rate of cooling decreases because solidification releases energy (heat). Instead of a changed slope, the first deviation is more or less an isothermal arrest. The rate of freezing is now fast, trying to "make up" for the delay, and decreases only when the temperature of the equilibrium is approximated. Further cooling bring the alloy to the temperature of the eutectic. The second solid phase is similarly reluctant to appear and, therefore a second undercooling is now experienced. Temperature rises again as in the present case both iron and graphite crystallize simultaneously. This rapid temperature increase is denoted as recelescence. If the rate of cooling continuously exceeds the rate of heat release, neither recalescence nor isothermal arrest is observed.

Finally, the rounding off of the cooling curve toward the end of the freezing merits a great deal of attention. It means [4] that the freezing of one of the solid phases is nearly complete.

2.7.2.1 Hypoeutectic Alloy (freezing).

Hypoeutectic ductile irons start their freezing with the precipitation of solid iron in the form of branched crystals called denderites. The freezing of the eutectic is characterized partially by the continued growth of the austenite dendrites and partially by a coupled growth of both austenite and graphite in the form of gloubles, the first forming a shell around the latter. When individual groups of globules form,in a random fashion, the groups are being separated by liquid iron. These groups are called eutectic cells.

At an advanced stage of freezing the melt is depleted in carbon and the cell boundary regions will be mostly graphite-free.

2.7.2 2 Hypereutectic Freezing

The solidification of hypereutectic ductile cast irons is similar to the hypoeutectic ones with the exception that the first (primary) phase to precipitate is graphite in the form of spheroids.

Graphite-austenite globules generally form in a layer-like fashion where the leading phase is graphite. The layers are perpendicular to the direction of the heat extraction. This phenomenon does not occur in hyphoeutectic irons because, initially, the leading phase is austenite.

Once a layer of globules has formed, the liquid next to it is depleted in carbon and will form a layer of graphite-free austenite. As the process repeats itself, a layer-type structure results in which the graphite-free phase resembles dendrites. The structure is not truly dendritic because the dendrite-like component is perpendicular to the direction of heat extraction rather than parallel to it.

The graphite-free layers should be considered as cell boundaries because all the segregation phenomena, such as non-metalic inclusions and, possibly, carbides, are observed in these areas. Such a stratified structure is unfavorable for machanical properties. Castings 25 to 40 mm thick and heavier should not be poured from hypereutectic iron.

The density difference between liquid iron and graphite is approximately 4.8 g/cm^3. There is a substantial driving force, causing the spheroids to move upwards with a velocity corresponding to Stoke's Law

$$v = \frac{2Dgr^2}{9h}$$

where

v : velocity (cm/sec)

h : viscosity of liquid iron = 0.000025 $gsec/cm^2$ (approx)

Dg : difference in density between liquid iron and graphite = 4.8 g/cm^3

r : radius of the graphite spheroid (cm)

Other influences being constant, floating velocity depends of the size of the graphite spheroid only. Large spheroids float very fast, small ones much slower. The length of travel depends on the velocity (i.e. of on graphite size) and on the time given for flotation

In heavy ductile iron casting large spheroids form, and there is ample time for flotation. The result is that not only some but all primary graphite will float to under cope and core surfaces in thicker section.

3. DESIGN AND CONSTRUCTION OF HOT BLAST SYSTEM

Hot blast cupola furnace may be suitable for the production of superheated ductile iron base. In this practice it is possible to obtain sufficiently high carbon in the melt and to reduce the sulphur content to a very low level by desulphurisation of the melt having a higher temperature.

The main types of hot blast cupola furnace are.

1) The recuperator type in which the waste heat of exhaust gases is utilized to heat the blast of air before it is introduced into the cupola.

2) The external combustion type where the cold blast of air is heated in a heat exchanger by hot gases produced by the combustion of oil or gas in a separate unit, the exhaust gases from the cupola are not utilized for heating the blast in this system.

First, attempts were made to apply this recuperator type of arrangement. The design of this recuperator type cupola furnace was critically assessed and finally the idea was given up because the recuperator system is more expensive and is affected by combustion inside the cupola[22]. The availability of hot blast and its temperature are dependant on the physical characteristics of exhaust gases in the recuperator system and it therefore lacks flexibility. It is, however, economical for continuously running a large sized cupola, which melts more than 150-200 tons of metal per week. For smaller cupolas, the external combustion type, Which requires lower capital cost, is more economical. For these reasons, it was decided to construct an external combustion type hot blast cupola furnace where natural gas will be used for the production of hot gases.

Accordingly a hot blast system was designed and the following works were done for the conversion of the cold blast cupola to a hot blast one (Fig. 12).

3.1 Heat Exchanger

The heat exchanger constructed is shown in fig 9. It is a rectangular box type exchanger with walls made of fire bricks. The size of the box is 330 cm long 200 cm in width and 200 cm in height. Two natural gas burners are located at the bottom level of it and four air tubes are placed in the upper portion of the heat exchanger. The exhaust gases produced are passed through the chimney which is placed at the middle on the top surface of the chamber.

The air tubes are heated by the burning of natural gases on the outside while cold air is being passed through the tubes. The air absorbs heat and become sufficiently heated before entering into the cupola.

3 1.1 Gas Burner

Two gas burners were constructed according to the design and size shown in the fig.10 . It is made of cast iron. The design and construction of the burner is very simple and its operation is quite convenient.

It operates on natural gas and it can be manually controlled.

It has a valve which regulates the air for burning and produces a temperature of about 700°C - 800°C in the chamber This type of burner is very suitable for heating and no blower is needed.

3.1.2 Air Pipe

In the combustion chamber, the in-coming air is passed through four channels made of mild steel pipes. The steel pipes were bent in the form of S as shown in Fig. 11, inside the combustion chamber to increase the total length and the contact area of the air with the hot gases. The length of each bent pipe is about 8m. The lenger the pipe the more is the passing time of the air through the heat exchanger. Internal diameter and thickness of these pipes are 85 mm and 3 mm respectively. The total cross-sectional area of the pipes is made more than that of the incoming pipe (15 cm) to reduce the velocity of the passing air inside the heat exchanger so that it can absorb sufficient heat. At both ends of the heat exchanager the pipes were conversed into a single channel and fit into the air flow line for the cupola A valve was placed on to the air flow pipe between the combustion chamber and the to control the supply of air This helps to increase the temperature of the air. Chromel-Alumel thermocouple introduced into the air pipe between the combustion chamber and the valve for recording the temperature of the air blast into the cupola.

Air passing through the heated tubes becomes sufficiently hot This heated air enter into the cupola and helps to increase the temperature and fluidity of the molten metal.

3.2 Blower

In order to achieve unifrom combustion of the coke and normal operation of the furnace, a certain quantity of air per unit of time must enter the cupola . The amount of air to melt the iron depends upon the quality of coke and the coke-iron ratio. It has been found that the best result is obtained when air is supplied at the rate of 100 to 150 cu. m. per minute per square meter of the cupola cross-sectional area.

The internal diameter of cupola is 600 mm. So the required amount of air is $\frac{22}{7} \times (0.3)^2$ (100 to 150) = 28.285 to 42.425 cu.m/min.

Blast pressure is of prime importent for the operation of cupola because it must overcome the resistance of the column of the charge. The following blast pressure are recommended[23] .

inside diameter of shaft	500	700	900
Blast pressure mm of H_2O	250-450	400-600	500-700

For the 600 mm diameter cupola the required amount of air is about 40 cu.m/min and air pressure is about 450 mm of H_2O. This requirement of air had been fulfilled by adjusting the rpm of a centrifugal blower and connecting it in the air flow line.

3.3 Arrangement of Hot Blast System

At first, the heat exchanger was placed before the blower with its one end opened to the atmosphere. The blower was sucking air through the heat exchanger and was passing the hot air into the cupola. With this arrangement the temperature of blast was measured to be about 250°C. This hot blast supplied into the cupola improved its performance. The temperature of molten metal was raised to about 1400°C. but the main problem was that the hot air passing through the blower, increased its temperature and there was a danger of its getting damaged In order to avoid the problems, the arrangement was changed. The heat exchanger was then placed between the blower and the cupola. Instead of sucking air through the heat exchanger, cold air was forced through it by the blower and eventually the air was heated before entering into the cupola. The temperature of blast was increased to about 300°C This hot blast increased the temperature of the molten metal to about 1450°C and the fluidity of the metal was also increased The detailed arrangements of the hot blast system are shown in Fig. (9,10 and 11).

4. PRODUCTION OF BASE IRON

Pig iron, cast iron scrap and steel are the main raw materials used for themanufacture of ductile base iron. In case of cupola furnace the percentage composition of ductile base iron and the melt temperature are very importent.

The problem of the melt temperature was overcome by adopting the hot blast system The other basic requirement for production of ductile cast iron, that is low sulphur are met through the technique as discussed below.

4 1 Charge Calculation

To reduce the high sulphur content in the melt the hard coke and ferrous charges were first analysed for sulphur and following was the result

Sulphur in hard coke-0.7%

Sulphur in pig iron -0 08%

Sulphur in cast iron scrap (bought from outside)-0 09% and

Sulphur in steel scrap - 0.03%

So the total percentage of S in the charge was 0.035%. The melt from these product showed a sulphur content of 0.082%; which was not suitable for the production of ductile cast iron

Then attempt was made to procure pig iron, hard coke and scrap with lower sulphur content and the following charge materials were obtained.

hard coke of S content 0.5%,

pig iron of sulphur content 0.05%,

cast iron scrap (home) of sulphur content 0.082% and

steel scrap of sulphur content 0.025%.

The proportion of these charges to get the required persentage of chemical composition that is total carbon 3.00% min, Silicon 2.5% max, P 0.08% max and S 0.04% max were calculated and a small quantity of Fe-Si-Mg alloy with 5% Mg and Fe-Si inoculant with 90% Si and free from C were also added for the production of ductile cast Iron. The charge calculated are as follows.

1) Pig iron	60%
2) Home Scrap	35%
3) Steel Scrap (home)	3%
4) Fe-Si	0.1%
5) Fe-Mg-Si	2.3%
6) Fe-Si (inoculant)	0.6%

The product of the charge was analysed and the following result was obtained C-3.2%, Si- 2.1%, P-0.069%, Mn-0.03%, and S-0.07%. Except for S, the percentage composition of the product was suitable for ductile iron production.

Desulphurizing the melt was then aimed at because high sulphur hindered effective nodularization. Desulphurization prior to treatment was justified[4] as the sulphur content in the base iron exceeds 0.04%.

4.2 Desulphurization

It was aimed to desulphurize the melt by Na_2CO_3. Certain percentage of the desulphurizing agent was placed in a big ladle and then molten metal was tapped over it directly from the cupola furnace.

The metal desulphurized with different percentages of Na_2Co_3 at the big ladle gave the following result.

% Na_2CO_3	% Sulphur in the Cast
0.4	0.032 to 0.041
0.75	0.027 to 0.04
1	0.030 to 0.042

The control of S was found almost satisfactory but other problems were noticed. Evolvement of obnoxious gases and slag inclusion in the melt took place.

Then desulphurization with CaO was then attempted and following was the result.

% CaO	% Sulphur in the cast
0.4	0.034 to 0.045
0.75	0.025 to 0.037
1	0.030 to 0.041

The control of S was again found almost satisfactory but the following problems were observed

i) difficulty in mixing CaO with the melt,

ii) fall of temperature due to longer holding time,

iii) increasing quantity of blow holes and

iv) some hard spots in the casting.

So some other chemicals for desulphurization were used. The Foseco chemicals were procured and used to overcome the problems. These chemicals are:

1) Desulfex 150 - to use in the ladle as a desulphurizer, this also increases melt temperature about 10° C

2) Ferrogen 12- a degasser to derive out oxides of metal and other gases and thicken the slag.

3) Ferrux 707- a highly exothermic compound to be used as cover over the ladle and at the top of the riser of the mould to maintain high temperature.

The foundry chemicals used in different castings gave the following result:

% Desulfex	% Sulphur in the cast
0.4	0.41
0.5	0.023
0 6	0.025

Melt temperature during pouring in the mould was found to be satisfactory Average casting quality was found to be free from blow holes and was quite dense.

4 3 Ductile Base Iron

With this preparation proceedings were made for the experimental production of ductile cast iron in the hot blast cupola.

The percentages of materials are mentioned in the article 4.1 and were charged into the hot blast cupola furnace. The molten metal was tapped directly from the cupola in a red hot big ladle containing 0.5% desulfex-150, and 0.1% ferrogen-12. After tapping the molten metal, slag was removed and the desulphurization was carried out. The temperature of the molten metal was about 1450° C.

5.PRODUCTION OF DUCTILE IRON

5.1 Standard Test Bar Pattern Preparation

Generally strandard test bars are made from the ductile cast iron to assess its quality. Test pieces must be as sound as possible otherwise wrong results will be obtained from the tests

So to ensure soundness of the samples the test bars were made from the 25 mm Y-block.

A Y-block pattern was made according to the design and dimension shown in the fig.14. The center line of the tensile bar is also shown in this figure .

5.2 Mould preparation

The molding sand used for the casting of Y-block has the following composition- 4% clay, 3.55% water and 1% flour A number of molds were made by hand molding process and were dried in an oven at about 150° C for 12 hrs.

5.3 Preparation of Treatment ladle

The ladle transfer treatmemt with magnesium based master alloys is a relatively violent process. So covered ladle treatment is very suitable for handling and production of ductile cast iron.

A treatment ladle with a lid was designed and constructed (Fig.13). The ladle was designed in such a way so that the height of the ladle is approximately twice its diameter. The height and diameter of the prepared ladle is 26 cm and 16 cm respectively The ladle was fabricated with mild steel sheet and then a lining of 4 cm thickness was made inside the ladle with refractory materials. In order to secure the spheroidizer (FeMgSi) into the bottom of the ladle a partition of 5 cm height and 2 cm thickness is placed at the bottom portion of the ladle The presence of a tundish above the lid limits the rate of filling but magnesium recovery improves substantially and reaction violence and MgO dust formation are minimized. Disregarding the sulphur content, the Mg recovery would amount to 86.5% and it is much better than in an open ladle.

5.4 Spheroidization and Inoculation

In the production of ductile iron FeMgSi with 5% Mg was used as a spheroidizer The amount of spheroidizer used was 2.3% of the weight of treatment metal. The size of spheroidizer particles was about 3 mm to 40 mm.

Fe-Si with 90% Si was used as an inoculant. The amount of inoculant used was 0.6% of the weight of treatment metal. The size of inoculant particles was about 1.5 mm to 10 mm.

Following Karsay[4] the inoculant was added together with the MgFeSi treatment alloy and good results were obtained. At first

Mg Fe Si was placed in the pocket of the treatment ladle and then Fe-Si inoculant was placed on it. Here, Fe-Si act as inoculant as well as cover of the treatment alloy (FeMgSi). The desulphurized molten metal was then poured over it (into the treatment Ladle) for obtaining higher recovery of Mg. Here spheroidizing and inoculation took place simultaneously.

5.5 Casting

The red hot special treatment ladle was prepared by placing 2.3% FeMgSi and 0.6% FeSi in the pocket and covered with its lid. Desulphurized molten metal was poured into the specially prepared treatment ladle through the hole on the lid. When the reaction between molten metal, FeMgSi and FeSi was complete, the cover was removed. Slag was removed from the treatment molten metal and was poured into the mould from the ladle and 0.1% Ferrux-707 was put on the top of the riser and allowed to cool slowly. During pouring the molten metal into the mold, the temperature of the molten metal was about 1360°C. Molds were broken down after slow cooling.

6. TEST PERFORMED

6.1 Chemical analysis of S.G. iron

Chips from the Y-blocks were collected for chemical analysis of the ductile iron. The percentage of C. S, Si, P, Mg and Mn contents of the ductile iron were determined by standard methods of chemical analysis.

6.2 Mechanical test of tensile specimens

Tensile specimens made from Y-blocks according to the Fig.15 and were tested with a tensile testing machine to obtain the ultimate tensile strength, elongation and reduction of area. The size of the tensile specimen is given in figure.

6.3 Impact Test

V-notched charpy specimens having 55 mm length and 10 mm cross section (Fig 16) were prepared from the same Y-blocks as was used for the making of tensile specimens. These specimens were tested by means of an universal impact testing machine under the as-cast conditions.

6.4 Metallographic test

For metallographic study specimens were cut from circular bars of as cast ductile iron having 25 mm diameter. The specimens were polished by using standard technique.

After polishing the specimens were cleaned by aceton Microstructure of these specimens were examined under the optical microscope both in the etched and unetched conditions. Photographs of microstructures were also taken .

7. RESULTS AND DISCUSSION

A number of castings were made for producing ductile cast iron by introducing hot blast system in a cupola furnace the results of the work are given below.

7.1 Temperature of hot blast and molten metal

The temperature of hot-blast from the developed heat exchanger was measured by a pyrometer and was found to be about 300°C. The molten metal temperature was also measured and was found to increase from 1350°C to about 1450°C after the introduction of the hot blast This hot blast is quite suitable for the production of ductile cast iron.

7.1.1 Melting Rate

The molten metal delivery rate of cold blast cupola furnace was about 17 kg per minute. The introduction of hot blast system in the cupola increased the delivery rate upto 23 kg per minutes Thus there is an increase in furnace efficiency.

7.1.2 Coke -metal ratio

The coke-metal ratio is a very important factor in the melting of iron in a cupola furnace. The coke metal ratio before the hot blast was 1. 5 This ratio inccreased to about 1:10 after the conversion, that is one ton of coke can melt 10 tons of metal. This ratio indicates the saving of imported hard coke besides the economic advantage.

7.2 Chemical Analysis

Molten iron for the production of ductile iron should be Low in sulfur and phosphorus relatively high in carbon content .and with silicon within established limits These elements in the molten iron were adjusted through chemical analysis.

7.2.1 Base Iron

The chemical composition of pig iron, steel scraps and cast iron scraps used as a charging materials for the production of ductile iron were determined by the standard methods of chemical analysis The compositions of the pig iron, steel scraps and cast iron scraps (bought from out side) are listed in the Table-1. To ensure the desired composition of base iron, the percentage of C, Si, Mn, S & P in the charge were caculated and gradually adjusted with the helps of chemical analysis. The results of chemical analysis of the iron produced in the 1st heat is shown in Table-2. Due to the presence of high S in the product, it was rejected for ductile iron production. It was the result of relatively high S content in the pig iron, steel scraps, and cast iron scraps (bought). As a result pig iron, steel scraps and cast iron scraps (home) with a lower S content were used The percentage composition of these materials were analysed and the results are shown in the Table-3. The desired compositions for the production of ductile base iron are shown in Table-4 Suitable Charge calculations for desulphurisation and production of ductile cast iron is shown in Table-5. The compositions of iron produced in the 2nd heat with low sulphur charge were also determined which has been listed in Table-6. The percentage of S in the base iron was 0.07% and this was suitable for desulphurization.

7.2 2. Desulphurization

Although desulphurization of the above base iron could be carried out with Na_2CO_3 and CaO, however, satisfactory performance was achieved by desulfex-150 for the production of ductile base iron. The results of chemical analysis of the desulphurized iron produced is shown in Table-7.

7.2 3 Ductile iron

The composition of the ductile iron produced was chemically analysed. The result of the analysis is given in Table-8.

7.3 Microstudy

Microstructures were observed under the optical microscope in the unetched and etched conditions Photographs of microstructures are shown in Figs. 17 and 18.

The structure shown in Fig.17(a). The microstructure of a bar having 25 mm diameter and is the product of a heat where pouring temperature was very low i e about 1315°C under the unetched condition. A mixture of nodule, flake and vermicular graphite were found in the microstructures with predominent flake and vermicular graphites Fig.17(b), shows the microstructure of the same sample under etched condition. The matrix contains pearlite, cementite and ferrite .

Fig. 18(a) shows a microstructure under unetched condition from a bar having 25mm diameter from another heat where the pouring temperature was about 1375°C. Spheroidal graphites were found in the microstructures. Fig 18(b) shows the microstructure of the sample under etched condition. The matrix contains only pearlite and ferrite and their percentages are about 90% pearlite and 10% ferrite.

7.3.1 Nodule count

The number of nodules observed per square milimeter in the microstructure of 25 mm diameter bar Fig. 18 (a) were count in the range of 75-100 nodules per square milimeter.

7.3.2 Nodularity

The average nodularity of nodules in this microstructure was also measured and it is about 80%.

7.4 Mechanical Properties

The mechanical properties of first heat product was not determined because it structure was similar to cast iron. The products of subsequent heat were ductile cast iron Mechanical properties from such sample were determined and are given in tabular form.

7.4.1 Tensile test

The tensile specimens were tested by the universal testing machine The testing results are given in the Table - 9.

7.4.2 Impact Test

V- notched impact specimens were tested by using the universal impact testing machine. Impact energy absorbed to break V-notch specimens in the as cast condition were measured in NM unit which is given in Table-9.

7.4.3 Hardness

Hardness of specimens were measured in B scale of rockwell hardness tester. The rockwell hardness in B scale are also given in the Table-9

Specimen1, showed higher U.T.S, percentage elongation and percentage reduction of area than specimen 2. Both the specimens showed low value of the percentege of elongation and the percentage of reduction of area. It was due to the formation of lower number of ferrite rings in the matrix.

The samples however, were quite malleable and could be bent without fracture. During machining of tensile specimens the machinability of the ductile iron produced was found satisfactory. It was also tried with welding and was found to the weld well.

The overall properties of the as-cast ductile iron obtained were not so good as that of produced in induction furnace[5] because temperature and chemical composition of molten metal were not easy to control in the cupola as in an induction furnace.

8. CONCLUSION

The following conclusion may be drawn from the work of the present investigation.

1. External combustion type hot blast can be used in the cupola furnace to raise the temperature of the hot blast to at least 300°C and that of the molten metal to at least 1450°C

2. Through the use of hot blast the melting rate of cold blast cupola furnace was increased from 17 Kg per minute to 23 kg per minutes

The coke metal ratio was also increased from 1:5 to about 1:10.

3. A hot blast cupola furnace is suitable for the production of ductile iron.

4. Microstructure is more or less similar to that produced in an induction furace, however, the property is slightly inferior.

9 SUGGESTIONS FOR FURTHER WORK

2. The temperature of hot blast may be further increased by improving the design and construction of the heat exchanger.

3. Attempt should be made to minimise the losses of heat through radiation from the blower pipe and wind belt by utilizing asbestos wool or glass wool.

4. A study on the treatment of molten metal into a reservor or pit furnace should be carried out for reducing the excessive temperature loss and also for controlling the chemical composition of ductile base iron.

5. Ductile iron production in a cokeless cupola should be attempted as there will be no sulphur pick-up from the coke.

6. Further investigaion should be carried out for the improvement of microstructure and property of ductile cast iron made in a cupola.

TABLES

Table- 1 : Composition of charged material

Charge material	Composition, wt%						
	C	Si	Mn	P	S	Mg	Fe
Pig iron	3.46	2.7	0.54	0.06	0.08	-	Balance
Steel scrap	0.25	0.20	0.31	0.04	0.031	-	Balance
Cast iron scrap (bought)	3.35	1.8	0.03	0.08	0.09	-	Balance
Hard coke	Fix.81.1	Ash10.4	mois. 7.2	Vola. 0.6	0.7	-	-

Table-2 Compositions of produced iron (in the 1st heat).

Composition, % Wt					
C	Si	Mn	P	S	Fe
3.19	2.6	0.7	0.08	0.082	Balance

Table- 3 Composition of charged material with low S.

Charge material	Composition, wt%						
	C	Si	Mn	P	S	Mg	Fe
Pig iron (Brazil)	3-4.75	2.75-3.25	0.5-1	0.80	0.05	-	Balance
Steel scrap	0.23	0.21	0.29	0.03	0.025	-	Balance
Cast iron scrap (Home)	3.32	2.1	0.03	0.69	0.082	-	Balance
Hard coke (Australia)	Fix. 82.4	Ash. 9.6	mois. 6.9	Vola. 0.6	0.5	-	-

Table - 4 Target composition of S.G.iron.

Composition, wt %			
C	Si	Mg	S
3.30-4.20	1.10-3.50	0.04	0.02 (Max)

Table- 5 Charge calculation for production of ductile iron.

Charge materials		Composition, wt%						
	%	C	Si	Mn	P	S	Mg	Fe
Pig iron (Brazil)	60	3 - 4.75	2.75-3.25	0.5 - 1	0.80	0.05	-	Balance
Steel scrap	3	0.23	0.21	0.29	0.03	0.025	-	Balance
Cast iron scrap (Home)	35	3.32	2.1	0.03	0.69	0.082	-	Balance
Fe-Si	0.1	-	50%	-	-	-	-	Balance
Fe-Mg-Si	2.3						5	-
Fe-Si Inoculant	0.6	-	90					Balance

Table-6 Compositions of iron produced (in the 2nd heat) with the charge having a low S.

Composition, % Wt					
C	Si	Mn	P	S	Fe
3.2	2.1	0.03	0.069	0.07	Balance

Table-7 Composition of desulphurised iron (by 0.5% Delsufex-150).

Composition, wt%					
C	Si	Mn	p	S	Fe
3.20	2.1	0.38	0.067	0.023	Balance

Table -8 Composition of manufactured ductile iron

Composition, % Wt						
C	Si	Mn	P	S	Mg	Fe
3.2	2.4	0.38	0.06	0.023	0.032	Balance

Table-9 Tensile properties, Impact energy and Hardness.

Tensile Specimen No.	UTS N/mm^2	% Elongation	% Reduction of area	Impact energy N/mm	Hardness in B scale
1	450	2.0	4.1	75	105
2	435	1.5	3.2	70	108

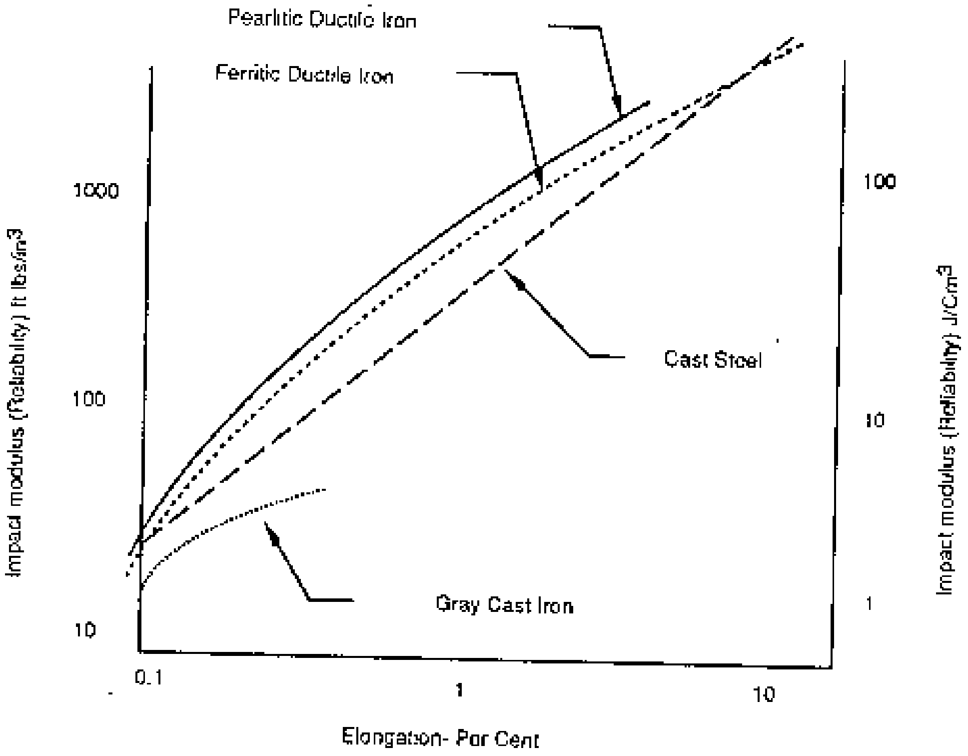

Fig 1- The Reliability of four Cast Ferrous Alloys Under Impact Load as a Function of the Plastic Deformation (Schematic).

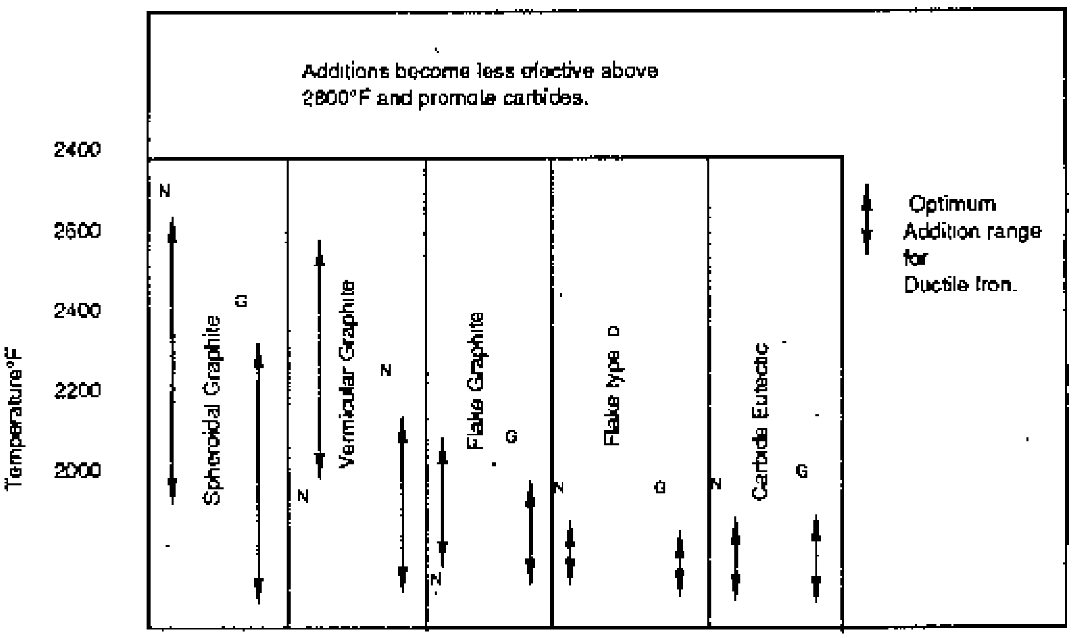

Fig 2- Nucleation (N) and growth (G) temperature ranges of graphite and carbides.

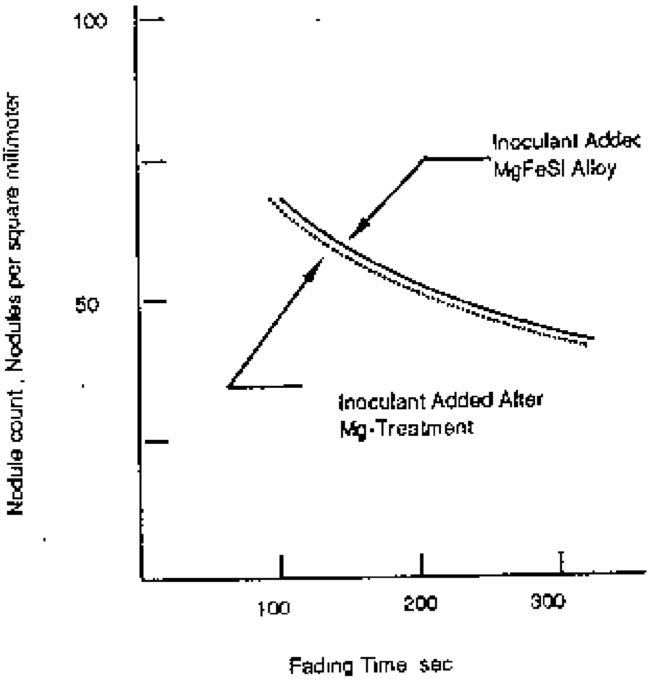

Fig. 3- Comparison Between Two inoculating Methods The Temperature of the Inoculation was practically Identical (2,485 & 2,500°F-1,363 & 1,371°C)

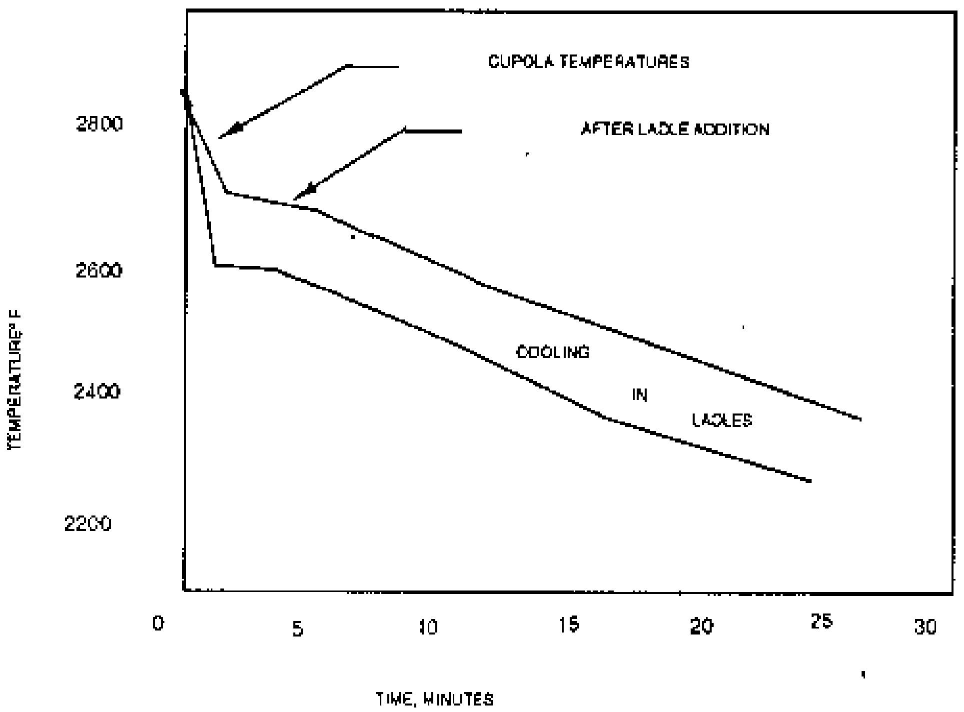

Fig 4-Typical time-temperautre cooling cycle during processing of ductile iron handled in 250 lb Pouring ladles.

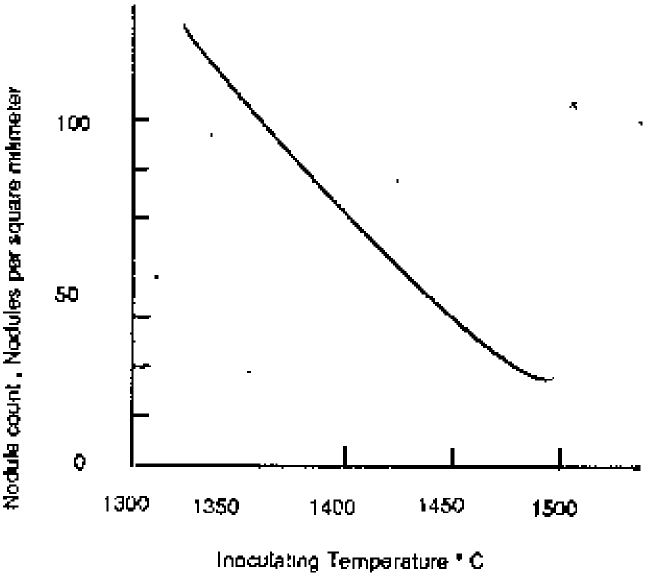

Fig. 5- The effect of temperature on the inoculated condition

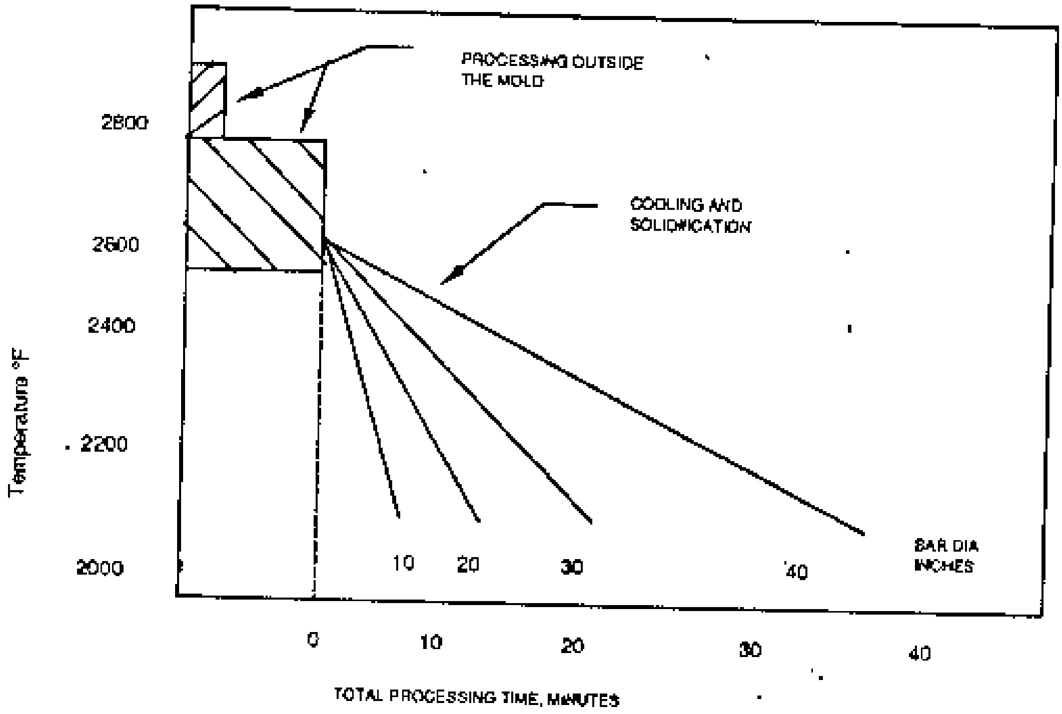

Fig.6- Total time-temperature cycle of processing from melting furnace to enable of solidification of ductile iron.

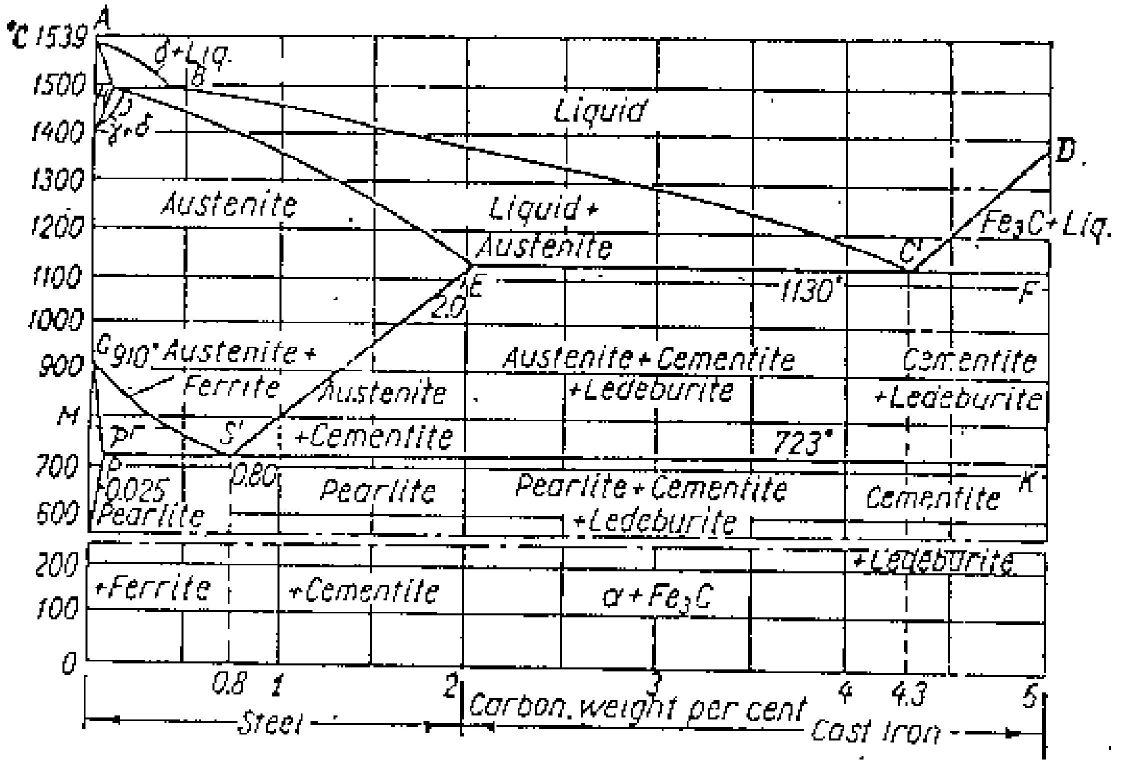

Fig. 7-Iron-carbon equilibrium diagram

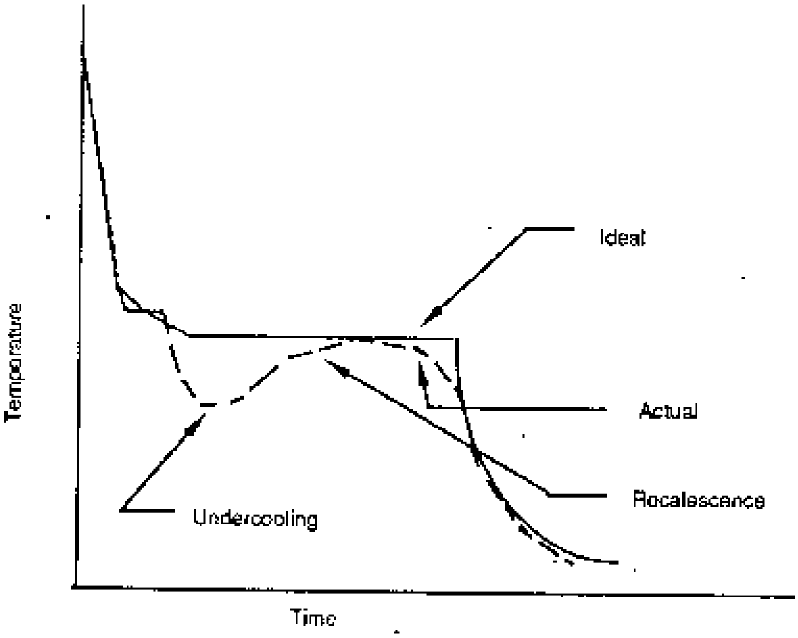

Fig. 9- Typical Ideal and Actual Cooling Curves of Hypo-eutectic S G iron.

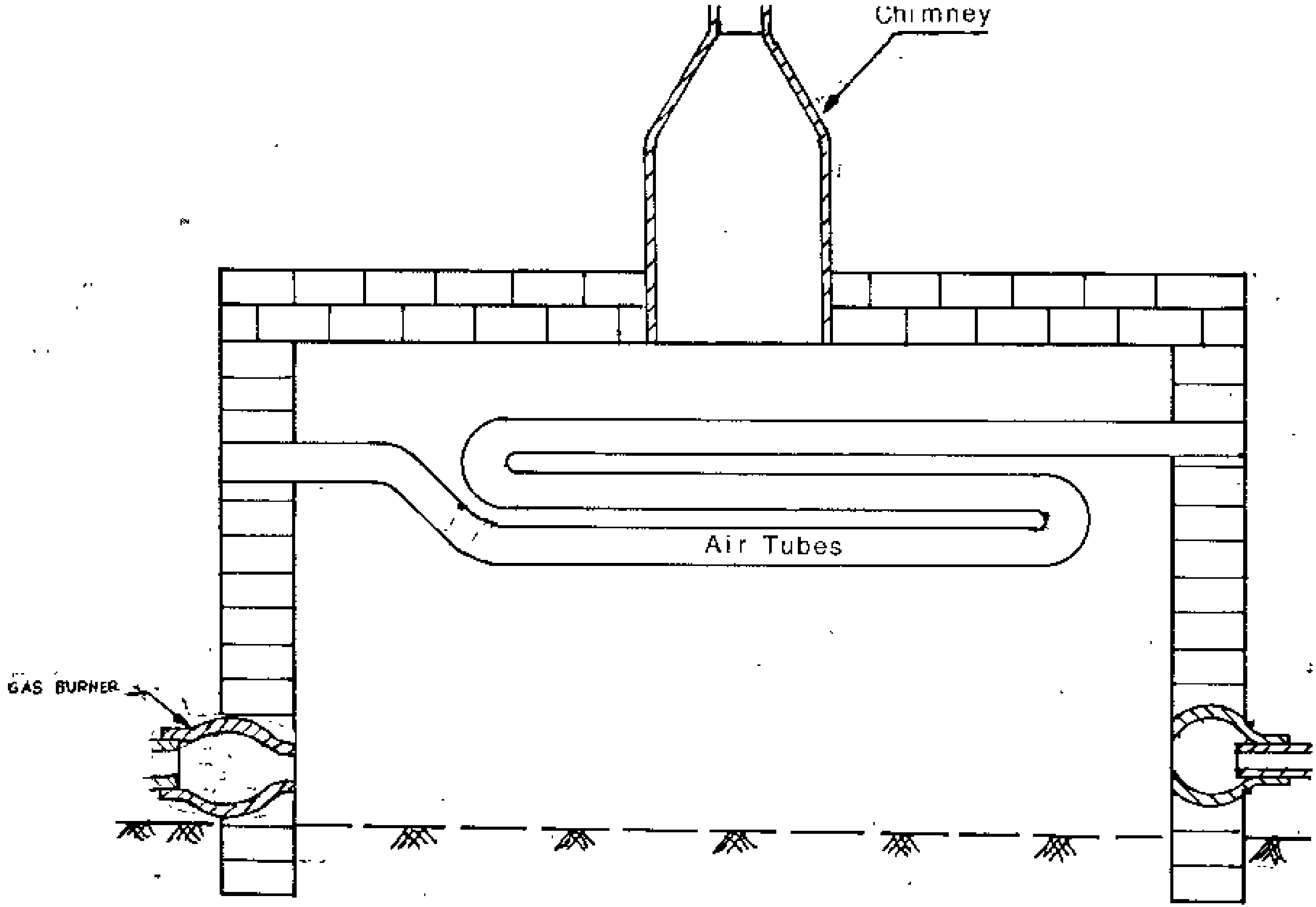

Fig.9- Heat Exchanger

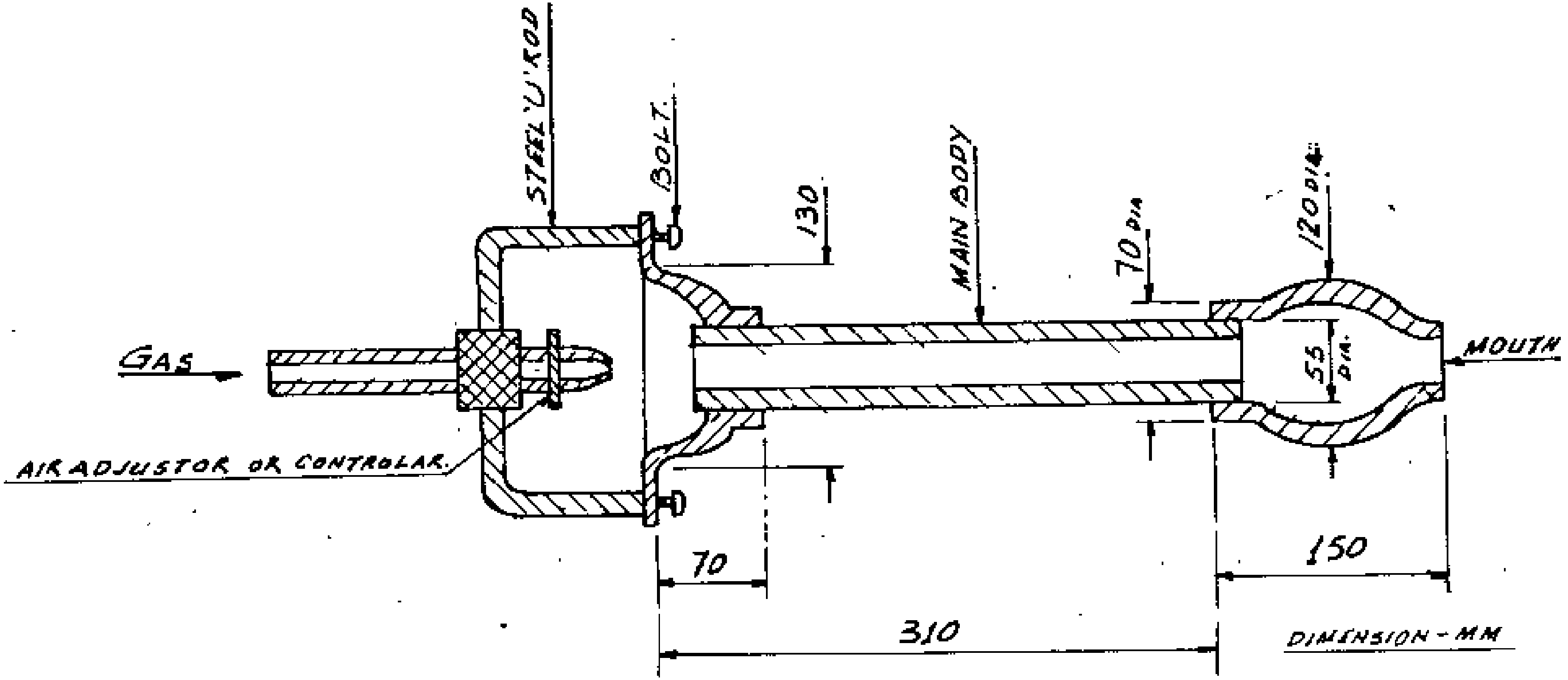

Fig.10- Gas Burner

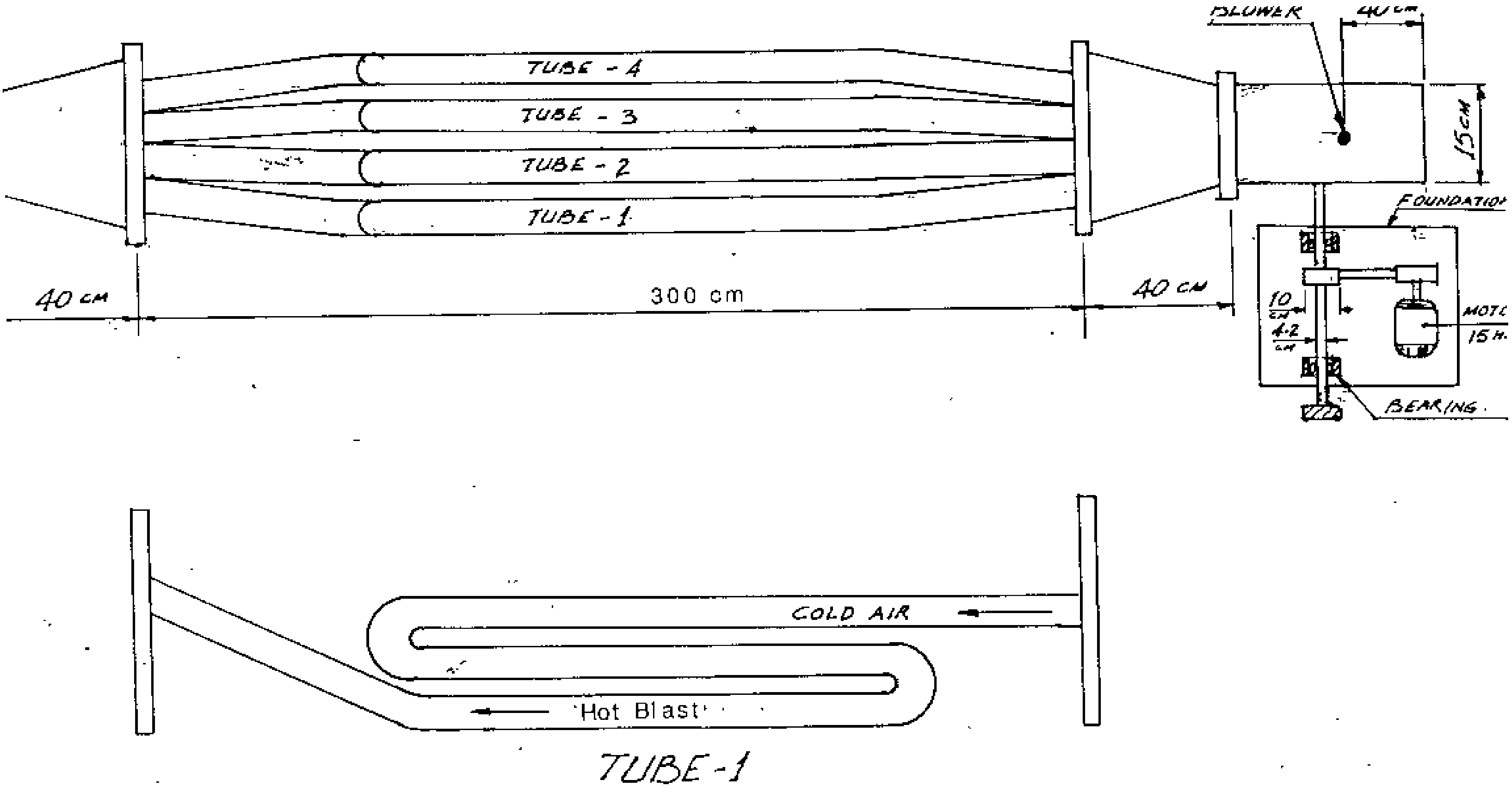

Fig.11- Arrangment of Air Tubes

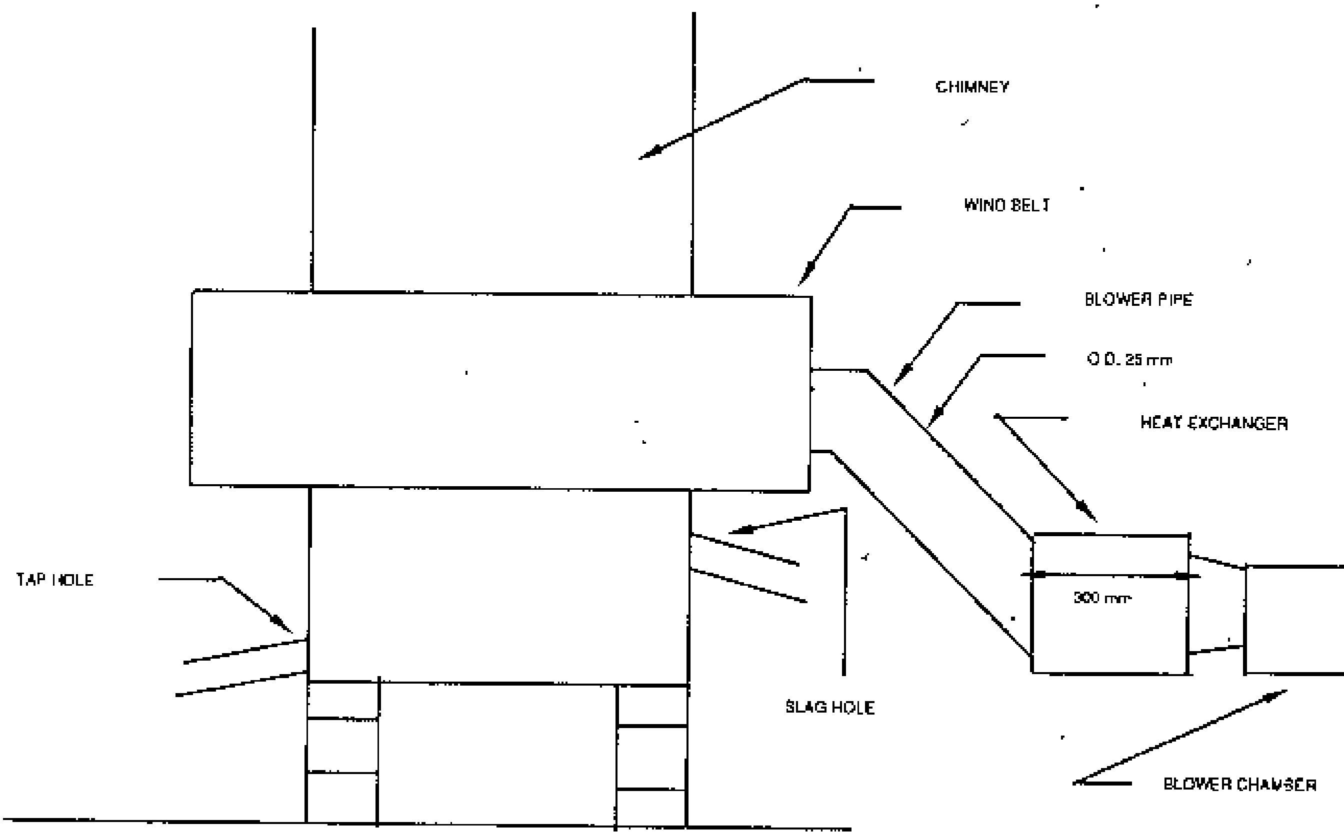

Fig 12- HOT BLAST CUPOLA FURNACE (SIMPLIFIED)

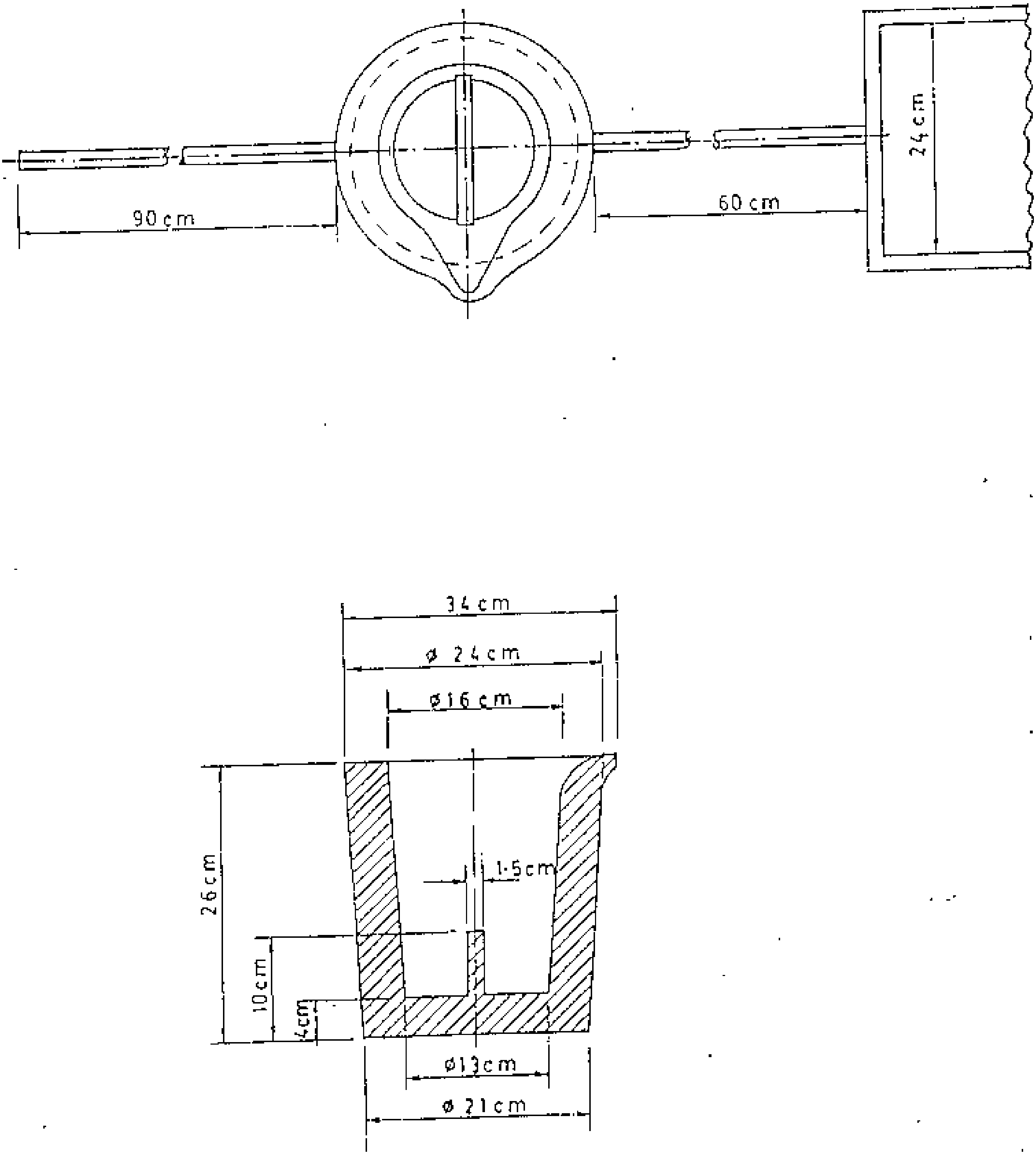

Fig.13- Treatment Ladle

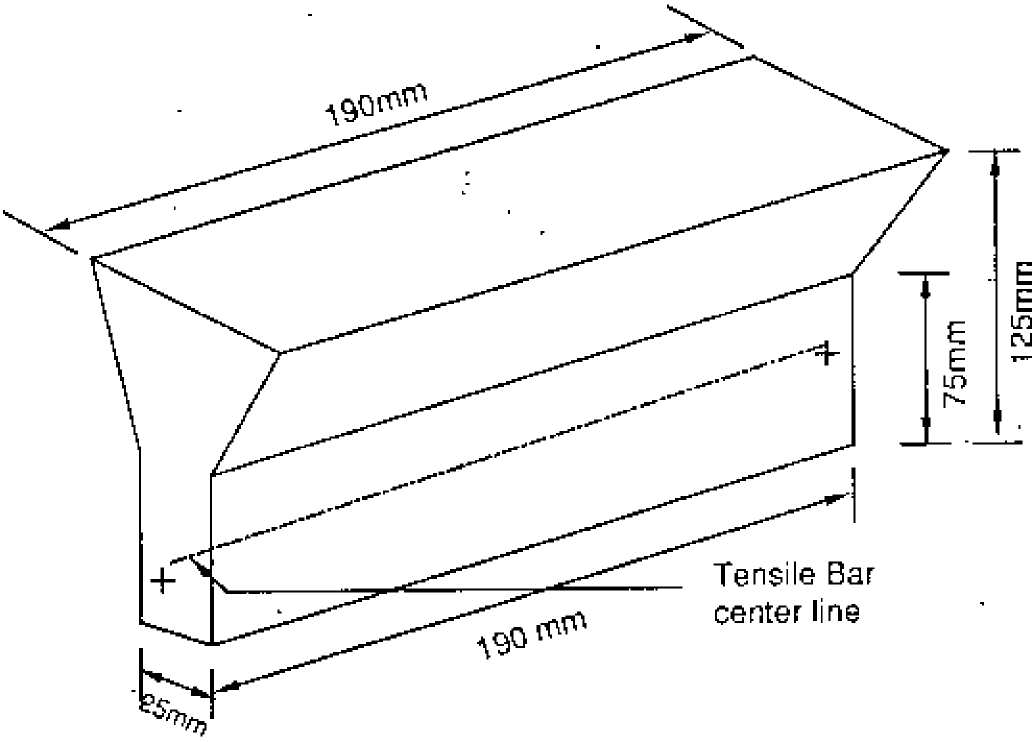

Fig. 14- Y-Block

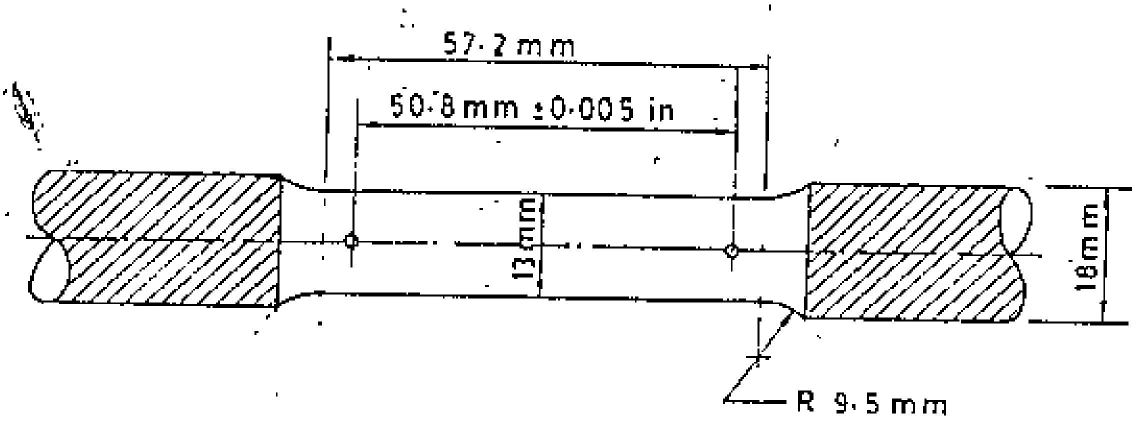

Fig.15 · Tensile Specimen

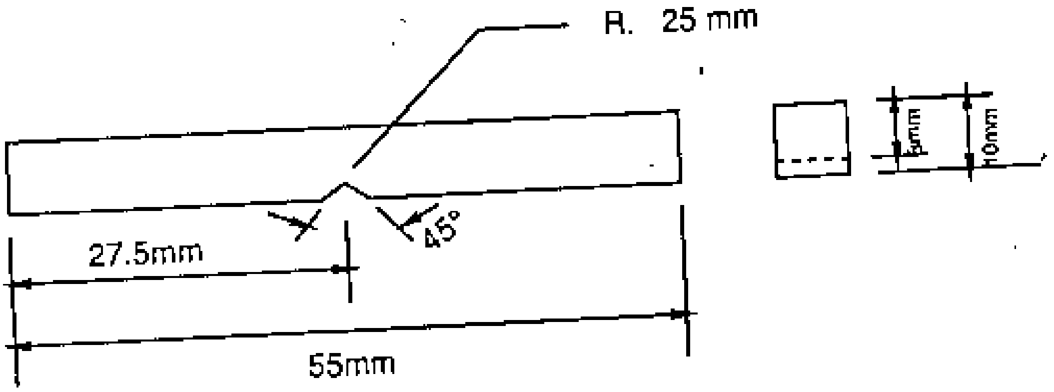

Fig. 16- V-notch impact specimen

Fig 17(a)- Microstructure of ductile cast iron in unetched condition (first heat).

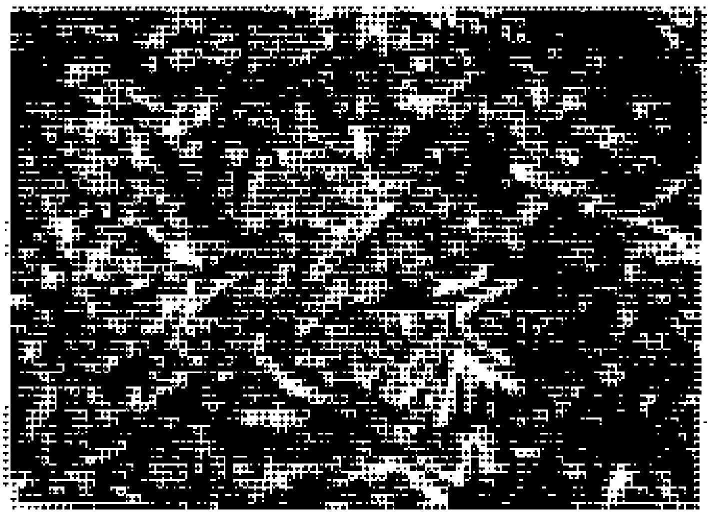

Fig.17(b)- Microstructure of ductile cast iron in etched condition (first heat).

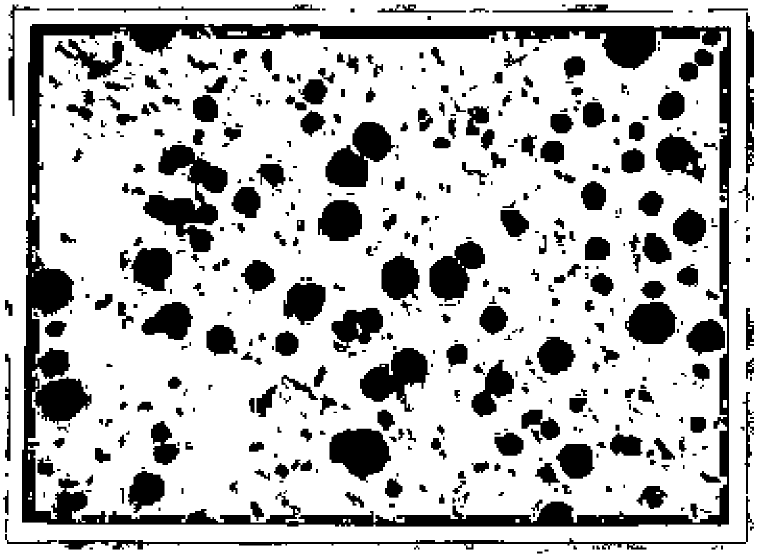

Fig.18(a)- Microstructure of ductile cast iron in unetched condition.

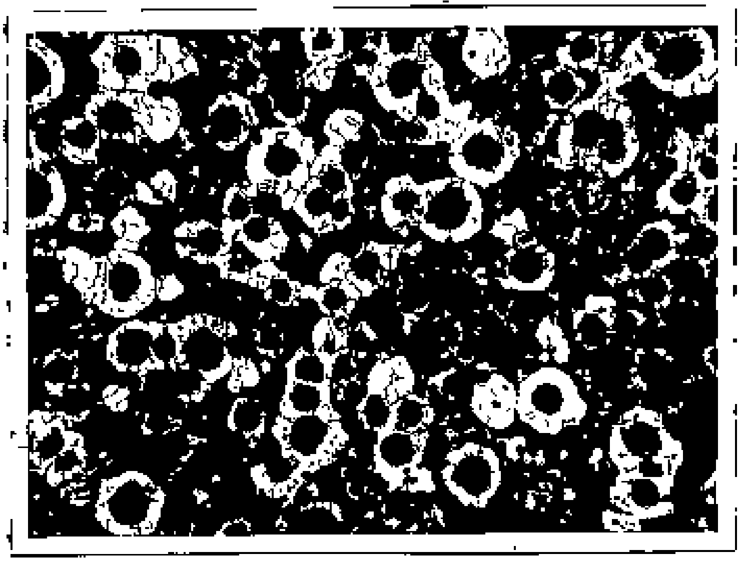

Fig.18(b)- Microstructure of ductile cast iron in etched condition.

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