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FRACTURE TOUGHNESS R-CURVES IN LAMELLAR GRAY CAST IRON

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Abstract: *Fracture mechanics properties in lamellar gray cast iron have traditionally been evaluated from parameters calculated at maximum load values from load vs. crack mouth opening displacement records. The evaluation has been carried out in this way as a consequence of the difficulty to measure the stable crack growth. The chemical tinting technique, presented in this paper, permits the stable crack growth in lamellar gray cast iron to be measured, and then, the determination of R-curve and* J_{IC} *values by the multiple specimens technique. A good agreement between the measured compliances and the theoretical ones was also observed. Maximum load values (*K_{pmax} *and* δ_m*) were also determined, and none of them presented any tendency for **a/W** ratios ranging from 0.45 to 0.65. The effect of the notch radius in the measured toughness was also analyzed and not any clear tendency was observed by testing specimens with radius from 0.2 to 3.5 mm.*

Key words: *Fracture Toughness, Gray Cast Iron, Mechanical Properties.*

1 INTRODUCTION

1.1 Mechanical Behavior of Lamellar Gray Cast Iron

Lamellar gray cast irons present a non-linear load-displacement record, meaning that the response to stress does not correlate with the Hooke's Law [1]. This macroscopic behavior is originated in the complex microstructure of these materials that are formed by two phases (one metallic matrix with distributed graphite lamellaes) that induce a non uniform distribution of tensile stresses. The graphite lamellaes act as stress concentrators that produce micro cracking of the lamellaes or interface debonding at very low stress level. Other authors have suggested that the non linearity and the hystheresis have also an important role in the matrix plastic deformation [2].

Fracture Mechanics was developed as a consequence of many catastrophic failures, giving a relationship between the load state, the geometry and the defect size in a cracked component. Structural materials like steels, Aluminum and Titanium alloys were its more important applications. As a consequence of the particular mechanical behavior of the lamellar gray cast iron, a direct application of the fracture mechanics techniques is not straightforward.

1.2 Microcracking Mechanisms

Not only the macroscopic aspects set the lamellar gray cast iron apart from the ordinary structural materials for which the Fracture Mechanics methodology has been developed; they do not respond to the crack tip plastic deformation model as well. The zone that is ahead of the crack tip is damaged by micro cracking as a consequence of the opening of the graphite lamellae, as well as by the matrix/graphite interface debonding. The microcracks are generated by the application of tensile stress, and they coalesce as the load increases, giving a macroscopic crack that produces indeed further microcracking ahead it. (Figure 1)

As the graphite lamellae act as stress concentrators, the microcracking occurs at very low stress levels. The formed microcracks coalesce by necking of the surrounding matrix. Then,

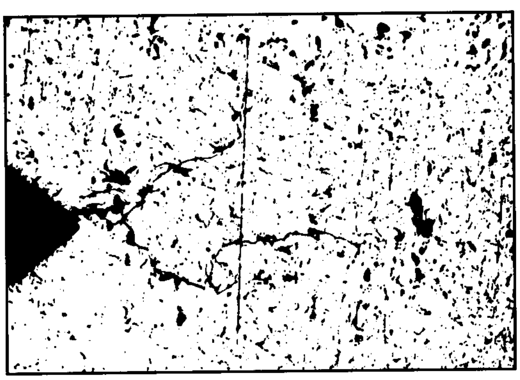

Figure 1. Microcracks around the notch tip

although the crack initiation toughness is low, the main crack growth needs a higher energy as a consequence that the stored elastic energy is low enough to cause crack instability [3][4]. This would suggest a rising R-curve.

This mechanism implies that the lamellar gray cast iron presents brittle behavior in tensile tests, but it exhibits large amounts of stable crack growth in Fracture Mechanics tests with bending geometry [4]. Some authors have indicated that the toughness measured in bending specimens overestimates the true toughness value because the Elastic Modulus in tension is lower than in compression [5][6].

The microcracks show complex shapes and are partially interconected when are analyzed in three dimensions. Haenny and Zambelli [7] proposed that the fracture is not the result of the propagation of a damaged zone, but the continuous damage increases in an area that spreads continuously. They also introduced a model that describes three confined zones (Figure 2):

I Microcracked zone

II Discontinuous crack zone

III Continuous crack zone

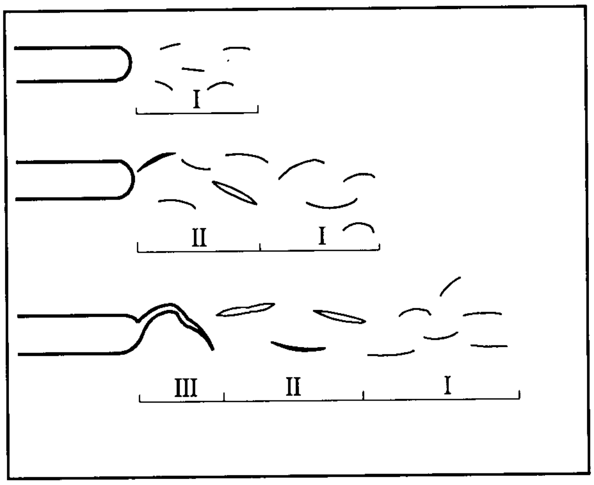

Figure 2 Zones proposed by Haenny & Zambelli

Baker [8] suggested a mechanism in which the damage begins at very low stress level when the graphite lamellae perpendicular to the tensile stress crack. These lamellae generally fracture by cleavage, but very often graphite/matrix interface decohesion takes place [2]. The microcrack tips act as stress concentrators and consequently plastically deformed zones are formed in the surrounding matrix. When the stress increases, the plastically deformed zones spread up until the matrix separation is reached. This separation could also occur by brittle mechanisms, depending, among other factors, on the matrix microstructure and temperature. Bradley [6] proposed that the microcrack formation and its subsequent coalescence dissipate more energy than that required to propagate an unique crack.

2 FRACTURE MECHANICS APPLICATION

2.1 Fatigue Precracking

It is not possible to distinguish the morphologies corresponding to fatigue and slow stable crack growth, at least from a macroscopic point of view [9][10]. There is an agreement between most authors [5][7][8][11] that the fracture toughness is not dependent on the notch tip radius. Then, there is no need to fatigue precrack the specimens

2.2 Application of Linear Elastic Fracture Mechanics. K_{ic} Criterion

The scarce lateral contraction that specimens suffer in an impact test, the brilliant aspect of the fracture surface and the limited macroscopic plastic deformation that the matrix suffers, suggest the application of the Linear Elastic Fracture Mechanics to evaluate the fracture properties in these materials. Unfortunately, there exists a major limitation in the application of the $\mathbf{K_{IC}}$ methodology because the standardized techniques [12][13] indicate that the $\mathbf{K_{IC}}$ calculation must be performed with a P_Q load that is obtained from the intersection of the load/crack mouth opening displacement record with a straight line with a 5% smaller slope than the first part of the record. As a consequence of the fact that the lamellar gray cast iron does not present a linear part, the P_Q load is not well defined.
Instead, several authors [3][5][6][7][11][14] calculated $\mathbf{K_Q}$ with the maximun load value, under the supposition that the stable crack growth begins near the maximun load and they considered the value representative of the material toughness.
The $\mathbf{K_{IC}}$ criterion application to lamellar gray cast iron was criticized from some empiric observations that will be described as follow.
a) Direct relation between $\mathbf{K_{pmax}}$ and the tensile strength: several authors [3][4][5][9][15][16] have pointed out that there exist a direct relationship between the tensile strength and the **K** value calculated in the maximum load point (that is called $\mathbf{K_{pmax}}$ in this paper). This behavior is not normally observed in metallic alloys where, when the tensile strength increases, the fracture toughness diminishes. Ingle [9] stated that $\mathbf{K_{pmax}}$

can not be interpreted as a measure of the fracture toughness, but only as an indication of the tensile strength.

b) Dependence of $\mathbf{K_{pmax}}$ with the geometry: The fracture toughness measurements are invalid when geometric factors (shape and size) affect their values. An important dependence of the $\mathbf{K_{pmax}}$ value with the geometry has been observed [4][5][15][16].

2.3 Application of the De Elastic-plastic Fracture Mechanics

2.3.1 CTOD Criterion

The experimental determination of the Crack Tip Opening Displacement, **CTOD**, involves the measurement of the elastic and plastic components of displacement. They are not clearly defined in lamellar gray cast iron as a consequence of the already discussed non-linearity. Perez Ipiña *et al* [4] considered as elastic component the one corresponding to the tangent through the origin in the load-displacement record. [9] suggested that the **CTOD** in lamellar gray cast iron is only a measurement of the crack tip ductility and can not be considered as a toughness parameter.

2.3.2 J_{IC} Criterion

The application of the $\mathbf{J_{IC}}$ method to lamellar gray cast iron presents the drawback of the stable crack growth measurement. The usually employed methods (Unloading Compliance, Potential Drop, Normalization, Multiple Specimen) need the final crack length datum in order to close the calculation. The final crack length is generally marked out by means of heat tinting or fatigue postcracking, both impossible to be applied to lamellar gray cast iron. This important limitation was the reason for the development of a new technique to mark the crack length out, the "Chemical Tinting Technique" that will be described afterwards in this paper.

3 MATERIAL AND METHOD

3.1 Chemical Tinting Technique

None of the conventional surface marking techniques has proved to be applied to lamellar gray cast iron. This peculiarity has prevented the R-curve construction and has been the reason of the chemical tinting technique developing. It is applicable to gray cast irons, steels and any other alloy in which the dissolution potential is noticeably lower to that of copper. The procedure consists in submerging the specimen during 20 minutes in a ultrasonic vat containing a solution of copper sulfate 5% wt., slightly acidified with sulphuric acid. The specimen is subsequently washed with abundant water, dried and detached in two pieces at room temperature. The copper is deposited on the surface, giving the characteristic copper color that is clearly distinguished from the non-exposed surface. The chemical tinting technique is convenient to be made shortly after the test is completed in order to avoid the need of chemical cleaning.

3.2 Testing Material and Specimens

The tested material was a lamellar gray cast iron with **A** Type graphite, size **4** and ferritic-pearlitic matrix. The chemical composition was C=3.5%, Si=2.5%, Mn=0.2%, P=0.09% and S=0.02% wt.

Three point bend specimens (3P-SENB) were machined with dimensions: thickness B=12.5mm; width W=25mm and span L=100mm. In order to study the effect of the a/W ratio, the tested ones were 0.45; 0.50; 0.55; 0.60 and 0.65. For the effect of the notch radius, the specimens were all with a/W=0.5 and radius from 0.2mm to 3.5mm.

3.3 Testing Method

Tests were made using the multiple specimen and unloading compliance techniques [17]. In order to verify the applicability of the unloading compliance technique, the compliance was recorded in some specimens at very low load level at the beginning of the tests. In other specimens, the compliances were recorded at the beginning and at the end of the tests. The latest tests were performed by making several unload/reload cycles in order to obtain enough information to build the R-curves. With the corresponding compliance values, the Effective Elastic Modulus values were calculated, founding that they ranged from 90 to 110 GPa, similarly to those informed by Weidnacht *et al* [18]. All the tests were performed under displacement control, making partial unloadings of about 20% of the applied load. The load value, as well as the crack mouth opening displacement and the load line displacement were recorded using load cell, clip gauge and LVDT instruments, respectively. These data were recorded in three different graphs: a load/load line displacement, a load/crack mouth opening displacement, and another amplified load/amplified crack mouth displacement, the latter only for the unloading and reloading cycles to measure the compliances.

The tests to study the effect of the notch radius were without measuring the unloading compliances, calculating only the $\mathbf{K_{Pmax}}$ values.

4 RESULTS

TABLE I: Specimen dimensions and J_{IC} results

SPECIMEN	a/W	B [mm]	W [mm]	J_{IC} U. C. [KJ/m^2]	J_{IC} M. S. [KJ/m^2]
S3-01	454	1298	2460	1668	
S3-04	602	1289	2507	1557	
S3-10	649	1260	2472	1584	
S3-01/02/05/06/07/09	~ 0.5	~12.9	~25		14

U. C.: Unloading compliance

M. S.: Multiple specimens

From the tests data, the following parameters were calculated:

4.1. Compliances: The initial and final compliances were analyzed against the **a/W** ratio and compared to the theoretical values (Figure 3). The specimens crack growth was also calculated to permit the R-curve determination. ASTM E813-89 was followed.

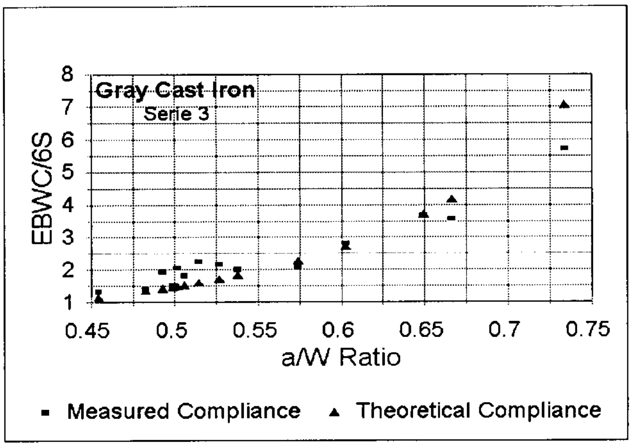

Figure 3- Compliances vs. a/W ratio

4.2. $\mathbf{K_{Pmax}}$ were calculated using the maximun load value and the initial crack length in the equations from ASTM E399. Figure 4 shows these values as a function of the a/W ratio.

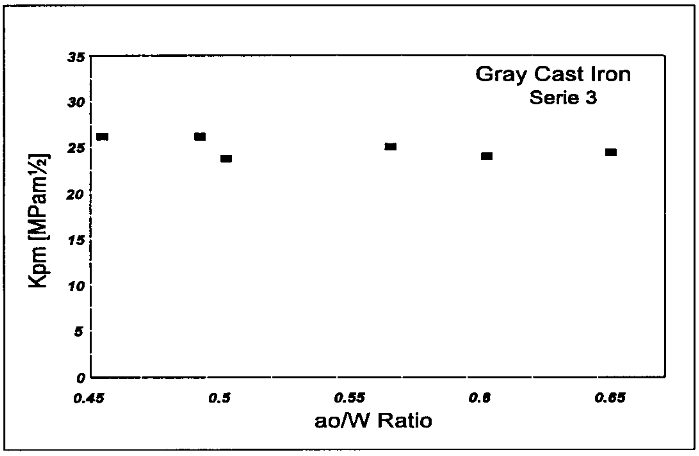

Figure 4- $\mathbf{K_{Pmax}}$ vs. **a/W** ratio

4.3. J vs. Δa: The **J-R** curves were obtained using both methods: Multiple Specimens and Unloading Compliance. $\mathbf{J_{IC}}$ values were calculated and are shown in Table I. It was considered σ_y=130MPa in the Blunting Line calculation. The procedure outlined in ASTM E813-89 was followed always when possible.

4.4. δ_{pmax}: Following BS7448:91, and reference [3] when this was not possible, the δ_{pmax} values were calculated using the maximun load and initial crack length values. Figure 5 shows these values as a function of the **a/W** ratio.

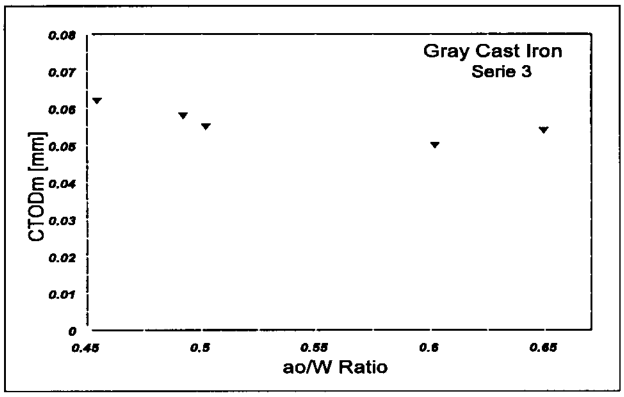

Figure 5- CTOD vs. **a/W** ratio

The fracture surface corresponding to a half specimen broken after the Chemical Tinting technique exposing marked and non marked areas can be clearly seen in Figure 6.

5 DISCUSSION AND CONCLUSIONS

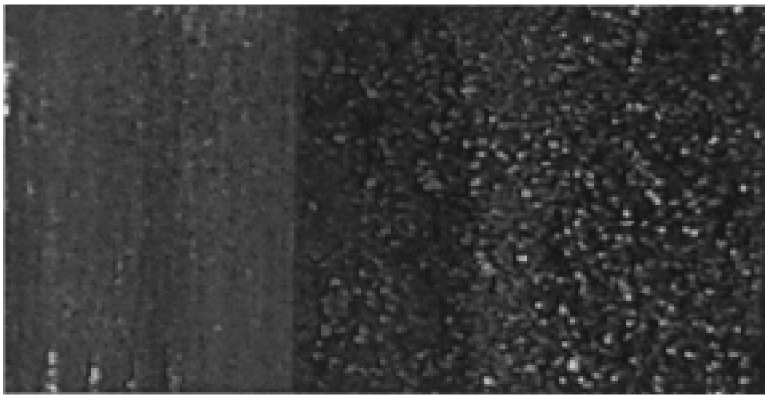

Figure 6: Broken specimen showing the chemical tinting

The possibility to measure the final crack length by means of the very simple chemical tinting technique opens new horizons in the Fracture Mechanics application to lamellar gray cast iron. However, it must be repeated that the technique permits to measure only the continuous crack length, or zone III in Haenny and Zambelli [7] interpretation. The other two zones (microcracked and discontinuous cracked zones) are assimilated to the plastically deformed zone in a conventional alloy, as stated by Bradley [6]. This technique is very simple and it can be enhanced using digital treatment of the images, giving a clearer separation between marked and non marked areas.

Figure 3 shows a clear correspondence between compliance and the **a/W** ratio. It is important to quote that most of the final **Δa** values calculated using this technique deviated from the ones measured by chemical tinting in less than the tolerances allowed by the standards [17][19]. The greatest differences correspond to **a/W** ratios larger than 0.65 that are unusual in fracture toughness tests. This correspondence would give support to the applicability of the Unloading Compliance method to lamellar gray cast iron. The **J-R** curves obtained using the Unloading Compliance Method are all similar, both in the $\mathbf{J}_{IC}$ values as well as the slopes of the curves. This is important taking into consideration the wide range of **a/W** ratios covered, from 0.45 to 0.65.

The **J-R** curve obtained by means of the Multiple Specimen Method gave a $\mathbf{J}_{IC}$ value close to those obtained from the Unloading Compliance Method. (Table I)

Figures 4 and 5 indicate that, under the analyzed experimental conditions, the toughness values at maximun load ($\mathbf{CTOD}_{Pmax}$ and $\mathbf{K}_{pmax}$) are approximately constant within the analyzed range of **a/W** ratios. Moreover, both parameter values present a similar trend, the larger δ_m values correspond to specimens that showed larger $\mathbf{K_{pmax}}$.

The $\mathbf{K_{pmax}}$ values for different notch radius did not present any clear tendency, showing that it is not necessary to precrack the specimens, giving an experimental confirmation to the most employed technique in lamellar gray cast iron.

These results can not be generalized because only one geometry was studied. In a future experimental stage, another geometries and load modes will be aim.

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