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EFFECTS OF THERMAL SHOCKING ON MECHANICAL PROPERTIES (CONVENTIONAL AND AGAINST FRACTURE) OF GREY CAST IRONS[1]

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Abstract

Grey cast irons are commonly employed for the design of engine blocks, brake discs, among many other mechanical components. However, they usually present low ductility and fracture toughness, which demand accurate protocols for design and structural integrity assessment. These properties can be additionally reduced if they are submitted to thermal shocking, leading to cracks nucleation or metallurgical transformations inducing brittle phases (e.g. Martensite) and therefore catastrophic failures. To better understand these phenomena and prevent catastrophic failures, this work investigates the mechanical behavior of a commercial grey cast iron in as-cast and thermal-shocked conditions. Samples were obtained from brake discs employed in heavy vehicles. Selected specimens were heated (> 800ºC, austenitic field) and quickly cooled in water to simulate critical operational conditions reported by the literature. Metallographic analyses, Charpy, tensile and fracture mechanics tests were carried out. Results reveal a remarkable loss of mechanical properties and decreased defect tolerance.

Key words: Grey cast irons; Thermal shocking; Fracture toughness.

EFEITOS DE RESFRIAMENTOS FORÇADOS NAS PROPRIEDADES MECÂNICAS CONVENCIONAIS E À FRATURA DE FERROS FUNDIDOS CINZENTOS

Resumo

Ferros fundidos cinzentos são amplamente utilizados na fabricação de componentes como blocos de motor, discos de freio, entre outros. Entretanto, apresentam reduzidas ductilidade e tenacidade à fratura, o que exige acurados protocolos de projeto e avaliação de integridade. Estas propriedades podem ainda sofrer reduções expressivas quando componentes sofrem choques térmicos, com a nucleação de trincas térmicas e/ou transformações metalúrgicas envolvendo a formação de fases frágeis como martensita, acarretando falhas catastróficas e perda de segurança. Objetivando um melhor entendimento de tais fenômenos, este trabalho investiga a resistência mecânica de uma liga comercial em condições original e após resfriamento simulado. Para a simulação de uma condição crítica real, dois lotes de amostras foram retiradas de discos de freio rodoviários de grande porte. Um lote foi submetido a um ciclo de aquecimento (> 800ºC, campo austenítico) e rápido resfriamento em água. Foram realizadas metalografias, ensaios Charpy, de Tração e de fratura C(T). Os resultados evidenciam severa redução de propriedades mecânicas e a redução na tolerância à presença de defeitos.

Palavras-chave: Ferros fundidos cinzentos; Choque térmico; Tenacidade à fratura.

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1 INTRODUCTION

Grey cast irons are largely employed in applications where intricacy geometries, good machining, dampening capacity and reduced costs are desired. Engine blocks, brake discs, large valves and flanges are only a few examples of typical applications. In addition, good wear characteristics, thermal conductivity and compressive strength are usually found and its attainment depend on the appropriate control of matrix and free graphite characteristics.(1,2) From a metallurgical point of view, grey cast irons contain large amounts of Carbon (2% to 4% by weight) and silicon (1% to 3%). This large amount of Carbon exceeds the amount that can be held in solid solution (2% in the case of elevated temperatures) and thus appears in the form of graphite flakes under normal cooling rates.(2,3) These graphite flakes are detrimental to structural integrity since easily develop into cracks under tension, leading to a relatively weak and brittle behavior under tensile loading. Under compression, conversely, strength and ductility are considerably increased since stress concentration from graphite flakes practically vanishes. According to recent work from Hanna,(4) the size, slenderness and distribution of graphite flakes are the most relevant parameters to define mechanical properties. As an example, the same author demonstrates that increasing flake length from 0.2 mm to 0.8 mm in a grey cast iron decreased its ultimate tensile strength from ~ 320 MPa to ~ 150 MPa (a 53% reduction). Cast irons are sometimes classified by the obtained fracture surfaces, but in most cases they are categorized based on microstructure, including shape, size and distribution of graphite. Two existing standards (albeit very similar) are ISO 945(5) and ASTM A247,(6) which will support some results and conclusion from this work. However, due to the central interest on mechanical properties, further metallurgical details will not be addressed here. The work of Collini, Nicoletto and Konecná(3) is recommended since it presents a comprehensive explanation about alloying elements and its effects on microstructures, porosity, brittle phases and mechanical properties.

Due to the aforementioned properties of grey cast irons, some real applications include exposure to high temperatures combined to severe non-uniform loadings. One such example is the case of high-performance brake discs employed in heavy vehicles. The combination of applied loads and high temperature is itself severe, but in some extreme cases the brake discs are submitted to high cooling rates as a result of, for example, water puddles. Thermal stresses and metallurgical transformations can thus occur forming brittle phases and decreasing the (already low) mechanical properties against fracture. Details of typical thermal cycles and defects identified in brake discs will be addressed in section 2 and call the attention for the need for accurate mechanical testing. Mechanical properties of cast irons are commonly evaluated in terms of Young Modulus, ultimate tensile strength under tension and compression, elongation and absorbed energy using Charpy tests. However, only a few results considering fatigue and fracture mechanics protocols could be found in the literature, probably due to the difficulties related to testing and post-processing data from cast irons, as will be discussed in section 3.

In this context, and as a step to better understand and quantify mechanical properties of grey cast irons submitted to thermal shocking simulating real conditions, this work addresses the effects of heat treatment including austenitization followed by severe cooling on mechanical properties (conventional and against fracture) of a commercial grey cast iron. This effort is of interest to investigate the losses on different mechanical properties and, at the same time, address the ability of the material to handle cracks. It was evaluated a commercial alloy in as-cast and thermal-shocked conditions. Samples were obtained from brake discs employed in heavy vehicles. Selected specimens were heated (> 800ºC, austenitic field) and quickly cooled in water to simulate critical operational conditions reported by the literature. Metallographic analyses, Charpy, tensile and fracture mechanics tests were carried out. Results reveal the loss of mechanical properties and decreased defect tolerance.

2 THERMAL CYCLES OF BRAKE DISCS AND TYPICAL CRACKING

2.1 Operating Temperatures and Thermal Cycles

Several automotive components expose grey cast irons to high temperatures, which cause thermal stresses and can in extreme situations lead to phase transformations. Otto and Diesel engine blocks, for example, can reach temperatures between 400°C-500°C and 700°C-900°C respectively. Considering brake discs, Bagnoli et al.(7) proved that temperatures can easily reach 500°C during desaccelerations of 0.1 G. Additional data presented by Mackin et al.(8) revealed that in extreme cases where desaccelerations reach 0.8 G, brake discs can reach 900°C for some seconds seriously compromising the system efficiency and safety.

Additional data obtained by the authors from real road tests of commercial vehicles revealed that subsequent desaccelerations of 0.3 G between 60 km/h and 0 km/h caused on the surface of the brake discs temperatures of 600°C after 30 minutes and 700°C-720°C after 50 minutes. During downhill road tests, considering constant 0.2 G desaccelerations between 40 km/h and 30 km/h, temperatures reached 750°C after 30 minutes. This context calls the attention for the severity of thermal loadings in brake discs and motivates this investigation.

As grey cast irons usually present chemical compositions (equivalent carbon) close to the eutectic point, the analysis of the Fe-C binary phase diagram reveals that ≈ 727°C is the temperature above which austenite phase stabilizes,(3,9) occurring combined to iron carbide (cementite). The evaluation of TTT and CCT diagrams for grey cast irons reveal that high cooling rates can promote martensitic transformation, potentially reducing material's mechanical properties and fracture toughness. In this work, such a severe thermal cycle will be simulated, as detailed next.

2.2 Typical Cracks

The aforementioned high temperatures are the responsible for several structural phenomena that can (alone or combined) conduct to failures:

- though ductility can be increased under high temperatures, tensile strength is usually decreased;
- the severe thermal gradients in brake discs cause thermal stresses that can lead to cracks nucleation and propagation;
- phase transformations (in special the incidence of martensite) lead to additional residual stresses and remarkable brittleness.(3,10)

This context, combined to the severe loadings found on braking systems cause great concern for structural integrity evaluations. Figures 1 and 2 present real examples of cracks found on grey cast iron brake discs studied by Mackin et al.(8) and by the authors. Additional failures and structural concerns can be found in the work of Goo and Lim.(10) Further details about the material of the discs from Figure 2 will be provided in section 5.

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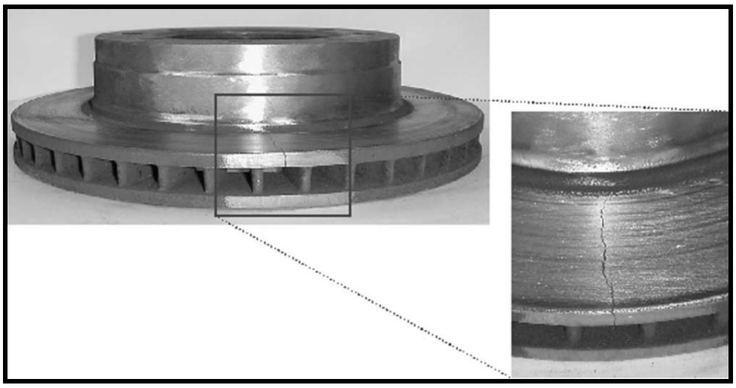

Figure 1. Cracks found on brake discs employed on Ford F-250 vehicles.[8]

Figure 2. Cracks found on brake discs employed on heavy trucks.

3 FRACTURE MECHANICS AND ITS APPLICABILITY TO GREY CAST IRONS

Several results regarding conventional mechanical properties could be found in the literature for grey cast irons,[3,4,11] including several results in the widespread Metals Handbook vol. 15.[11] However, only a few studies including fracture mechanics concepts and results could be found. The work of Bertolino and Perez-Ipiña[12] and Östensson[13] deserve attention since address the main difficulties regarding cast irons fracture testing and data post-processing. According to these authors, conventional fracture mechanics techniques cannot be directly employed to cast irons for some reasons: first, because its microstructure is composed of two phases with very distinct mechanical behavior (graphite flakes surrounded by ferritic-pearlitic matrix); second, because in grey cast irons the shape of the graphite flakes act as a severe stress raiser leading to several internal microcracks under tensile loading. These internal microcracks are, according to these authors, as critical or more critical than the induced macroscopic crack in fracture specimens; and third, due to these microcracks, precracking is complicated (sometimes unfeasible due to brittleness) and crack length check even after failure is difficult.[13]

Bertolino and Perez-Ipiña[12] employed C(T) and SE(B) specimens[14] of varying a/W ratios and notch root radius and did not find any effect of these parameters on fracture toughness. Figure 3a illustrates a C(T) specimen with its main dimensions to support the discussion and Figure 3b reproduces selected results from these authors regarding the effect of notch root radius on maximum stress intensity factor (K) values. Based on these and previous results, they suggest that precracking is not necessary for grey cast irons, since notch root is machined with a small radius. The authors believe that small microcracks (and stressed graphite flakes ahead of the crack tip) can act as the triggers for fracture with slight influence of the induced fatigue precrack. This approach was adopted in this work as a primary approach.

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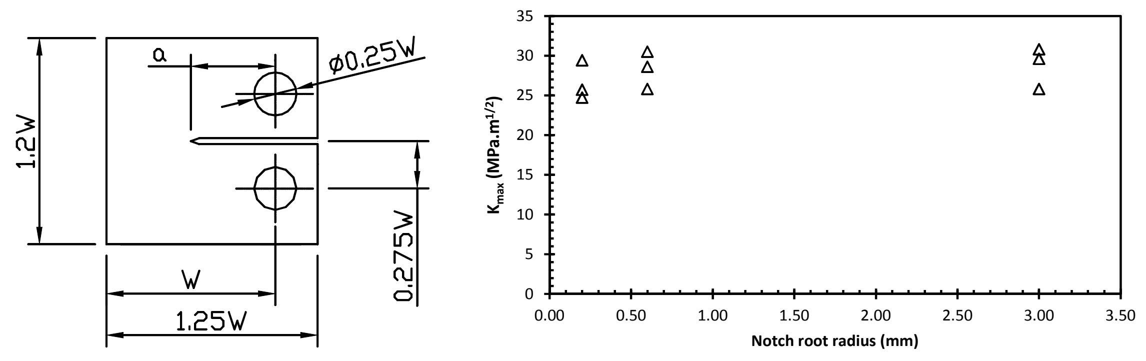

(a) Specimen thickness = B (b)

Figure 3. (a) C(T) fracture specimen; and (b) Fracture toughness (K_{max}) evaluated for grey cast iron using SE(B) specimens with different notch root radius. Here, $B = 15\ mm$, $W = 30\ mm$ and $a/W \approx 0.5$.[12]

Most results found for cast irons are based on extreme values of the stress intensity factor (K).[14] However, from a theoretical point of view, K has limitations when applied to cast irons. These materials, albeit brittle, usually present non-linear elastic stress-strain evolution, and the question is that the stress-fields ahead of the crack tip are only well described by K in an isotropic linear elastic material.[14] Consequently, K is not capable of precisely describing the crack-tip singularity and K-controlled fracture cannot be assured. The existence of similitude (same fracture conditions in a small-scale specimen and real structures) thus cannot be guaranteed.[14]

An alternative approach, already mentioned by Bertolino and Perez-Ipiña[12] is to employ the J integral proposed by Rice as a more adequate parameter to describe stress fields ahead of the crack-tip.[14] This approach is in great accordance with the theoretical basis of J, which was idealized as has proven to be accurate for nonlinear elastic materials. The advantage of using J as a fracture parameter is that it can be understood as a stress intensity parameter and also as a nonlinear energy release rate (energy released by the crack to propagate), analogous to G interpretation in linear-elastic solids. Even under nonlinear stress-strain response, J-controlled fracture can be more easily guaranteed.

For the grey cast irons under investigation in this work, thus, parameters K, J and the equivalent K_J will be evaluated for mode I based on ASTM E399[15] and E1820[16] statements reproduced here respectively by Equations 1 to 3 considering C(T) specimens without side-grooving. The main objective is to quantify fracture toughness and assess the effects of using K or J for experimental measurements. J integral is evaluated based on the load-displacement evolution (based on CMOD – Crack Mouth Opening Displacement) integrated using the eta (η) method to account for the nonlinear contribution of the nonlinear strain energy to J.[14,16]

$$K = \frac{P}{\sqrt{B^2 W}} f\left(\frac{a}{W}\right) \qquad (1)$$

$$J = J_{el} + J_{pl} = \frac{K^2\left(1-\nu^2\right)}{E} + \frac{\eta_{nonl} A_{nonl}}{Bb} \qquad (2)$$

$$K_J = \sqrt{\frac{JE}{\left(1-\nu^2\right)}} \qquad (3)$$

Here, as failures were brittle, P represents the failure load, A_{nonl} is the nonlinear area under the load-displacement curve (analogous to the plastic area for elastic-plastic

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materials), $b = W\text{-}a$ is the remaining ligament and η_{nonl} is a dimensionless factor that accounts for the contribution of nonlinear strain energy to J integral.

4 TESTED MATERIALS AND EXPERIMENTAL PROCEDURES

The investigated material was a grey cast iron with A-type graphite, size 4 and ferritic-pearlitic matrix (a micrograph for the as-cast condition can be seen on Figure 4a and was evaluated according to ASTM A247).[6] The material's chemical composition is presented by Table 1. The "as-cast" condition considered specimens removed from the braking surface of discs (all measuring directions were tangent to the brake rotating axis), while the "heat-treated" condition exposed the same kind of specimens to high temperatures (800°C for 20 minutes in vacuum), followed by water cooling to simulate real critical conditions.

Initially, tensile tests based on ASTM E8M[17] and impact Charpy tests based on ASTM E23[18] and ASTM A327M[19] were carried out. Tensile tests included a minimum of four valid specimens in each condition while Charpy testes included a minimum of five valid specimens in each condition. Fracture mechanics tests included C(T) specimens with B = 15 mm, W = 30 mm, a/W ≈ 0.5 and other geometrical features following Figure 3a. Were tested six C(T) specimens for the as-cast condition and six additional specimens for heat treated material. Notch root radius was kept below 0.6 mm (measured with profile projector) and fatigue precracking was not performed as carried out by Bertolino and Perez-Ipiña.[12]

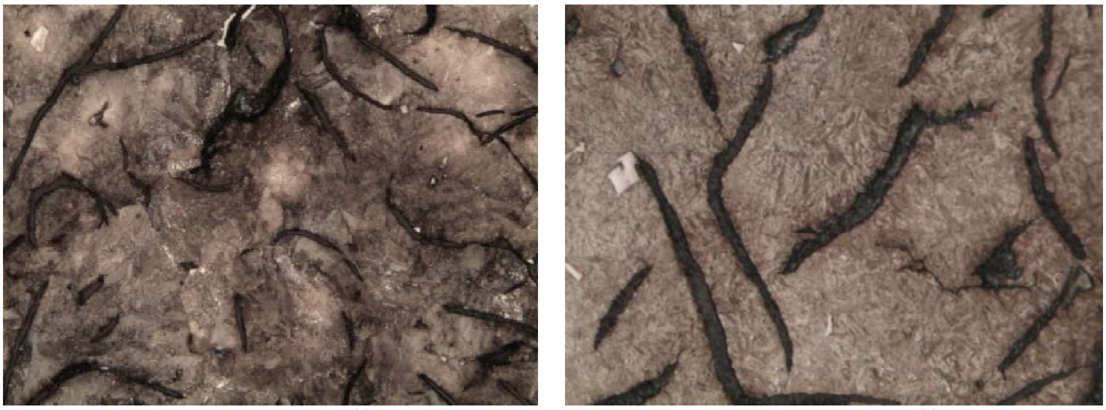
Fracture tests were conducted using a servo-hydraulic 250 kN MTS testing machine, model 810, under displacement control. The instantaneous load was acquired using the machine's load cell, while the displacement (CMOD) was monitored using a clip-gage. ASTM E399[15] and E1820[16] standards were followed whenever possible and monotonic loading was employed, without unloadings.

Table 1. Chemical composition evaluated for the studied grey cast iron

Chemical Element (%)							
C	Si	S	Mn	Cr	Ni	Mo	Cu
3.44	0.99	0.065	0.59	0.24	0.13	0.70	0.13

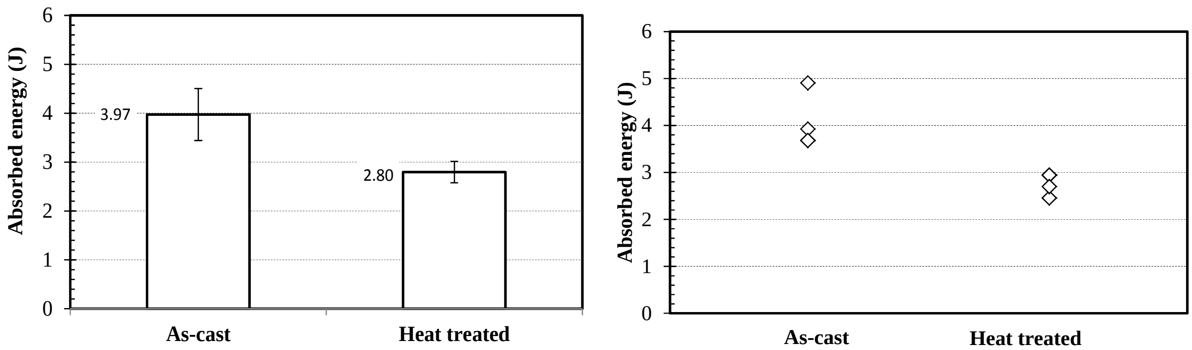
5 EXPERIMENTAL RESULTS AND DISCUSSION

Figures 4a and 4b present the microstructures obtained respectively for "as-cast" and "heat treated" conditions. The as-cast grey cast iron presented A-type graphite, size 4, in a ferritic-pearlitic matrix. The heat treated material presented very similar micrographs and more amplification was necessary to identify the very fine martensite and a small amount of retained austenite, as can be seen in Figure 4b. This refined martensite probably took place due to the relatively low temperature in which austenite was stabilized. However, this temperature level was representative to the work since could reproduce critical real applications (which lie between 750°C and 900°C for critical cases as already addressed). Figure 5 presents absorbed energy from Charpy tests for the as-cast and heat treated conditions. Figure 5a shows average values and standard deviations, while Figure 5b shows all five points tested for each condition. Average values reveal a 41.8% reduction on absorbed energy after the heat treatment.



(a) 200X – Nital 3% (b) 500X – Nital 3%

Figure 4. Micrographs for the studied grey cast iron consisting on A-type graphite in (a) ferritic-pearlitic matrix for the as-cast condition – graphite size 4; and (b) ferritic-pearlitic matrix with fine martensite and retained austenite for the heat-treated condition – graphite size between 4 and 5.



(a) (b)

Figure 5. absorbed energy from Charpy tests for the as-cast and heat treated conditions.

To corroborate the insights that emerged from Figure 5, Figures 6a and 6b respectively illustrate stress-strain evolutions obtained from tensile tests carried out on as-cast and heat treated specimens. The authors call the attention for the different scales used in the axes to enhance comprehension. It can be realized that all stress-strain curves presented good agreement, but it is clear that remarkable reductions on strength, ductility and resilience took place in the heat treated condition. Table 2 summarizes all results regarding conventional mechanical properties, including the loss of mechanical properties after thermal shocking. A 33% reduction was observed for the Young modulus, which is probably a result of the reduced load-carrying capacity of brittle phases even for low loadings. In addition, a 74% reduction was found for the ultimate tensile strength (σ_{uts}) and 95% reduction was found for the resilience. These losses on mechanical properties are extreme and clearly indicate that structural integrity cannot be guaranteed after such severe thermal shocks. The brake discs presented by Figures 1 and 2 probably did not suffer a catastrophic failure because in these real components the material submitted to phase transformation and embrittlement is confined to a thin layer of the braking surface. Figure 7a illustrates the tensile test with 25 mm of measuring length and the graph of Figure 7b illustrates the reduction encountered on resilience.

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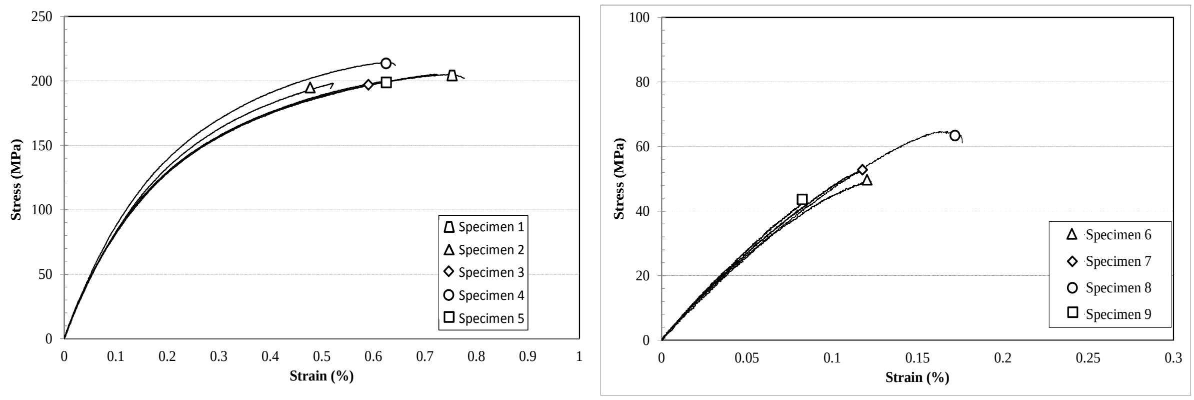
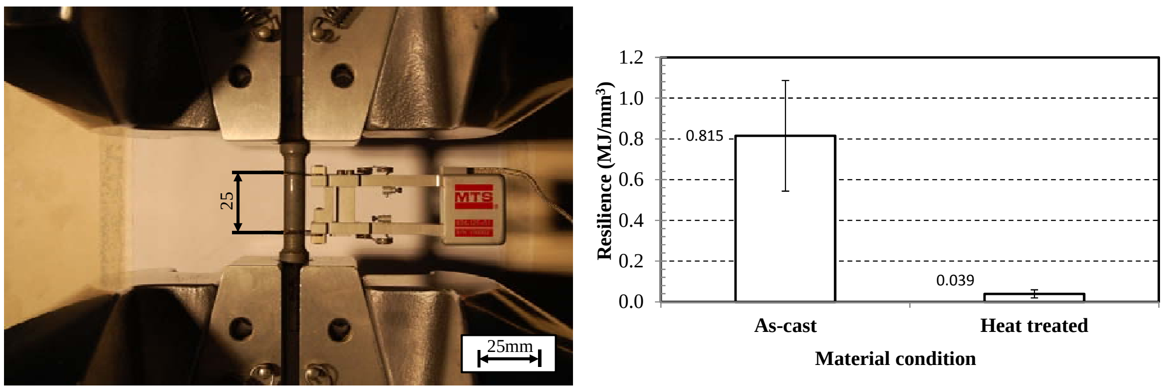


(a) (b)

Figure 6. Yield strength.

Table 2. Conventional mechanical properties evaluated for as-cast and heat treated conditions

Property	E (MPa)			σ_{uts} (MPa)			*Resilience Ur* (MJ/mm³)		
	Aver.	St.Dev.	% loss	Aver.	St.Dev.	% loss	Aver.	St.Dev.	% loss
As-cast	78.40	2.88	---	204.46	6.43	---	0.82	0.27	---
Heat Treat	52.25	2.99	-33%	52.45	8.98	-74%	0.04	0.02	-95%



(a) (b)

Figure 7. (a) Illustration of tensile tests; and (b) remarkable reduction encountered on resilience.

Figure 8 presents the load-displacement curves obtained from fracture mechanics tests carried out using the C(T) specimens presented by Figure 9a. As expected, loads and displacements (CMOD) at failure were reduced for the heat treated specimens if compared to as-cast ones. However, one additional phenomenon calls the attention: curves from different specimens presented poor agreement, even for very similar geometrical features and a/W ratios. Different from ductile metallic materials (in which a better agreement is usually observed between different specimens), the authors believe that the brittleness of the studied grey cast irons and the random sizes and distribution of graphite flakes (and martensite in heat treated specimens) influence load-displacement evolutions. However, Figure 9b reveals that scatter for the obtained fracture toughness data was relatively small, especially considering K_{JC} values, which derive from J integral and are considered by the authors as more adequate to characterize grey cast irons.
Table 3 contains the main fracture toughness data obtained using Equations 1 to 3. K values did not meet ASTM requirements to be considered K_{IC} data, being therefore denoted here K_Q. All J values, conversely, met deformation limits and were considered J_C, leading to equivalent K_{JC} results. All computed values of K_Q, J_C and K_{JC} were fitted using bi-parametric Weibull distributions. In this table are presented, for each parameter, the characteristic toughness (63.21% failure probability) and the

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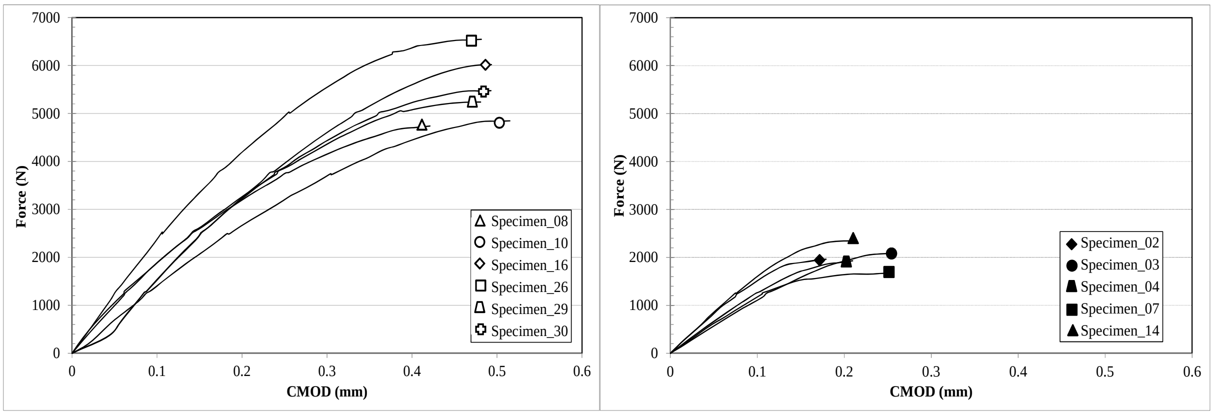
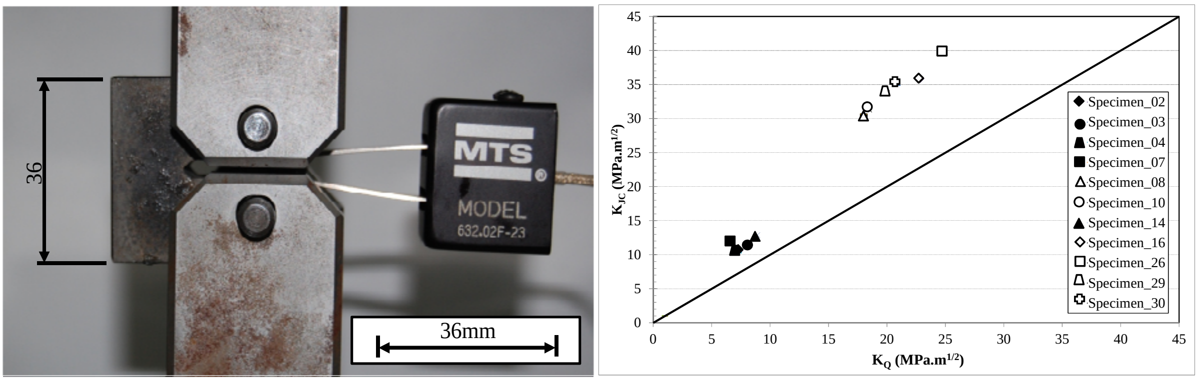
Weibull modulus for as-cast and heat treated conditions. As expected, K_{JC} is higher than K_Q as illustrated by Figure 9b, since J integral is capable of including the contribution of the nonlinear strain energy to the crack driving force. In addition, following similar trends if compared to conventional mechanical properties (σ_{uts} and U_r), fracture toughness reduction for the heat treated condition based on characteristic values was between 65% and 83%. Overall, the remarkable reduction obtained for several mechanical properties call the attention for the importance of considering conventional and fracture mechanics data for safe designs and structural integrity evaluations of brake discs or other grey cast iron components considering solid mechanics and defect tolerance approaches.



(a) (b)

Figure 8. Load-displacement (CMOD) curves obtained from fracture mechanics tests carried out using the C(T) specimens of (a) as-cast material; and (b) heat treated material.



(a) (b)

Figure 9. (a) Test scheme considering C(T) specimens; and (b) fracture toughness results considering K_{JC} and K_Q data. The solid line represents K_{JC} = K_Q.

Table 3. Mechanical properties against fracture evaluated for as-cast and heat treated conditions. Results were adjusted following a bi-parametric Weibull distribution and are presented characteristic values (63.21% failure probability) and Weibull module (slope)

Property	K_Q (MPa.m$^{1/2}$)			J_C (kJ/m^2)			K_{JC} (MPa.m$^{1/2}$)		
	Caract.	Slope	% loss	Caract.	Slope	% loss	Caract.	Slope	% loss
As-cast	21.91	9.08	---	15.47	5.63	---	36.06	11.27	---
Heat Treat	7.98	9.86	-65%	2.57	7.49	-83%	11.91	13.88	-67%

6 CONCLUDING REMARKS

From this work it is possible to conclude that:

- the thermal cycle to simulate thermal shock and real temperatures reached by brake discs provided phase transformation leading to fine martensite combined to the graphite flakes and ferritic-pearlitic matrix;
- all conventional mechanical properties presented remarkable reduction for heat treated specimens, including -42% for Charpy absorbed energy, -33% for E, -74% for σ_{uts} and -95% for U_r. Resilience reduction clearly reveals that martensite combined to graphite flakes completely compromise the straining capacity of the studied grey cast iron;
- fracture toughness reduction was also severe and quantified between -65% and -83% considering characteristic toughness from Weibull distributions;
- scatter from fracture toughness data was relatively small, especially considering K_{JC} values, which derive from J integral and are considered by the authors as more adequate to characterize grey cast irons;
- the results overall should be taken into account for safe designs and structural integrity evaluations of brake discs or other grey cast iron components considering solid mechanics and defect tolerance approaches.

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