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Mechanical properties dependency of the pearlite content of ductile irons

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Properties

ABSTRACT

Purpose: In this work, it is pretended to make a comparison of different pearlite contents in pieces with similar shape and dimensions and to analyze the variation of mechanical properties as pearlite content increases. The three pieces used had form of stair made of ductile cast iron.
Design/methodology/approach: The present study was based on an adequate balance of alloying elements. None heat treatment was used to obtain different pearlite contents in the microstructures. Many specimens taken from the cast were mechanized to be polished and swabbed with nital to analyze the microstructure. To study the mechanical properties these casts present many tests were done such as Charpy impact test, done at different temperatures. Fracture toughness and tensile strength tests were done, as well.
Findings: This study gave evidences that heat treatments are not necessary to obtain different pearlite content in the microstructure. Good mechanical properties are obtained by an appropriate balance of alloying elements.
Research limitations/implications: They are that of natural sources. Besides, high and precision technology must be applied to get the present results better.
Practical implications: Cast iron productions are focussed straight on machine building and automotive industries and constructions. The low cost production of ductile cast iron, its mechanical properties and low cost transformations are the tempting for application.
Originality/value: The whole experimental work and the appropriate results obtained as consequences of the analysis carried out are novel, although applied methods are well known. Values presented in tables are given as new results of our experiments. This work is of great importance for the development of new economical methods for ductile iron production. This study is directed to researchers and metallurgy centres.
Keywords: Microstructure; Hardness; Mechanisms of fracture; Fracture toughness; Yield strength; Charpy test

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1. Introduction

Ductile cast iron has a short and important history because was not developed until 1948. In the last three decades the ductile cast iron production, (also known as Nodular iron) has been increased. Many analysis and experiments have shown this cast presents good mechanical properties [1,2]. These mechanical properties are not so far from other mechanical properties steels present.

When the solidification rate and the subsequent cooling rate leave inadequate opportunity for the carbon to form the equilibrium graphitic structure exclusively, some carbon may form a pearlitic structure. Beyond ours thoughts, the natural of this process is well known but also is important to emphasize that faster solidification and post-solidification cooling rates favour the formation of pearlite in preference to ferrite in the matrix by limiting the diffusion of the carbon in solution in the matrix to the second phase graphite which formed during solidification [3,4,5].

Keeping this process invulnerable a pearlitic structure can be obtained but not always is kept due to outer agents. The use of alloying elements stabilizing the pearlite can be considered as the most appropriate method to control the amount of pearlite in the matrix [6].

This means that cooling rate has great influence on microstructure but a good control of the alloying elements permits to obtain the microstructure desired and hence, heat treatments can be substituted by an adequate alloying elements control [7,8].

2. Experimental procedures

Three pieces in form of stair made of ductile cast iron were mechanized to analyze the microstructure they present. Some specimens with shape of little plate with dimensions of 10x10x10 mm, were taken from each casts to be polished. After being polished they were swabbed with nital at 2%, to analyze the matrix microstructure. These little plates taken from the casts in form of stair were also used to determine the hardness of the matrix.

Two SENB specimens were taken and mechanized from each casts to carry out the fracture toughness test. The maximum stress intensity was at less than 0.6% K_{IC}. The toughness test specimens were fractured under condition of three points bending in the servohydraulic machine. Charpy impact tests were done at different temperatures, at -20º, -30º grades and at room temperature, as well. An instrumented impact test machine, with Charpy-V notched specimens, was used. Tests were performed according to EN 10045 at impact velocity 5.52 m/s [9,10].

3. Experimental results and discussions

3.1. Microstructures

Figure 1 reveal that photos (a, b) after being etched with nital at 2%, present a ferritic-pearlitic microstructure with 60/40%. The consideration of percentage of pearlite and ferrite content has been done using the tables of comparison of ductile iron on standard classification of nodular cast iron.

To obtain this kind of matrix, commonly the cast is also normalized at 850ºC for one hour with subsequent cooling in air. The purpose of this heat treatment process is mainly to obtain the pearlite formation in the matrix. Besides, cooling phase also plays an important roll in pearlite formation. When pearlite appears, its arising produces an increase of hardness of the matrix and, at the same time, the increase of mechanical properties of resistance is observed, see sub-point 3.5 [11,12].

Photos (c, d), also etched with nital at 2%, present a pearlitic microstructure with 100%. To obtain this microstructure, usually the normalizing heat treatment at 850ºC is used for one hour. In this process, to obtain a fully pearlitic microstructure, since it is smelting alloyed with some percentages of cupper, also the cooling rate plays a very important roll and the cooling in air is just enough to obtain the total pearlitizing of the matrix.

A ferritic-pearlitic microstructure with 30/70% is observed in photos (e, f). The ferrite and pearlite content present in these microstructures was compared with the tables of specification for ductile cast iron made available by the international standards. According to some other studies, to obtain this matrix, it is necessary to apply a normalizing heat treatment at 850ºC during one hour with subsequent cooling in air. To be concise, the arising of pearlite, in the matrix, confers very important mechanical properties such as hardness and strength. Fragility of the matrix is greatly increased [13].

This difference of pearlite content it is supposed that will influence on mechanical properties, as we try to show, in the present work. In Figure 1 graphite morphology is observed. Photographs indicate that graphite is merely nodular.

At simple sight, the graphite shape obtained is the adequate form required by the international standards. In obtaining these matrices none heat treatment was used which means heat treatments are replaced by a proper balance of alloying elements.

Although photos (a, b, e, f) of the Figure 1 present the same microstructure, results presented indicate that mechanical properties of the microstructures of the photos (e, f) are better. This microstructure is also known as “Bull Eye” because of its appearance. The ferrite and pearlite content present in it, makes the difference in obtaining good mechanical properties.

From microstructures obtained, it is necessary to understand that an element alone can not react. To transfer its properties must react in combination with other alloying elements. Therefore, effectiveness in the obtaining better mechanical properties in the cast will depend on the set of addition of the alloying elements.

3.2. Chemical analysis

The results of the chemical analysis shown in Table 1, indicate that it is important to take special control of alloying elements to obtain a mixture of ferrite and pearlite in the matrix microstructure. The pearlite forming alloying elements such as copper, manganese, phosphorus, chromium and nickel have been well controlled to obtain these microstructures studied in the present work. The ferritic-pearlitic and fully pearlitic matrix obtained is explained by the reaction manganese produces when acting jointly with phosphorus. They promote the pearlite formation in the matrix but the affect arisen from these two element combinations is eliminated by the action of silicon. Hence, the content of this element must be kept the lower as possible to avoid the ferrite formation [14,15].

The balance of the alloying elements presented in Table 1 shows that heat treatments can be substituted by an adequate balance of alloying elements. Mechanical properties obtained in whole the present work indicate that each alloying element has played an important roll. Table 1 indicates that pearlite forming elements are kept at appropriate levels to obtain the microstructures and mechanical properties required by ductile iron standards.

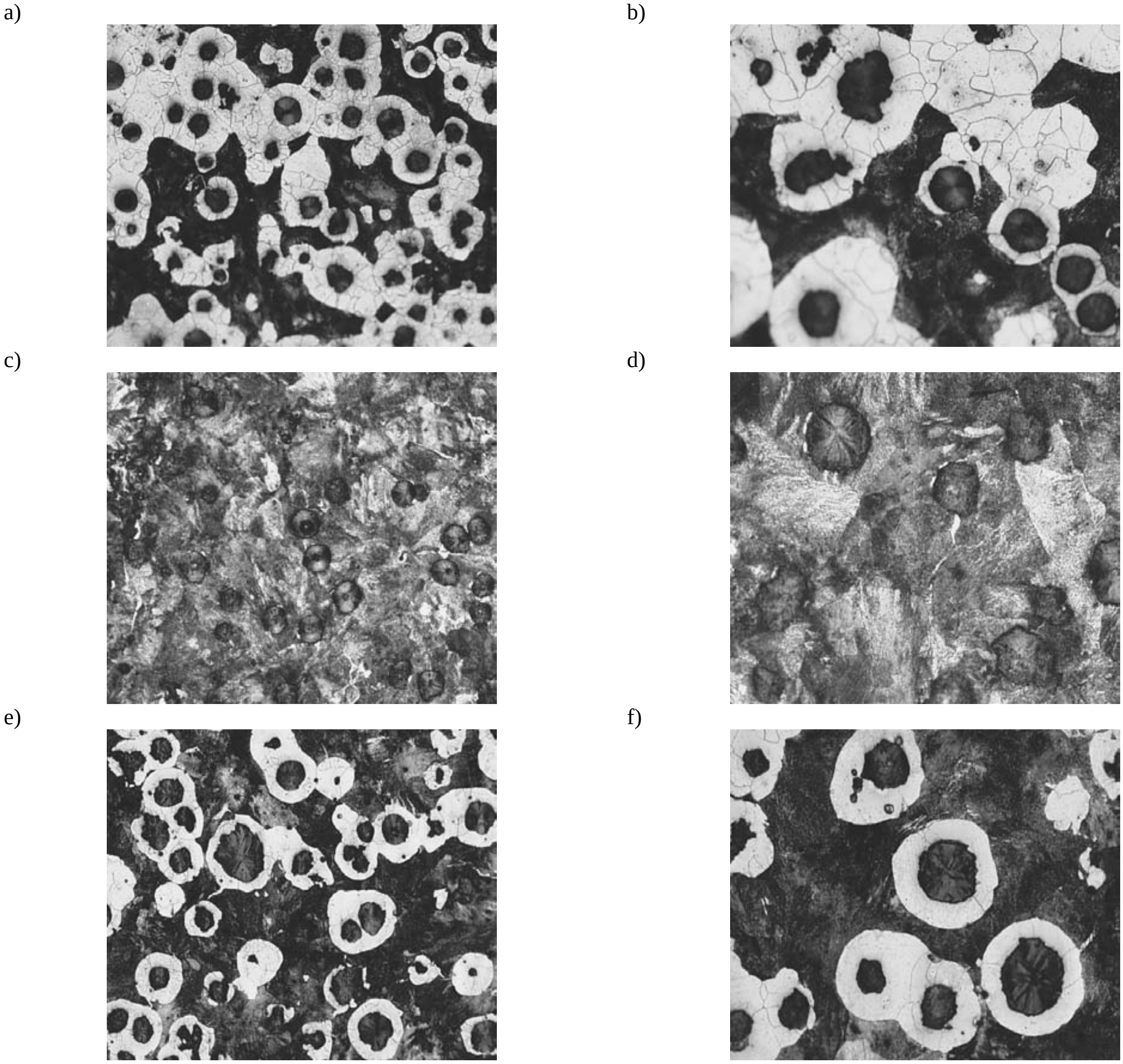

Fig. 1. Matrix microstructures: a), c), e) Magnification 100x, b), d), f) 200x

Table 1.
Alloying elements

Nodular iron	CE	C%	S%	Si%	Mn%	P%	Mg%	Al%	Cu%	Cr%	Ni%	Mo%	N%
FP-60/40%	3.9	3.21	0.023	2.28	0.32	0.021	0.04	0.014	0.14	0.038	0.026	0.001	0.0102
P-100%	3.3	2.61	0.019	2.04	0.11	0.019	0.046	0.011	0.31	0.044	0.025	0.001	0.0075
FP-30/70%	4.1	3.30	0.009	2.50	0.47	0.019	0.067	0.017	0.46	0.044	0.047	0.001	0.0073

FP- Ferritic-pearlitic cast iron, P- Pearlitic cast iron

The lower copper content, the adequate chromium, manganese and silicon content were the determining factors to obtain the microstructures presented.

Manganese functions as an alloying element, increasing the hardness and strength of ferrite, stabilizing and refining the pearlite.

Increasing the manganese content, in the way shown in Table 1, results in significant increases in tensile and yield strength. Increasing manganese content at various silicon content results in the structural and properties changes noted in Tables 3 and 4 and in Figure 1, respectively.

Nickel is weak pearlite promoter and is usually avoided where a ferritic structure is desired, The contribution of nickel to hardenability is significantly enhanced by additions of molybdenum, It is used in ductile iron for low temperature applications where low ductile-to-brittle transition temperatures are required.

Copper is potent pearlite promoter, It is commonly used to develop pearlitic microstructures, Copper decreases the ferrite content in favour of pearlite formation and increases strength and hardness through increased pearlite formation [16].

If we compare the copper content is present in each microstructure, it is evident that the higher copper, chromium and manganese content found, are to obtain a full pealitic microstructure.

Chromium is a pearlite promoter in ductile iron but its reaction depends up on the nodule count.

Nickel, copper and molybdenum have to be carefully added because they influence on the matrix microstructure with severity when are added to the cast, Besides, they have important effects on hardness, strength and on corrosion.

3.3. Mechanisms of fracture

In Figure 2 differents mechanisms of fracture are shown. According to photographs none or few plastic deformation is observed, preveiling the fracture by cleavage. This kind of fracture is ralate to the material hardness and strength.

In photographs (a, b) a strong voids coalescence is observed. The small dimples observed represent the coalescence voids.

In the picture (b) many particles of second phase are appreciate which suppose to be initiated the voids coalescence. It is possible that dislocation pile-ups observed might have occurred during plastic deformation.

Fracture surfaces observed in photographs (a, b) of the Figure 2, give the key to rightly analyze the process of void growth and coalescence. The kind of fracture observed in them, is that of cleavage fracture. This fracture may have few or none plastic deformation.

The most of casts follow a process known as voids coalescence and these voids nuclei in continuous regions of localized deformation as the associated to second phase particles that include inclusions, joint of grain and pile ups of dislocation. According to our analysis, the amount of inclusions observed in photographs (a, b) they are of less importance because they do not influence on fracture process, althougth they affect, in a negative manner, the ductility of the material and, in the other hand, they do determine the instant and location of ductile fracture but they do not play a role in the process of ductile fracture itself [20,21].

The present tests carried out have shown that these particles are not easy to deform as matrix is deformed and the existing coherence respect to matrix, fades away due to the appearing plastic zone in their vicinity which favours tiny voids are formed growing by slip, as shown in picture (b).

In photos (c, d, e, f) of the Figure 2 cleavage fracture is observed. This mechanism is better defined in pictures (e, f). It is appreciate that cleavage has spread through grains showing a flat fracture which represents the main characteristic of cleavage fracture. Fibrous fracture aspect is appreciate in pictures (c, d), it is may be caused by the low resistance this matrix presents.

In photographs (c, d) small plastic deformation is observed, This deformation has to do with the brittle fracture that can be identify when observing the surface that fails.

These photographs of the Figure 2, revealed, as we have already analyzed that cleavage has been spread through grains. It is observed that neighbouring grains have slightly different orientation hence, cleavage crack changes direction at a grain boundary continuing its propagation on the preferred cleavage plane.

It is suggested that particles of second phase observed, in Figure 2, have influenced on the lower fracture toughness value and on yield strength as shown in the sub-point 3.5. These particles also reduce the ductility of the cast affecting both, the fracture toughness and yield strength, The higher fracture toughness and the lower yield strength values are really related to ferrite and pearlite content.

The small plastic zone observed may bring someone to confussion because of the concept of ductility which is seemed to be indicated that material deforms, This region of yielding, also known as plastic zone, in ductile cat iron has a limit, This plastic deformation must not be excessively large if LEFM is to be applied [22].

This plastic zone can be calculated as:

$$r_{dp} = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_{YS}}\right)^2 \tag{1}$$

where K_I, is the stress intensity factor and σ_{YS}, is the yield strength.

3.4. Hardness Rockwell and hardness Brinell

Tables 2 and 3 show that as pearlite content increases. resistance increases, as well. From results obtained, in both Tables, it is easy to understand that increasing of hardness has to do with different pearlite content, When comparing the pearlite content of 40% with the maximum content presented of 100 % of pearlite, the variation of hardness values in each matrix is evident, It is supposed that higher hardness values have direct influence on the smaller elongation values obtained [17].

Table 2.
Hardness Rockwell

Nodular iron	HR	HR	HR	HR (average)	Resistance ($Kg\cdot mm^{-2}$)
FP-60/40%	77.5	77.0	79.0	77.8	50.0
P-100%	99.0	98.5	100.0	99.2	82.0
FP-30/70%	90.5	90.0	91.5	90.7	68.0

FP- Ferritic-pearlitic cast iron, P- Pearlitic cast iron

Table 3.
Hardness Brinell

Nodular iron	HB	HB	HB	HB (average)	Resistance ($Kg\cdot mm^{-2}$)
FP-60/40%	158	160	163	160	50.0
P-100%	267	273	280	273	82.0
FP-30/70%	194	180	186	187	68.0

FP- Ferritic-pearlitic cast iron, P- Pearlitic cast iron

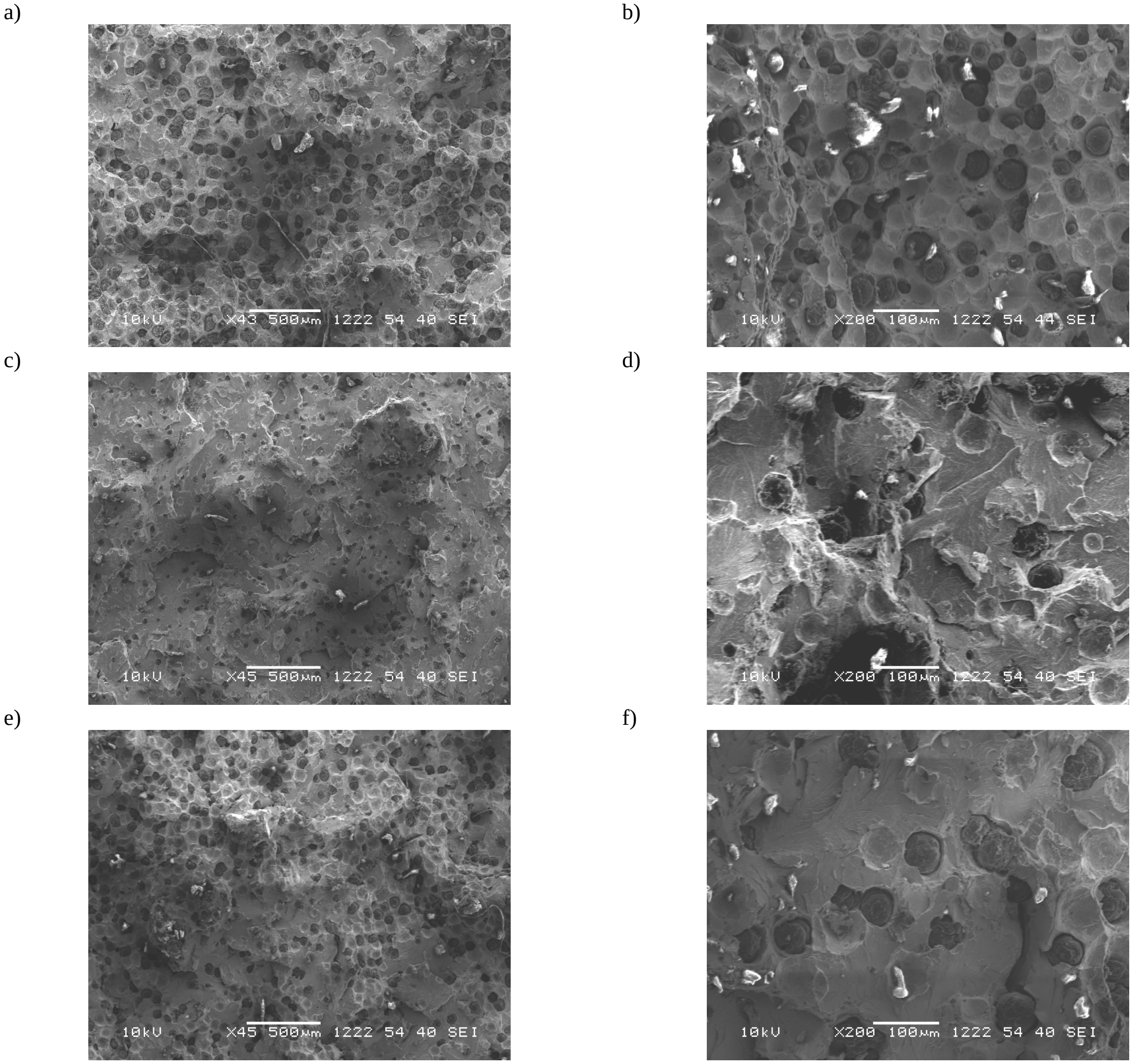

Fig. 2. Mechanisms of fracture

It is stated that hardness is only a parameter to predict some mechanical properties such as tensile strength and yield strength because these mechanical properties vary in dependence of the grade of the cast, Within the grade, strength and ductility vary somewhat with hardness but, once again, it is important to consider some alloying elements as we have explained before.

From results presented in Table 4, it is more clear that matrix microstructure is not always going to be related to mechanical properties but these are related to ferrite and pearlite content in the matrix. Results shown in Tables 2 and 3, according to our point of view and the data of hardness obtained, the cast with 100% of pearlite should exhibit a decrease in fracture toughness due to the high pearlite content this matrix presents.

When talking about pearlite content and its mechanical properties, it is very important to not forget, as we have already explained before, that copper is a potent pearlite promoter and it is commonly used to develop these microstructures. Besides, copper decreases the ferrite content in favour of pearlite formation and increases strength and hardness through increased pearlite formation. Copper is the most influential and potent element on these mechanical properties.

High hardness values are not convenient if the material is going to be under impact due to the fragility this material presents which can provoke its destruction. If material is going to be under a friction force high hardness values are recommended. If material is under both conditions, a mixture of pearlite and ferrite in the microstructure is the most desired because good hardness and strength values are needed, In such conditions the cast that presents 30/70 % of ferrite-pearlite content is the choice, see Tables 2 and 3, respectively [18,19].

3.5. Mechanical properties

If we consider the graphite shape is observed in Figure 1, this graphite shape has influenced on tensile and yield strength values presented in Table 4.

Table 4.
Fracture toughness and yield strength values

Nodular iron	P_{max} kN	P_Q kN	$K_Q = K_{IC}$ $MPa\cdot\sqrt{m}$	σ_{TS} MPa	σ_{YS} MPa
FP-60/40%	6.6	6.3	41.0	488.3	310.0
P-100%	5.9	5.9	38.5	804.6	416.0
FP-30/70%	7.3	7.1	46.4	664.6	339.0

FP- Ferritic-pearlitic cast iron, P- Pearlitic cast iron

Results show that size, uniformity and graphite distribution influence on yield and tensile strength of the cast. Hence, degeneracy in graphite shape influences on these mechanical properties, Ductility and resistance properties are affected when graphite deformation increases [25].

In order to compare some mechanical properties of ductile cast iron, in Table 4, the behaviour of yield strength and fracture toughness is observed. Fracture toughness values (38.5 $MPa\cdot m^{1/2}$) and yield strength values (416 MPa) obtained can be acepted as most promesing.

To understand the existing relationship between fracture toughness and yield strength three casts with different content of pearlite are studied, to some way show that pearlite content has a direct influence on both parameters.

Lower yield strength values obtained are not always going to be in accordance with the higher fracture toughness values because of the appearing defects on the surface that sometimes go unnoticed.

A cording to our results given in Table 4, we can agree with the observation done by Chi and Ruizhen and other when indicating, in theirs works, an improvement of fracture toughness of pearlitic ductile iron due to the increase of nodule count.

In pearlitic microstructure a high nodule count will favour fracture toughness but, at the same time, this improvement in fracture toughness is affected by the high values of hardness, Hardness influences on the increase of tensile strength, shown in Tables 3 and 4. Hardness values presented indicate that these values are inversely proportional to fracture toughness. When hardness increases fracture toughness clearly decreases.

Values offered, in Table 4, were obtained according to international standards. The higher tensile strength values obtained are related to pearlite content of 100%. It is evident from the same table that with increasing pearlite content tensile strength also increases and a pronounced reduction of elongation is observed, decreasing yield strength, as well.

Pearlite hardens the matrix and, as consequence, it becomes into a fragile material. This material fragility drastically reduces the fracture toughness (K_{IC}) which means material presents few or none resistance against impacts. Fracture toughness can be obtained from the rough estimation of $K_Q = K_{IC,}$ If all geometrical parameters required by ASTM are fulfilled then K_Q, is calculated as:

$$K_Q = \frac{F_Q \cdot S}{B \cdot \sqrt{W^3}} \cdot f(a/W) \tag{2}$$

The nodular iron with a pearlite content of 40% presents the lower tensile and yield strength and the lower fracture toughness values. Theoretically, it was expected this cast had the higher values of resistance [23].

The 70% of pearlite content presented in the nodular iron as indicated in Figure 1 and the small content of ferrite that surrounds the nodules and the proper globular shape graphite presents, in this cast, have influenced on the higher fracture toughness, tensile and yield strength values obtained.

The higher yield strength values obtained in Table 4 where high pearlite content is present, it has sometime been explained, as the main cause of the increase of yield strength and that's right, The higher yield strength and the lower fracture toughness values obtained have to do with the microstructure.

This means that yield strength and fracture toughness are inversely proportional because results presented indicate that when yield strength increases tenacity decreases but both, yield strength and fracture toughness depend on the microstructure, Higher yield strength produces a smaller plastic zone.

Using the definitions of engineering stress and strain we can determine the amount of work done in deforming the material, This work in material design is assessed as:

$$U = \int_0^{x'} P\,dx \tag{3}$$

Let the applied force be *P* and *x*, the displacement over the gage length, *U*, is the amount of work done in deforming the material.

Applying the same concept of engineering stress and strain hence, it is easy to find the work done per unit of volume of material used [24].

This equation is given by:

$$u = \frac{U}{A_i L_i} = \int_0^{x^i} \frac{P}{A_i} = \int_0^{\varepsilon} \sigma\, d\varepsilon \tag{4}$$

$A_i\, L_i$, is the volume of material in the gage length, ε^-, is the strain, σ, is the stress and *u*, is the work done per unit of material.

Table 5 indicates that temperature is another influencing factor on resilience, If material resilience increases, material ductility increases, as well. This mean material becomes more resistant to impact.

Table 5.
Charpy impact test results done at different temperature

Nodula iron	A_V (J) (25ºC)	K_V ($J\cdot m^{-1}$) (25ºC)	A_V (J) (-20ºC)	K_V ($J\cdot m^{-1}$) (-20ºC)
FP-60/40%	13.88	17.35	8.26	10.33
P-100%	3.23	4.00	4.33	5.41
FP-30/70%	6.85	8.60	4.56	5.70

To a better understanding, resilience depends on temperature of the test and, as much as greater the resilience value is, material becomes more resistant to impact increasing its ductility. Resilience is given by the following formula:

$$a_k = \frac{A}{F} \tag{5}$$

a_k , is the resilience, A, is the work done by the pendulum and F , is the transversal area.

From results shown, it is easy to understand that pearlite, at room temperature, is less resistant to impact. Nevertheless, a matrix formed by ferrite and pearlite is more resistant to impact but its resilience, anyway, depends on test temperatures and on the pearlite content.

The absorbed energy and resilience values given in Table 5 were obtained during the impact test. Matrices tested showed different values of absorbed energy and resilience due to the microstructures and pearlite content they presented. The impact tests confirm that ductility and impact properties are mainly determined by the percentages of ferrite and pearlite content in the matrix [26].

According to microstructures studied, decreased pearlite content and increased ferrite content in the matrices reduce impact energy, at room temperature, for ferritic ductile iron.

This means, if matrix presents a fully ferritic microstructure impact energy is affected. Curiously, in the present work, the microstructure presenting a 60/40% of ferrite and pearlite shows an important increase of impact energy, see Table 5.

The decrease of impact energy observed in microstructures containing 70% and 100% of pearlite, respectively, is due probably to the progressive increase of pearlite content.

Besides, impact properties of nodular cast iron presenting a ferritic microstructure are affected by both, nodularity and nodule count. Impact test values given in Table 5 were also obtained at low temperatures to appreciate the material behaviour when it is under adverse conditions.

There are not doubts that little variation observed on impact energy and on resilience of the full pearlitic matrix and ferritic-pearlitic one, is due to the increase of pearlite content. During impact test was observed that absorbed energy changed because of the microstructures [27].

3.6. Fracture toughness test

If we compare the curve obtained in Figure 3 with the curves shown in Figures 4 and 5, it is evident that pearlite has played an important roll when increasing the hardness and fragility of the matrix.

This is the reason by which curve obtained in Figure 3 is less pronounced. Small plastic deformation is observed in it. The plastic deformation zone observed in the graphic of Figure 3 is lesser than in the two next graphics.

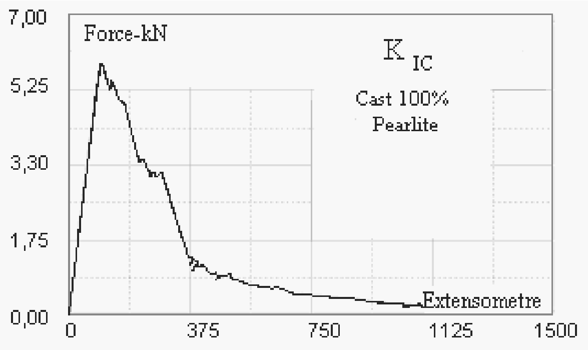

Fig. 3. Load displacement curve

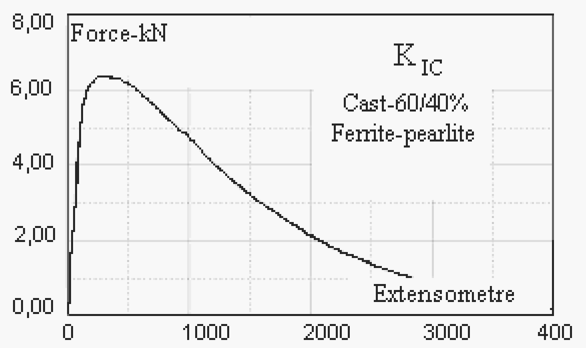

Fig. 4. Load displacement curve

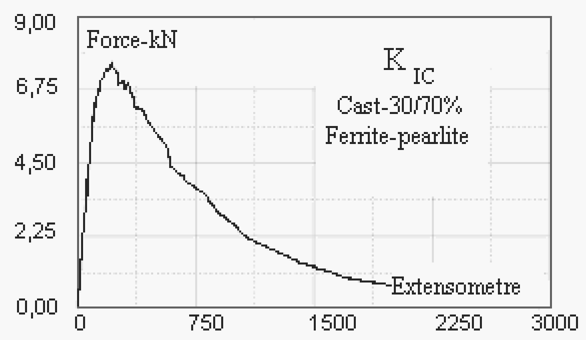

Fig. 5. Load displacement curve

Figure 5 shows that the plastic zone deformation is smaller than the rest of the casts studied. Measures done during the test revealed that the plastic zone at fracture is too small compared with specimen dimensions used which it means that fracture toughness values obtained are valid.

The displacement curves behaviour has been obtained according to ASTM standards [28]. It is appreciated that materials behave in a linear plastic manner prior to failure or suffer any damage. Graphics of Figures 3, 4, 5 indicate that plastic zones observed are smaller than specimens dimensions and that's why the values for K_{IC} obtained are valid. They were also performed according to ASTM [29,30].

4. Conclusions

A ferritic-pearlitic or pearlitic microstructure can be obtained without using heat treatments, Heat treatments can be substituted by an adequate balance of the alloying elements.

If pearlite forming alloying elements are carefully added, a mixture microstructure of ferrite and pearltite or a full pealitic microstructure with good mechanical properties can be obtained.

The higher hardness values were obtained in a nodular cast iron with a content 100% of pearlite.

Pearlite hardens the matrix and, at the same time, increased pearlite content also resistance of the matrix increases.

Elongation is lowed while tensile strength is increased as consequence of pearlite increasing.

Pearlite reduces the fracture toughness values. The higher fracture toughness and the good tensile strength values were obtained in the matrix that presents a mix microstructure of ferrite and pearlite of 30/70%, This microstructure is also known as bull-eye microstructure.

A mix microstructure of ferrite and pearlite presents more resistance to impact.

The high yield strength values obtained in pearlitic structure had a straight influence on the lower fracture toughness values.

The high yield strength value obtained produces a small plastic zone thus, a drastic reduction on fracture toughness values is observed.

The mechanisms of fracture appreciate during the tests were that of ductile and cleavage fracture. The small plastic zone and the voids coalescence are due to matrix microstructure.

Fracture toughness values are affected by dimension specimens.

High nodule count and nodularity improve fracture toughness values of perlitic microstructure but, at the same time, this microstructure influences on the lower fracture toughness values and increases hardness.

Particles of second phase have not really important influence on fracture process but they do decrease ductility.

The drastic reduction of resilience observed is because of the higher pearlite content. This reduction is evident in the microstructure with 100% of pearlite.

Pearlite reduces resilience at room temperature and at lower temperatures its resilience increasing presents little variation.

If material is going to be under a friction force high hardness values are recommended.

Measures done during the test revealed that the plastic zone at fracture is too small compared with specimen dimensions used which it means that fracture toughness values obtained are valid.

All formulas presented have been used for verifying the results obtained from the tests.

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