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Rolled ductile cast iron DCI as reinforcement element in construction & building applications

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Abstract

Hot rolled ductile cast iron has properties similar to steels with relatively low cost and easy fabrication. It can be used as reinforcement element in construction applications. The effect of double annealing techniques on the properties of hot rolled ductile cast iron was studies. the graphite nodules were deformed as result of rolling progresses. The hot rolled ductile cast irons were subjected to double annealing by heating to 900°C and holding for 3hr then furnace cool to 700°C and holding at this temperature for 3hous then furnace cool to room temperature. The mechanical properties such as tensile strength, impact and yielding criteria of DCI were discussed. The effect of double annealing treatment on hot rolled DCI was studied at different reduction percentages from 26% to 52 %. Scanning electron microscope was carried out to examine the fracture surface of tension and impact specimens. Stress analysis model was developed to study the effect of microstructure variation on the flow stress. The results of these study show that the cost of rolled DCI was less than the steel used in reinforcement with relatively reasonable mechanical properties.

Keywords: DCI, Rolling, Construction, Tensile, Impact, Fracture Analysis

1. Introduction

1.1. Ductile Cast-Iron as a New Constructional Material

Before discovering the method of production of ductile cast-iron with globular graphite or simply ductile cast dated May 1948, designers used only two types of cast-iron: gray cast-iron with zero plasticity and malleable cast-iron with graphite of flaky shape, which was made by means of long and power-consuming high-temperature annealing of so called white cast-iron. Till the beginning of fifties the only constructional material for medium and big cast details, which should have high plastic and ductile characteristics, there was a cast steel [1]. Ductile cast-iron, having high technological, operational and economic qualities, replaced during the last four decades great part of castings of steel, malleable and gray cast-iron and welded constructions.

In narrow minded understanding cast-iron is something fragile and unstable. This opinion may fairly refer to the products of gray cast-iron. Due to unique properties of ductile cast-iron products the growth of production of this material in the world is impressive [2],[3]. At year 2000 total production of ductile cast-iron was more than 20 million tones per year. The importance of ductile cast iron can be appreciated from production statistics, which that they represent 21% (by weight) of all ferrous castings produced in the world. Up to the first half of the last century, only malleable irons were able to partially offer a combination of grey iron cast-ability and steel mechanical properties (first of all, toughness). These cast irons were obtained as a result of extended annealing treatment of white iron, with a matrix microstructure that was characterized by different ferrite and pearlite volume fractions, as a function of the cooling cycle [4],[5]. The main problems of this procedure were the high costs and the difficulty to cast sound white iron components. In 1943, in the International Nickel Company Research Laboratory, a magnesium addition allowed to obtain a cast iron containing not flakes but nearly perfect graphite spheres.

In 1948, at the American Foundry man Society Convention, it was announced that a small amount of cerium allowed to obtain the same result [6].

After more than fifty years, ductile iron should be considered as a family of materials offering a wide range of properties depending on the chemical composition and heat treatment and the consequent microstructure modifications [7],[8].

Matrix microstructure importance is emphasized by the use of matrix names to commonly designate the different types of ductile irons

A Ferritic DCI: this DCI is characterized by a good ductility and impact resistance; ultimate tensile and yield strength are equivalent to a low carbon steel.

B Pearlitic DCI: a pearlitic DCI is characterized by high strength, good wear resistance and reduced ductility and impact resistance.

C Ferritic-pearlitic DCIs: these are the most common DCI; properties are intermediate between ferritic and pearlitic grades and good machinability is obtained with low production costs.

D Austenitic DCI: this DCI shows a high corrosion and oxidation resistance, with good strength and dimensional stability at high temperature.

E Martensitic DCI: these DCI are obtained controlling both the chemical composition (to prevent pearlite formation) and the heat treatment (quench and temper): very high strength and wear resistance are obtained, but with lower values of ductility and toughness.

F Bainitic DCI: this DCI is obtained controlling chemical composition and/or heat treatment: the result is a hard and wear resistant material.

G Austempered DCI (also ADI): ADI are obtained after an austempering heat treatment, with very high tensile strength values (twice than a pearlitic DCI), high elongation and toughness.

Compared with steel, ductile cast iron has generally inferior ductility, weld-ability, toughness and fatigue resistance however, it has superior cast-ability (high Ca and Si), machine-ability, wear, corrosion resistance and damping capacity [9],[10].

Ductile cast-iron is also widely used in construction. During the last 15 years almost all leading firms, that work in this field, began in producing new grades of this material, which allowed increasing loads and decreasing the price the production of casting of ductile cast-iron needs the use of special technologies, equipment, high-quality materials, trained staff and special means of control [11].

2. Experimental Work

2.1. Material

The ductile cast iron used in this work is obtained from El-Nasr Casting Company. The slab cut from centrifugal casting pipe with 1000 mm diameter and 10 mm thickness, which consider as the main commercial product in the Company . The chemical composition of the ductile cast iron is shown in table (1).

Table (1). *The chemical composition of the ductile cast iron*

Contents	C	Si	Mg	S	Mn	Fe
Percentages %	3.68	2.1	0.0042	0.017	0.35	balance

2.2. Treatment before Rolling

- Slices were double annealed (L.H.T) to 900°C and hold for 2hr prior to furnace cooling to 700°C, then held at this temperature for 3hr before the furnace cooling to the room temperature.
- Some of the slices were feritizing annealed (F.H.T) at 920°C for 30min then furnace cooled for 30min Full feritizing Annealing used to remove carbides and stabilized Pearlite, heat to 900˚C, holding long enough to dissolve carbides, then cooling at a rate of 85˚C/h to 705˚C, and still air cooling to room temperature. It improves low temperature fracture resistance but reduces fatigue strength.

2.3. Preheat before Rolling

- The L.H.T specimen is soaked at 950°C for one hour before rolling, while the F.H.T specimen is soaked at 900°C for one hour before rolling.

2.4. Rolling Process

Rolling was carried out on the slices in the circumference direction of the pipe by using a laboratory two - high reversing mill with 320mm diameter rolls and 450mm length. The slices were heated to a temperature range between 900°C and 950°C there soaked for one hour at this temperature. The rolls speed was 25m/min. Reduction in cross sectional area was carried out on 2 to 4 passes. Some of the rolled strips were air cooled A.C, while the others were furnace cooled, F.C at 700°C. Figure (1) shows schematic diagram for the steps of manufacturing, rolling and treatment

2.5. Heat Treatment

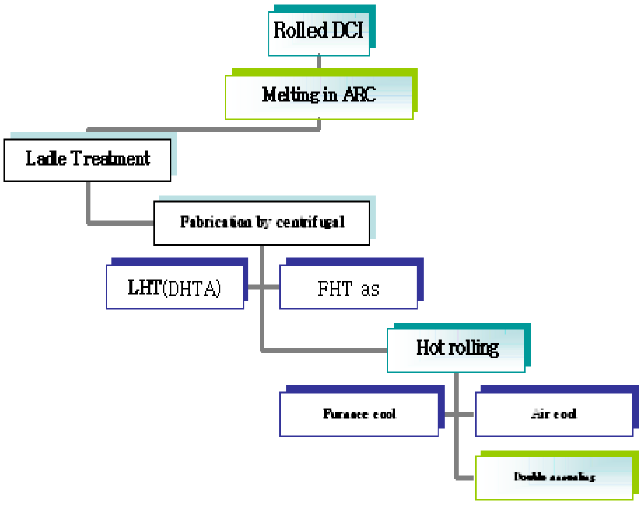


Fig (1). *Schematic diagram for the steps of manufacturing, rolling and treatment*

All specimens were double-heat-treatment annealed (DHTA) by heating in the muffle furnace to 900°C :910°C and holding for 3hr then furnace cool to 700°C and holding at this temperature for 3 hours and then furnace cool to room temperature. Figure (2) shows the cycle of double annealing heat treatment (DHTA).

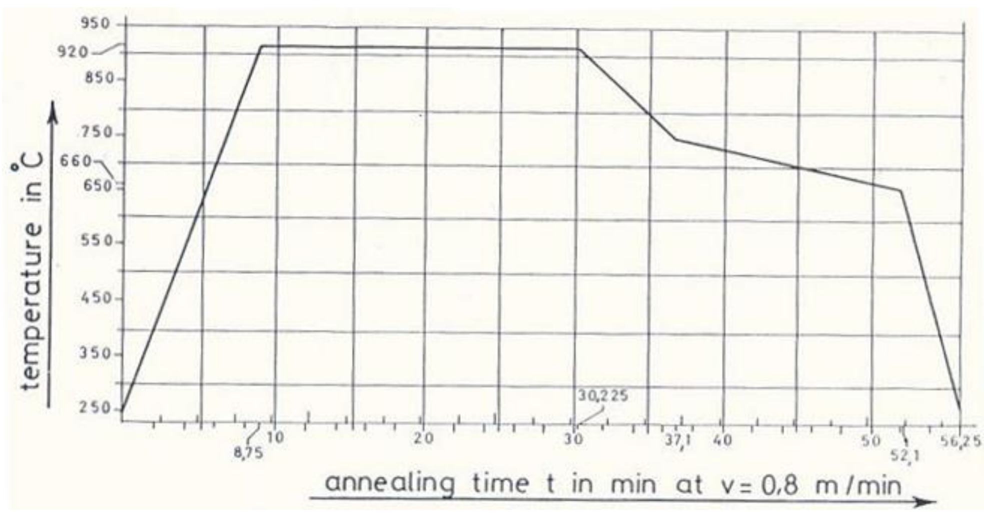


Fig (2). *The cycle of double annealing heat treatment (DHTA).*

2.6. Metallographic Examination

All specimen wear prepared by grinding on different grades of silicon carbide "Sic" emergency paper, coarse grinding and fine grinding were done to produce a uniform level of graphite matrix, finally polishing with alumina were done. The details of the microstructure were revealed after etching in 3% nital solution (3% nitric acid solution in ethanol)

2.7. Tensile Testing

All tensile tests were made by using universal testing machine model 2M1090. in Maadi company for engineering industries. Results were recorded on x-y plotter connected to the testing machine. The tests were carried out at room temperature at the full scale load 5000kg and strain rate was 6mm/min. according to B.S standard.

2.8. Impact Testing

Specimens were machined to the standard size for notched charpy impact test as. The capacity of the impact testing machine is 15kg-m. The initial lifting angle ($\theta 1$) was set at 160^{o}. The absorbed energy required to break the specimen was calculated by using the relation

$$I = GL (\cos \theta - \cos \phi). \qquad (1)$$

Where

I = capacity of the machine 15kg-m

G = wt of pendulum

L = the length of the pendulum arm

ϕ = the impact angle

2.9. Fracture Analysis

The fractured specimens were examined by means of scanning election microscope (SEM) operating at a nominal accelerating voltage of 30kv. Specimen preparation is very simply accomplished by cutting a thin slice of the specimen containing the fracture surface of interest and inserting it into the specimen chamber for direct examination.

3. Results & Discussions

3.1. Mechanical Properties

3.1.1. Tensile Properties

Figures (3) and (4) show both Ultimate tensile strength and yield strength respectively. Both of them increase with increase in reduction percentages. As the result of ductility decrease gradually by increasing the amount of reduction.

3.1.2. Impact

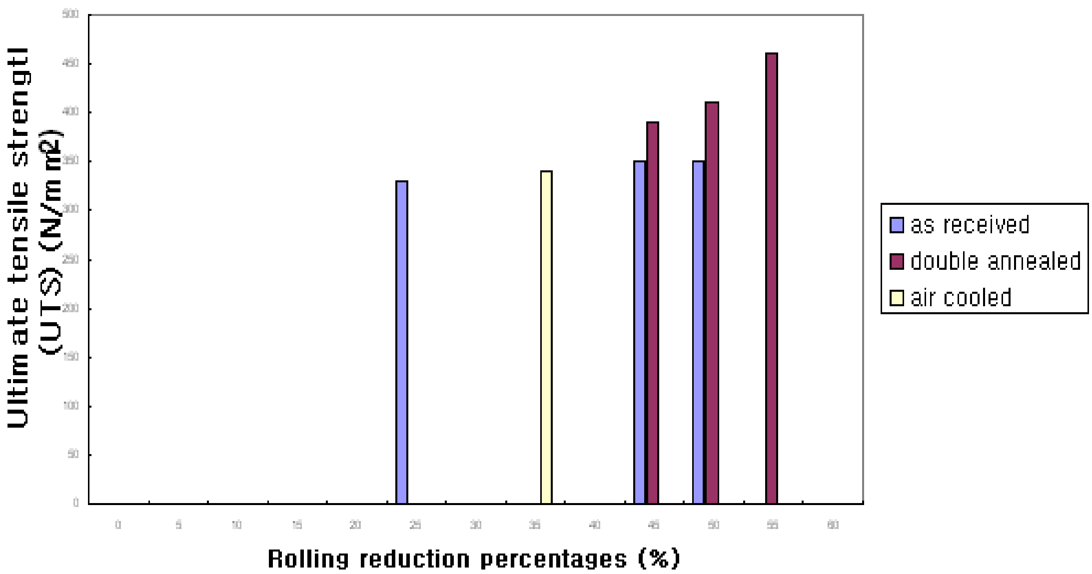
The relation between the impact value and the amount of reduction by rolling at different conditions is shown in fig (8). The impact value decreases with the increase of the amount of reduction. Furnace cool after rolling improves toughness appreciably. The formation of secondary graphite when the amount of reduction increase have negative effect on toughness.

3.2. Fracture Analysis

Figure (6) shows SEM of the fracture surface of an annealed ferrite ductile iron tension test specimen at room temperature. A ductile fracture appearance was recorded, graphite was deformed by hot rolling and large dimples were appeared.

Figure (7) shows impact fracture at room temperature indicates a minimal amount of deformation with no stretching was occured in graphite nodules. In addition, several graphite were appeared to be broken up. This observation could serve as an additional characteristic in differentiating between slow and fast fracture.

The fracture surface of annealed ductile cast iron appeared to consist of big dimples for the tensile test, while irregular fracture features exist on impact test.



Fig(3)The effect of reduction percentages on Ultimate tensile strength (UTS) at different rolling conditions

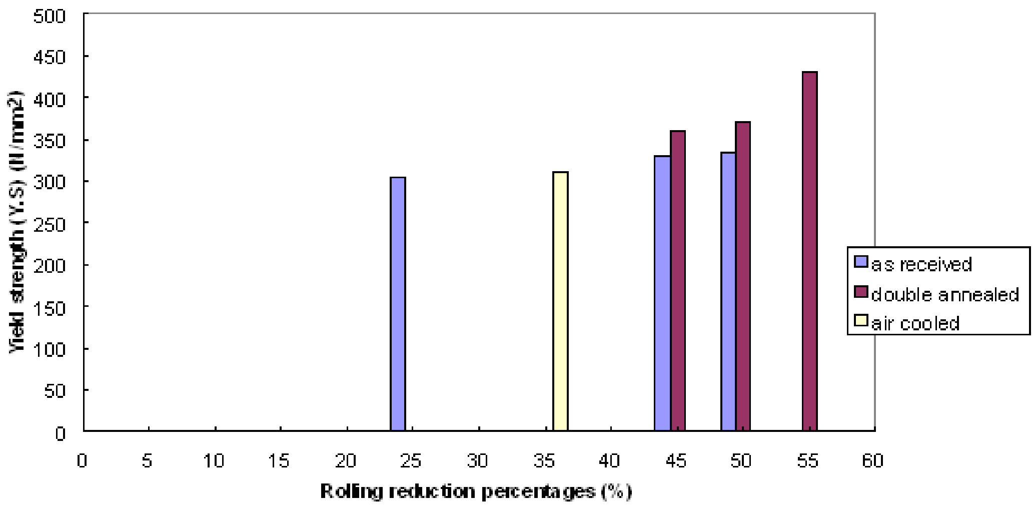


Fig (4) The effect of reduction percentages on yield strength (YS) at different rolling conditions

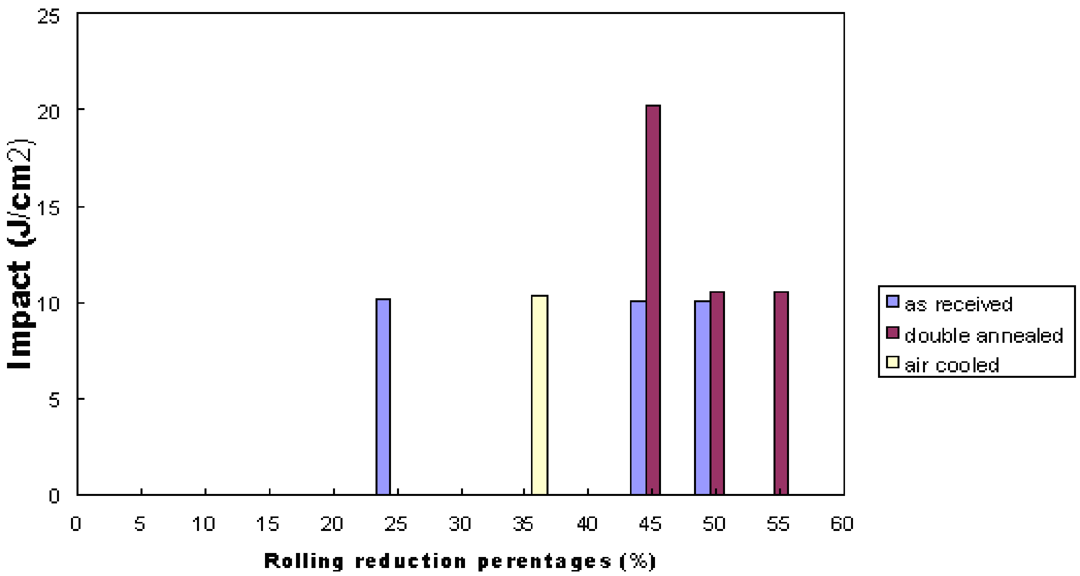


Fig (5) The effect of reduction percentages on toughness at different rolling conditions

Fig (6). *SEM of the rolled D.C.I after tensile test at 1000X*

Fig (7). *SEM of the rolled D.C.I after Impact test at 1000X*

The ferrite grain size became finer with the graphite nodules diameter decrease. When the microstructure was very fine, the inter-granular fracture can be eliminated due to elongation increase with decreasing ferrite grain size.

Above (40%) reduction graphite start to break and the shape ratio of graphite decreases with increase in the reduction percentage because the formation of secondary graphite. The ferrite grain size decrease is dropped due to enhance nucleation due to decrease in M.F.P and increases stress concentration [11].

3.3. Stress Analysis

The determination of the stress analysis for the specimen chosen for Fracture analysis (fractography) the following relationships may be used, Fig (8) shows model of stress analysis :-

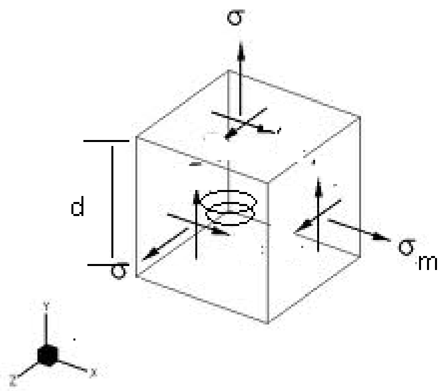


Fig (8). *Model for hydrostatic tensile stress analysis*

$$a = \frac{d}{2n} - r_2 \qquad (2)$$

a is half of M.F.P (mean free path)

d lattice constant

n Shape factor r_o/r (S.F) (shape factor)

r_2 average graphite radius in the transverse direction

σ_m the maximum hydrostatic tensile stress and can be calculated from :

$$\sigma_m = \left(\frac{x}{2} + \frac{1}{3}\right)\sigma_{re} \qquad (3)$$

6_{re} Tensile stress

$$X = \frac{a}{r_2} \qquad (4)$$

The flow stress as a function of graphite volume fraction and ferrite grain size as follow:-

$$\sigma_u = (1 - K_1 V_g)(\sigma_o + K_2 d_f^{-1/2}) \qquad (5)$$

σ_o, K_1, K_2 is constant determined by experimental work and the equation becomes:-

$$\sigma = (1 - 2.2 V_g)(394 + 26.7 d_f^{-1/2}) \qquad (6)$$

V_g graphite volume fraction

d_f ferrite grain size μm

σ_u flow stress Results are recorded in table (2)

Inter granular fracture will occur when the ratio of the hydrostatic stress (equivalent stress) is larger than one

$$(\sigma_m / \sigma_u > 1). \quad (7)$$

Table (2). *The stresses as function of ferrite grain size*

ferrite grain size d_f μm		Hydrostatic stress σ_m (N/mm²)	Equivalent flow stress σ_u (N/mm²)
Impact specimen	85.77	389.83	311.76
Tensile specimen	84.01	500.75	302.78

σ_m / σ_u = 1.1 : 1.2 in this case within a stressed specimen. The stress necessary for crack nucleation will depend on the grain size because the size of the grain will determine the length of the dislocation pile up and the intensity of the stress concentration [12],[13]. a material could be made infinitely strong if the grains are made infinitely small. This is impossible though, because the lower limit of grain size is a single unit cell of the material. Even then, if the grains of a material are the size of a single unit cell, then the material is in fact amorphous, not crystalline, since there is no long range order, and dislocations can not be defined in an amorphous material.. The effect of grain boundaries on resistance to deformation described by equation is shown in fig (9).

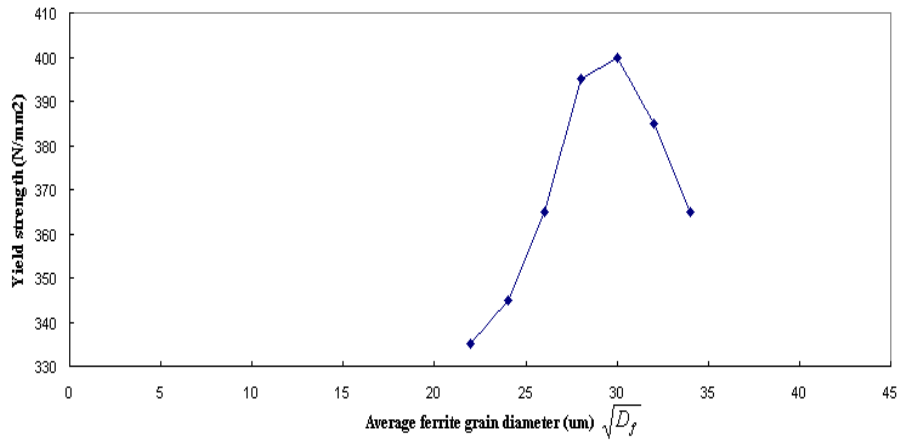


Fig (9) Hall_Petch relationships

Fine microstructure can eliminate intergranular fracture the effect of ferrite grain size and triaxial stress field around graphite nodules on intergranular embrittlement. It is based on the observation that grain boundaries impede dislocation movement and that the number of dislocations within a grain have an effect on how easily dislocations can traverse grain boundaries and travel from grain to grain. So, by changing grain size one can influence dislocation movement and yield strength.The hot rolling of ductile cast Iron leads to plastic deformation , heat treatment after plastic deformation and changing the rate of solidification are ways to alter grain size.[4]

4. Conclusions

Based on the results obtained in this work the following conclusions are presented :-

1 Hot rolling play a great role in the improving the mechanical properties of DCI such as tensile and yield in the rolling direction(Longitudinal direction), it also changes the microstructure of matrix and graphite nodules.The tensile properties also improved by raising the amount of rolling reduction.

2 Toughness decreases gradually by increasing the amount of reduction by rolling but furnace cooling after rolling improve toughness.

3 The fracture surface of annealed ductile cast iron were appeared to consist of big dimples for the tensile test, while irregular fracture features exist on impact test. Hot rolled DCI was similar to steel in fracture behavior so it is recommended in different construction applications

4 The effect of grain boundaries on resistance to deformation described by the equation is manifest indirectly through the effect of strain hardening with a more rapid increase of dislocation density.

5 The barrier effect of cell boundaries is evident in hot rolled ductile cast Iron with large deformations, which leads to deviation of $\sigma_f=f(d^{-2})$ from linear.

6 With decreasing relative length of grain boundaries (large grains) or enrichment of grain boundaries in impurities and precipitates of second phase the number of potential dislocation sources near grain boundaries decreases.

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