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REVIEW OF THE STATUS OF DUCTILE IRON CASTINGS FROM DIRECT REDUCED IRON IN TRINIDAD AND TOBAGO

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ABSTRACT

This paper proposes that ductile iron castings could be made in a developing country such as Trinidad and Tobago using indigenous sources of iron in a foundry equipped with a small typical medium frequency induction melting furnace. The source of iron chosen was direct reduced iron (DRI) pellets, which are produced in Trinidad and Tobago.

One basic requirement of an iron-carbon melt needed to produce ductile iron is that it should contain a minimum amount of undesirable impurities such as sulphur. The iron content of direct reduced iron pellets meets this requirement as confirmed by a series of melting tests. Ductile cast iron was produced using the recommended procedures with comparable physical properties to castings produced from conventional iron sources both in the as-cast and heat-treated conditions.

1.0 BACKGROUND

The twin island state of Trinidad and Tobago became a fully independent country in the year 1962. It had, at the time of independence, a reasonably well-balanced economy and social structure. Its three main agricultural crops, (sugar, coconut and citrus), provided permanent as well as seasonal employment for a large section of the rural population. The declining revenues earned from the agricultural exports were more than offset by revenues earned from the export of oil and petroleum products. During the first decade of its independence, efforts were made to improve productivity in oil sectors and to raise the standard of living and of education in the country. The cost of these efforts were met by the value of its export revenues.

The increase in the price of petroleum products in the 1970's, following the creation of OPEC, resulted in an economic 'boom' in oil-producing countries, including Trinidad and Tobago. During the period between 1973 and 1981, the economic activities in Trinidad and Tobago, based on increased oil revenues, expanded at an unprecedented rate. This expansion resulted in the creation and enlargement of import-oriented businesses, a shift of the rural population towards urban centres with the consequent neglect of agriculture, and high employment at escalating salaries. Such a state of affairs, high import bills as well as high salaries, resulted in severe inflation and a growing dependence on imported goods, including food and services. Owing to the increasing rates of inflation, the cost of large-scale, social and economic development projects escalated until the point was reached in 1981, where the total revenue of the country was barely sufficient to cover recurring expenditure in capital projects and the import bill. By 1983, Trinidad and Tobago was beginning to draw upon its foreign currency reserves in order to meet its financial commitments.

During the following decade, (1983 - 1993), there occurred a series of economic setbacks. The decrease in world oil prices caused a sharp drop in Trinidad and Tobago's revenue. Two major sectors of the economy, the construction industry and the automobile assembly industry, were the first to be affected and they contracted rapidly. These being labour-intensive industries, such a contraction created the first wave of unemployment and reduction of national spending

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power. Subsequently, several major businesses, involved in the importation of goods and services, either had cut-backs or closed down completely. High salaries and production costs combined to make locally-produced goods and agricultural products uncompetitive on regional and world markets. This lack of competitiveness stifled hopes for growth of the newly established manufacturing sector. In order to meet local expenditures and import bills, as well as to service a now-growing foreign debt, the Trinidad and Tobago dollar was devalued twice and finally allowed to float. Its current (1998) value in relation to the US dollar is approximately 2.5 times lower than it was in 1983. This economic downturn accompanied by the high unemployment has created not only a general decline in the standard of living but also an increase in the number of social problems. Prominent among the latter is a decrease in the standard of public health services, decreases in the levels of maintenance of both public utilities and infrastructural elements, (roads and buildings), and a sharp increase in the crime rate.

Steps taken by the government to address these problems included the encouragement of a broader manufacturing base to reduce the country's reliance on imports and to increase job opportunities. In particular, efforts have been directed toward developing "downstream industries" based on existing primary industries including the existing steel plant. To date, despite the attempts made by the government to diversify the productive base with the aid of tax incentives and import restrictions, manufacturing still only plays a small part in the economy. One major obstacle to the government's initiatives is the small size of the local market which limits the type of manufacturing which can be carried out on a viable basis.

The Faculty of Engineering at The University of the West Indies (UWI) has identified casting of metals as a promising manufacturing technique for batch production of metal components. The Department of Mechanical Engineering at the UWI to this end has installed a demonstration foundry unit and associated support and testing laboratories to be involved in the areas of research and development in foundry work in Trinidad and Tobago. UWI's involvement also includes investigations leading to the establishment of an efficient production facility where quality cast products which meet international standards can be manufactured economically utilising all the resources of Trinidad and Tobago which includes raw materials, manpower and equipment. There is an existing small foundry capacity in Trinidad and Tobago which produce gray iron castings from local and imported scrap. The supply of local scrap is dwindling and the situation is aggravated by competition for the supply by the local steel plant which currently uses 80% scrap to produce steel which is largely for export.

Given the situation described above, this paper proposes the production of ductile iron castings under conditions existing in Trinidad and Tobago. Ductile cast iron is becoming increasingly important in industrialised countries because of its higher ductility over gray cast iron which makes it much more versatile. It is capable of being welded, heat-treated and surface-hardened and retains the easy melting and castability of gray cast iron. With properties approaching those of cast steel, it can therefore be used in a cost-effective manner in a variety of fields, such as automotive, agricultural, earth-moving and general engineering [1].

The production of ductile iron from conventional iron sources such as steel scrap has been well-documented in the literature. It is proposed however, to produce the ductile iron in Trinidad and Tobago from direct reduced iron (DRI) which is made by reducing iron oxide to metallic iron in the solid state [2]. Direct reduced iron is produced in Trinidad by Caribbean Ispat Limited (CIL) as a supplement for steel scrap in their electric arc furnace method for the manufacture of steel.

It is further proposed that the foundry facility in Trinidad and Tobago use a medium frequency coreless induction furnace to melt the iron. These furnaces are commonly used in small foundries because they provide a vigorous stirring action [3] and good temperature control which is essential for the production of ductile iron.

2.0 RAW MATERIALS USED TO PRODUCE DUCTILE IRON

To gain control over tramp-element content, ductile iron is generally made from melts using special grades of pig iron, selected steel scrap, and foundry ductile iron return scrap. Pig iron which is the unrefined product of an iron blast furnace is used in ductile iron production for controlling chemical composition [4] and improving inoculation. The quantity of pig iron used is also determined by this need. Since both magnesium and alloying elements (when used) are added separately, the ideal pig iron should be high in carbon (4.0%+), low in silicon (less than 1.0% and for most operations, preferably less than 0.5%) and contain no other element or impurity.

Steel scrap is an excellent charge material for ductile iron provided that it is of consistent quality and free of elements which either interfere with the nodularisation of graphite (such as lead) or cause carbides to form (such as chromium). When comparing economies between pig iron and steel scrap, the cost of carburisation of steel scrap to the level of the carbon content of pig iron must be included. Ductile iron return scrap is an excellent charge material for ductile iron. It should be used in all ductile iron charges. With the use of the correct amounts of magnesium and cerium, good inoculation practice, rapid spectrographic analysis, and control for quality of metal structure by microscopic examination, the amount of the raw materials entering the charge can be varied as economy, metallurgy for the product mix, and the quality of steel scrap allow.

Purchased cast iron scrap cannot be used because the phosphorous content is too high and other elements detrimental to ductile iron are usually present in objectionable quantities [5]. Most steel scrap is higher in manganese than is desirable for best mechanical properties of the as-cast metal, especially in light sections. Cost and availability of melt materials, as comparted with the cost of heat-treatment for the correction of proper as-cast structure of the iron, are the deciding factors in shop practice.

It is highly desirable that the sulphur content of the charge materials be low so that the melt has a sulphur content of less than 0.02%. A typical composition for ductile cast iron is shown in **Table 1** [4].

ELEMENT	WT%
Carbon	3.0 - 4.0
Silicon	1.8 - 2.8
Manganese	0.1 - 1.0
Phosphorous	0.100 max
Sulphur	0.020 max
Magnesium	0.04 - 0.10

Table 1: Chemical Composition of a Typical Ductile Iron Charge

3.0 PRODUCTION OF DIRECT REDUCED IRON

Almost all of the world's supply of metallic iron is produced by the chemical reduction of iron ore which is mainly iron oxide. By far, the largest proportion of this iron is produced in iron blast furnaces using carbon (metallurgical coke) both as a fuel and a reducing agent. The ore is smelted in the blast furnace and the iron product is tapped as a liquid called pig iron, while the unreduced impurities are tapped as liquid slag.

The impure pig iron is somewhat similar in composition to cast iron but it is saturated with carbon and contains a number of metallic impurities which have been reduced along with the iron. **Table 2** gives a typical chemical analysis for pig iron [6]. One notable impurity, with respect to ductile cast iron, is a relatively high sulphur content. Many of these impurities are removed during subsequent refining operations to produce steel but the pig iron "as tapped" is an unsuitable feed for ductile iron manufacture.

ELEMENT	WT%
Carbon	4.3
Silicon	1.11 - 1.48
Manganese	0.53 - 0.73
Phosphorous	0.03 - 0.20
Sulphur	0.12

Table 2: Typical Chemical Analysis for Pig Iron [6]

As mentioned previously, steel (a refined form of pig iron) is an acceptable feed material for the production of ductile cast iron but there is competition for iron from this source. Steel scrap is in demand for remelting to produce steel, particularly in countries without a large scale primary steel production capability such as Trinidad and Tobago.

A second source of primary iron was introduced in the early 1950's in which the iron oxide is reduced at temperatures below the melting temperature of iron. The product of this solid state reduction process is called "sponge iron" or "direct reduced iron" (DRI). Because of the lower temperatures involved, the iron product contains far less carbon and other metallic impurities including sulphur than pig iron produced in a blast furnace. On the other hand, because the charge has not been melted, any unreduced non-metallic impurities originally in the ore, remain in the iron product. The gangue can be removed in subsequent melting operations as a slag, but its presence must be taken into account for calculating the flux requirements and for the energy required to melt it.

A number of successful direct reduction processes have been developed including the Midrex Process, HyL, SLRN and Esso FIOR which use a variety of sources of iron oxide and reducing agents. As a result, the DRI products can vary widely in terms of composition, size and density. The majority of direct reduced iron is used as a supplement for steel scrap in the electric arc furnace production of steel. It provides a source of iron units when scrap is scarce or too expensive and its low impurity levels help to dilute unwanted impurities from the scrap in the balance of the charge.

The high purity of the metallic iron content of DRI has attracted several investigators to use it for the production of ductile cast iron which will be described later. These investigators have been confined to the use of cupola or arc furnaces for melting. This study will investigate the melting of DRI in induction furnaces to produce a melt suitable for the production of ductile cast iron. The investigation will focus on the melting of DRI pellets produced by the Midrex process because this is one of the most common methods for making DRI and also because it is the process used in Trinidad by Caribbean Ispat Ltd. (CIL).

3.1 The Midrex Process For The Production of DRI

The iron oxide feed material for the Midrex process consists of iron ore pellets made from beneficiated iron ore. When the iron ore is mined, it contains unwanted impurities which are removed by mineral beneficiation processes. In order to remove the impurities, the ore is ground into a fine state of subdivision. After beneficiation, the fine iron ore or concentrate particles must be agglomerated before they can be used in many metallurgical processes.

One of the agglomeration processes used is called pelletising. This process, usually carried out at the mine site, consists of tumbling the concentrate particles in a drum or disc with enough water to cause them to ball into pellets about 1 - 3 cm in diameter. These pellets have a low initial green strength but after they are dried and heated to an elevated temperature (indurated), the ore particles sinter together and the pellet becomes quite hard and easy to handle. It is important that the reduced pellets be cooled before they are exposed to air as they are prone to re-oxidation because of their porosity and high internal surface area.

A typical chemical analysis for DRI produced by the Midrex process (Caribbean ISPAT Ltd.) is shown in **Table 3**, and **Table 4** shows a typical chemical composition of cast iron and melted Midrex pellets.

Note that during the melting process, most of the residual carbon in the direct reduced iron has been removed by reaction with residual iron oxides. **Table 5** shows the variation in chemical analysis of Midrex DRI pellets from various sources.

ELEMENT	WT%	ELEMENT	WT%
Fe(T)	92.700	S	0.010
Fe(M)	86.600	Cu	0.010
FeO	6.000	Cr	0.020
Fe_2O_3	2.100	Sn	0.003
C	1.530	Bi	0.005
SiO_2	1.320	V	0.150
Al_2O_3	1.350	As	0.005
CaO	0.200	Sb	0.001
MgO	0.480	Zn	0.010
TiO_2	0.250	Pb	0.010
Mn	0.080	P	0.015

Source: Caribbean ISPAT Ltd.

Table 3: Typical Chemical Analysis of DRI (Wt %)

ELEMENT SOURCE	WEIGHT %			
	GRAY IRON	DUCTILE IRON	MIDREX 100% SIDBEC DOSCO	MIDREX ISPAT
C	2.5 - 4.0	3.0 - 4.0	0.07	0.03
Si	1.0 - 3.0	1.8 - 2.8	-	0.0032
Mn	0.2 - 1.0	0.1 - 1.0	0.35	0.086
P	0.05 - 1.0	0.100 max	0.00	0.016
S	0.05 - 0.24	0.03 max	0.011	0.011
Mg	-	0.04 - 0.10	-	-

Table 4: Typical Chemical Composition of Cast Iron and Melted Midrex Pellets

ELEMENT SOURCE	WEIGHT %		
	SIDBEC-DOSCO [7]	BSC [8]*	CIL [9]
Total Fe	88 - 93	93.0	92.7
Metallic Fe	78 - 87	90.0	86.6
Degree of Metallisation	89 - 94	96.7	93.5
Oxygen, as Iron oxides	1.5 - 3.0	ae	2.0
C	0.7 - 2.5	1.7	1.53
Total Gangue	3.0 - 8.8	4.2	3.60
$SiO_2 + Al_2O_3$	2.0 - 8.0	ae	2.67
CaO + MgO	0.6 - 1.5	ae	0.68
S	0.003 - 0.008	0.008	0.010
P	0.010 - 0.030	0.009	0.015

* British Steel Corporation

Table 5: Chemical Analysis of Midrex DRI Pellets from Various Sources

Among the chief concerns in the selection of DRI for the production of ductilie cast iron are the degrees of metallisation and the gangue content [9]. Metallisation is dependent on the amount of unreduced iron in the DRI. The higher the degree of metallisation, the better the DRI for foundry use. Unreduced iron in the furnace requires additional energy and reducing agents and these increase the production cost. The degree of metallisation of the DRI at CIL is 93.5% which is more than adequate for steel-making consumption and still leaves enough reducible oxide to lower the carbon content to the desired level.

The low density of DRI has an important effect on its subsequent melting behaviour [2]. Depending on the method of production, its apparent density can vary between 1.6 and 6.0 g/cm^3. This makes DRI pellets one of the lightest types of iron units charged into melting furnaces. The low apparent density of the pellets arises mainly from their high porosity which is in the order of 60%. **Figure 1** shows a schematic of a 500 kg induction melting furnace similar to the Inductotherm unit in the Department of Mechanical Engineering, UWI. The problems of low density and continuous charging of DRI pellets to the furnace is

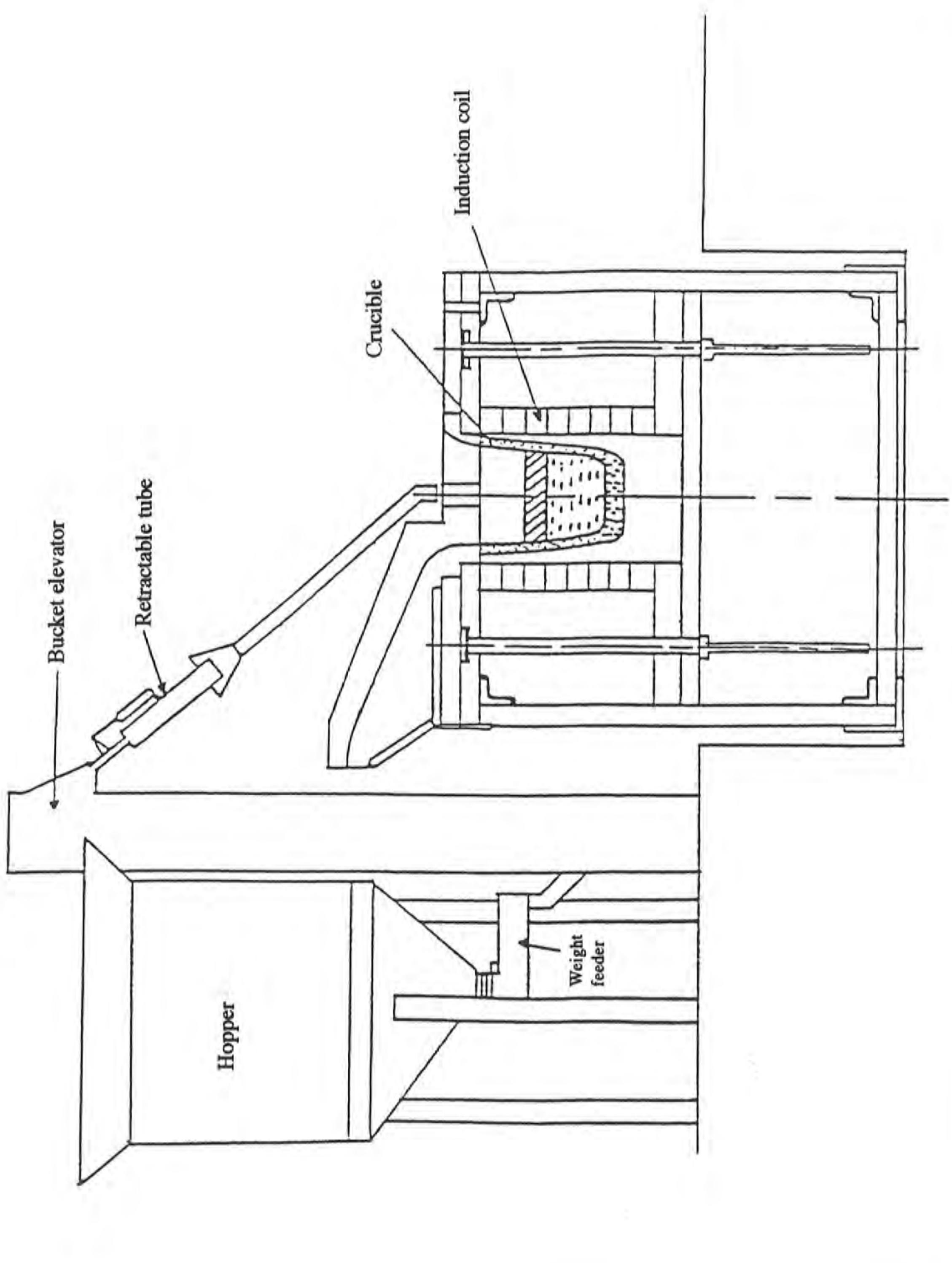

Figure 1: Chemical Analysis of Midrex DRI Pellets from Various Sources

overcome by use of the charging system shown in **Figure 1**.

4.0 PROPERTIES OF DUCTILE IRON MADE FROM DRI PELLETS

The most distinguishing characteristics of ductile cast iron is its ability to be cast with an "as cast" structure containing graphite in the form of spheres instead of flakes. The critical parameters which must be controlled are the melt chemistry and the technique of making timely and efficient additions of the correct inoculants.

Utilising cast iron made from Midrex DRI pellets, physical and chemical tests were conducted on the castings to confirm that ductile iron could be made from the pellets. **Table 6** shows the melt chemistry achieved. From these results, it can be concluded that DRI is a suitable feed stock for ductile cast iron production.

ELEMENT	WT%
C	3.8
Si	2.9
Mn	0.19
S	0.0084
P	0.018
Al	0.020
T_1	0.024
Mg	0.120
Pb	<0.005

Table 6: Chemical Analysis of Ductile Iron Produced with DRI

Ductile cast iron is a very versatile engineering material. It can be heat-treated to produce a wide variety of physical properties. In general, castings made of ductile iron may be heat-treated to relieve internal stresses, improve machinability, increase toughness and ductility, and increase strength and wear resistance. The properties of the ductile iron made in this investigation were determined in the as-cast condition as well as after heat treatment.

5.0 EXPERIMENTAL PROCEDURES

A number of standard 9 mm round tension test specimens were made out of the ductile cast iron produced with the DRI pellets. These were then subjected to a series of heat treatments before mechanical testing was conducted. The results of these tests are presented in **Table 7**.

The following procedures were used to heat-treat the ductile iron test specimens:

Sub-Critical Annealing:

The specimen was heated at 720°C, and held for one hour. It was then cooled slowly, at approximately 55°C per hour, i.e., furnace cooled to room temperature.

Above-Critical Annealing:

The specimen was heated at 820°C, and held for one hour at this temperature. It was then cooled to 720°C and held for four hours followed by furnace cooling to room temperature.

Normalising:

The specimen was heated to 900°C and held for one hour at this temperature. It was then removed from the furnace and force air-cooled.

Quenching and Tempering:

The specimen was heated before quenching in an identical manner to that for normalising, i.e., 900°C for one hour. It was then transferred to the quenching medium (oil) and left in the bath until the temperature was approximately 150°C. The specimen was then tempered at 450°C for one hour.

6.0 DISCUSSION

Production of ductile iron castings in Trinidad and Tobago from DRI pellets can be efficiently achieved in small cast iron foundries with induction melting capabilities. The use of induction melting furnaces are emphasised because they are very versatile, clean and present a minimal of environmental problems. Their use is growing and innovations in the design of power supplies have lowered their capital cost and made them more energy-efficient.

The use of DRI pellets as a raw material in the production of ductile iron castings has not been addressed in the literature to any extent and has

TYPE OF DUCTILE IRON	TEST RESULTS				STANDARD SPECIFICATIONS [6]			
	TENSILE STRENGTH MPa (psi)	YIELD STRENGTH MPa (psi)	% ELONGATION	HARDNESS bhn	TENSILE STRENGTH MPa (psi)	*** YIELD STRENGTH MPa (psi)	% ELONGATION	HARDNESS bhn (minimum)
As-cast	617 (89,440)	*	2.85	217	593 (86,000)	40393 (57,000)	2	201**
Above-critical Anneal	519 (89,391)	471 (68,265)	15.70	156	393 (57,000)	245 (35,500)	18	156**
Sub-critical Anneal	585 (85,277)	*	4.15	196	552 (80,000)	379 (55,000)	6	187**
Normalise	756 (109,617)	*	2.56	255	482-986 (70,000-143,000)	345-848 (50,000-123,000)	0.5 to 7	170-350
Quench and Temper	786 (114,056	*	2.60	302	689-827 (100,000-120,000)	482-620 (70,000-90,000)	2-3	241-302

* The Yield Strength was too close to the UTS to measure.
** Minimum hardness.

Table 7: Summary of Physical Test Results on Ductile Iron Produced form DRI Pellets

therefore formed an important part of this investigation. It has been confirmed that the chemistry of iron melts made from DRI pellets is favourable for the production of ductile iron. The physical properties of castings made from this source were comparable to those of castings made from traditional feed materials both in the as-cast condition and after the usual annealing and hardening heat treatments given ductile iron.

In terms of cost, it would appear from the literature that iron from DRI processes is competitive to typical iron units used to make ductile iron and is likely to remain so in the predictable future. Since DRI is produced in Trinidad and Tobago, it would be a convenient source of iron for a foundry situated there and must be utilised in the production of quality ductile iron castings.

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