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A preliminary investigation of strength models for degenerate graphite clusters in grey cast iron

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Abstract

Defects morphology primarily affects the mechanical properties of grey cast iron. In large castings, porosity and clusters of degenerate graphite are heterogeneously dispersed into the ferrous matrix and serve as initiation sites for fatigue and fracture processes. Strength and toughness of nodular cast iron compare to many grades of steel but experiments show that nodular cast iron also exhibits some specific effects, different from those typical of steels and due to cast iron microstructural inhomogeneity. In the present communication, we report on a preliminary investigation aimed at correlating the effect of the graphite microstructure to the mechanical properties of the material via a simplified geometrical description of the defects.

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Keywords: Grey cast iron; graphite morphology; defects; stress analysis; interacting ellipitcal holes; stress concentration factor.

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1. Introduction

The mechanical properties of ductile cast iron are highly dependent on its microstructure, consisting of a coherent metallic matrix throughout which particles of graphite are dispersed. Matrix microstructure (ferritic, pearlitic, austenitic or intermediate), free graphite morphology (shape, dimension and distributions) and loading conditions affect the ultimate strength and percent elongation at fracture. Hütter et al. (2015) present a review of experimental studies and constitutive models for nodular cast iron, with an overview on different micromechanisms responsible for damage and failure.

Nomenclature

σ_n	nominal tensile stress
σ_{max}	peak stress in the Inglis' solution (single ellipse)
$\sigma_{max,w}$	peak stress in a plate with finite size (single ellipse)
K_I	mode I stress intensity factor
K_{I0}	reference mode I stress intensity factor
FE	finite element
a, b	elliptical semi-axis
w	plate size
r	polar distance
ϑ	polar angle
ψ	ellipse rotation

In the literature, several different approaches have been reported aimed at understanding the role of free graphite under stressing. Prior investigations into the behavior of cast iron under different loading conditions have shown that the graphite either cracks or debonds at the matrix interface (Dong et al. (1997), Rausch et al. (2010), Mottitschka et al. (2012)). A common approach is to consider the graphite particles as voids or cracks embedded in a metal matrix (cf. Brocks et al (1996), Kuna and Sun (1996), Dahlberg (1997), Costa et al (2010)).

In cast iron, like in most part of natural materials, defects and voids come in a mixture of diverse shapes, as shown in Fig. 1a. A possible simplifying assumption is to replace them by elliptical holes of different shapes and aspect ratios whose distribution could be identified from microstructural information, as done in Fig. 1b. The holes' distribution is expected to have a significant effect on fatigue strength, especially when they are close enough so that interaction occurs depending upon the loading conditions.

Different approaches have been applied to study stress concentrations for interacting holes and a fundamental treatise on the subject was compiled by Savin (1961). Mixtures of holes of different shapes, which are typical in real materials, were analyzed by Tsukrov and Kachanov (1994, 1997) by using the Schwarz's alternating procedure described in Section 2 (cf. also Kachanov (1993), Ting et al (1999), Ukadgaonker et al. (1993, 1995), Zhang et al. (2003)). Tsukrov and Kachanov (1994, 1997) focused on the impact of holes' eccentricities and relative dimensions on the interaction effect and they discussed possible microfracturing patterns in mixtures of defects of different sizes and shapes. Interestingly, when discussing whether the highest tensile hoop stress occurs at the boundary of the smaller hole or of the larger one, they found that the answer depends on the shape of the holes. For two collinear circular holes, the highest concentration factor is found at the boundary of the smaller hole; for two collinear cracks, the opposite is true. For the case of two interacting elliptical holes, which can be considered an intermediate case between the previous ones, the pattern is not obvious and the interaction effect depends on the eccentricities of the holes and on the distance between them.

In Section 3, we present some numerical results on the interaction between two elliptical holes in plane elastostatics. The two elliptical holes have the same size and small eccentricity (0.1) but arbitrary orientation and relative positioning (cf. Fig. 3). Focusing on the hole 1 in Fig.3, our primary goal is to identify a region around the hole 1 outside which placing the hole 2 in order to have a small interaction effect on the first hole. We quantify the smallness by requiring an increase of the stress concentration factor due to interaction smaller or equal to 10%. The identification of the region relies on a FEM analysis and the results obtained are validated by a comparison with literature data taken from Rooke and Cartwrigth (1976).

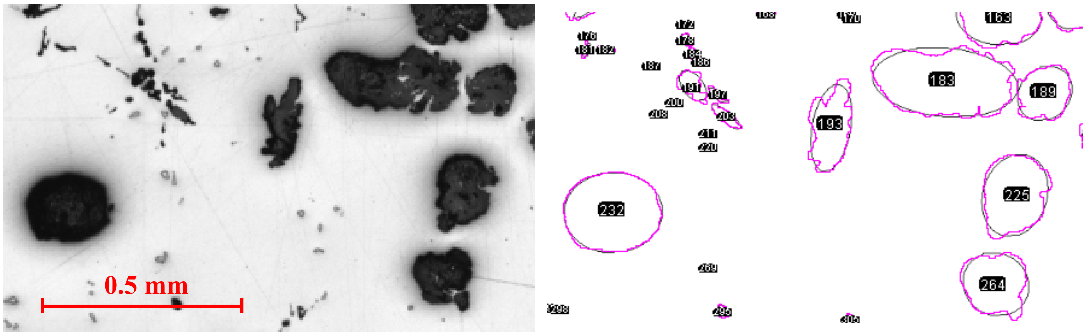

Fig. 1. (a) Typical morphology of graphite inclusions and defects in cast iron. (b) Proposed simplified distribution of elliptical voids approximating the various defects.

2. Schwarz's alternating method

Using the Schwarz's alternating method, the boundary value problem of an infinite linear elastic isotropic plate with two elliptical holes and subjected to remote traction loading reduces to a sequence of boundary value problems in an infinite plate with a single hole, as sketched in Fig. 2. In virtue of the superposition principle, this is possible by a repeated elimination of the redundant surface tractions induced by the solution of the former single hole problem. Considering first the problem of the infinite plate in presence of the single hole 1 (cf. Fig. 2), the analytical stress solutions for the stress state $\mathbf{T_0}$,$\mathbf{T_{01}}$ and $\mathbf{T_{02}}$ are given by Muskhelishvili's complex variable function techniques (Muskhelishvili (1953)). The solution for $\mathbf{T_{01}}$ satisfies the boundary condition of vanishing surface tractions at the boundary of the hole 1 but it causes redundant surface tractions on the boundary of the hole 2. The latter can be balanced by applying surface tractions of opposite sign at the boundary of the hole 2.

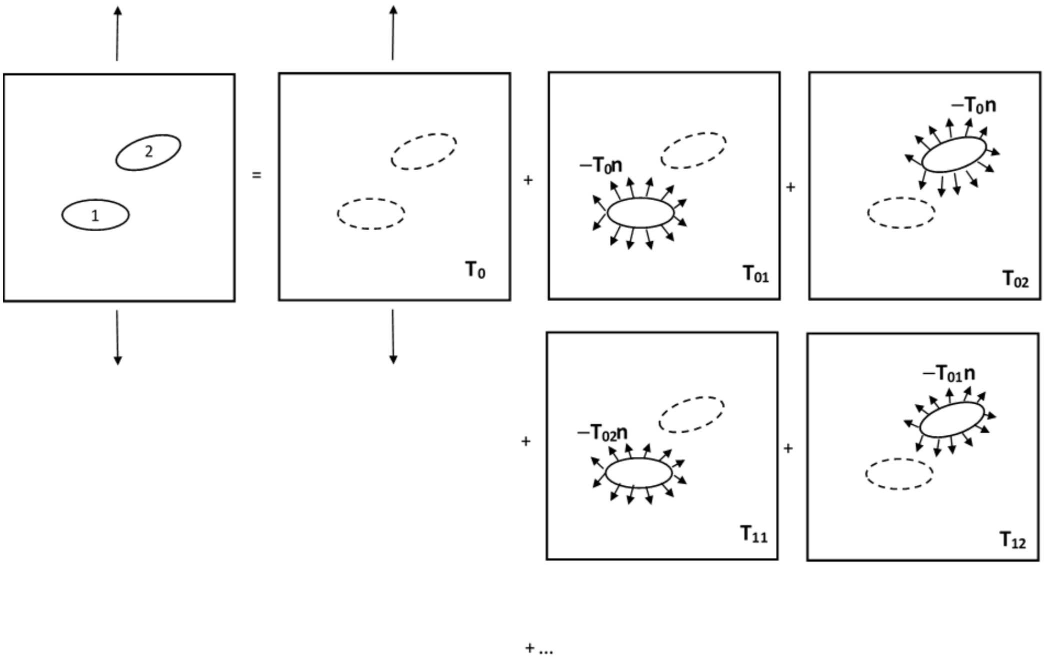

Fig. 2. Sketch of Schwarz's alternating method.

Thus a second boundary value problem in an infinite plate with only the hole 2 loaded by the reversed surface tractions has now to be solved. The corresponding stress state, $\mathbf{T}_{12}$, satisfies the condition of vanishing surface tractions at the boundary of the hole 2 but it gives redundant surface tractions on the boundary of the hole 1, which can be calculated and applied with reversed sign to the boundary of the hole 1 and so on.
The process can be iterated and it is stopped when the redundant surface tractions on the two hole boundaries are small enough with respect to a chosen accuracy. The final stress solution can be obtained by superposition of the stresses computed for all the single hole problems at the different steps of the methods.

Using this procedure, Ukadgaonker et al. (1993, 1995) obtained the complex stress function at the second order corresponding to the stress states $\mathbf{T}_{11}$ and $\mathbf{T}_{12}$ (cf. Fig. 2). Superposition of the stress states $\mathbf{T}_{0}$, $\mathbf{T}_{01}$ and $\mathbf{T}_{02}$, which are analytically given by Muskhelishvili (1953), with the stresses states $\mathbf{T}_{11}$ and $\mathbf{T}_{12}$ computed by Ukadgaonker et al (1993, 1995) allows to calculate an approximated solution, which is in good agreement with literature data for hole spacings not too small. Zhang et al. (2003) obtained accurate stress calculation in terms of a complex variable series used to approximate the redundant tractions.

3. FEM analysis

The evaluation of the safety factor of welded structures could be done by using a fitness-for-service procedure present in European framework or international code. A simple assessment procedure can be used to derive the fatigue strength of welds containing defects, as proposed by Hobbacher (1995), British PD 6493 or SINTAP/FITNET procedure. The designer can simplify the calculations by considering three types of welding reference defects:

1. planar flaws (all types of cracks or crack-like imperfections such as cracks, lacks of fusion or penetration, undercuts);
2. non-planar flaws (cavities, solid inclusions, gas pores);
3. shape imperfections (all types of misalignment, including center-line mismatch, i.e. linear misalignment and angular misalignment).

However, for defects such as pores not parallel to axis of the plate, the simplified procedure could be excessively conservative. To avoid the over-estimation of the equivalent flaw size by applying the suggested assessment procedure, Livieri et al. (2001) proposed an alternative method of defect size measurement, which accounts for the actual defect shape. In particular, for pore defects the dimensions were measured in a frame of reference parallel to its principal axes, instead of along the main plate free edges. Doing so, a smaller equivalent flaw size was derived and the interaction criteria were modified according to a new frame of reference.

In order to investigate the stress concentration related to defects as shown in Fig. 1, a parametric FE analysis will be performed in this paper. For the sake of simplicity, only two elliptical sharp notches are take into account in a plate with a finite size *w*. Figure 3 shows the reference geometry used in the analysis. The ratio between the two semi-axis, *b/a,* is equal to 0.1 whereas *w/a* is equal to 20. As is well known, the Inglis's maximum stress σ_{max} of an isolated elliptical defect in a wide plate under remote uniform tensile stress is given by $\sigma_{max}/\sigma_n = 1+2\cdot a/b = 21$.

Firstly, a FE analysis was performed for the evaluation of the stress concentration due to an isolated ellipse in a square plate with *w* equal 20 times the major semi-axis *a* of the ellipse. The maximum stress $\sigma_{max,w}/\sigma_n$ was found to be 22.3 when the ellipse is put in the centre of the plate. This value is about ten per cent greater than the theoretical Inglis's (1913) stress concentration factor.

Next, FE simulations were carried out with one of the two ellipse always placed at the centre of the plate and the second ellipse moving in the plate and rotating of an angle equal to ψ. The three parameters r, θ and ψ determine the location of the second ellipse. Furthermore, the geometrical cases where the two ellipse could overlap were also considered (see Fig. 4).

In general, the hoop stress σ_θ at the free border is maximum in the neighbourhood of the notch tip because a mixed mode I plus mode II are present. In our analyses, the maximum hoop stress on the free border of the two ellipse has

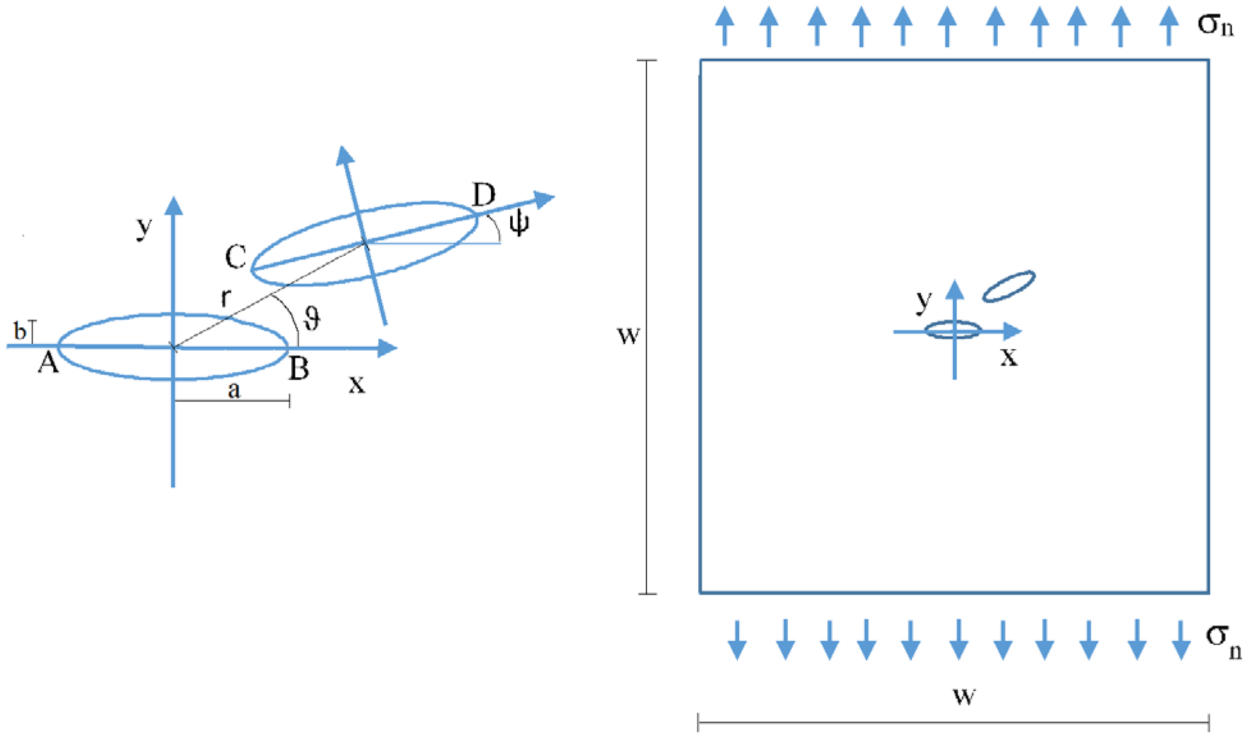

Fig. 3. Reference geometry. Two identical elliptical cracks in a plate (a/b=10, w/a=20).

been taken into account as reference stress. As a synthesis diagram of the FE analysis, by considering the maximum $\sigma_\theta/\sigma_{max,w}$ as key parameter, Figure 5 reports the region where the presence of the second ellipse gives an increasing of $\sigma_\theta/\sigma_{max,w}$ greater than 10%. This region is a simplified result but it shows that when the centre of the second ellipse is inside the marked region, the increasing of the hoop stress is greater than a prefixed per cent value. Finally, as a comparison with the literature results taken from the handbook of Rooke and Cartwrigth (1976), Figure 6 shows magnification factors of two collinear cracks in an infinite plate under uniform remote tensile loading (triangular symbols in the figure). For the crack case, the magnification factor is relative to the ratio between the mode I stress intensity factors K_I, evaluated by means of diagram present in the handbook of Rooke and Cartwrigth (1976), and the reference K_{I0} of an isolated crack in a plate under remote tensile stress: $K_{I0} = \sigma_n\sqrt{\pi a}$. The lines are relative to the present analysis obtained with the two ellipses. The comparison is made at the points B and C. The trend of magnification factor is very similar for both cases of stress concentrations.

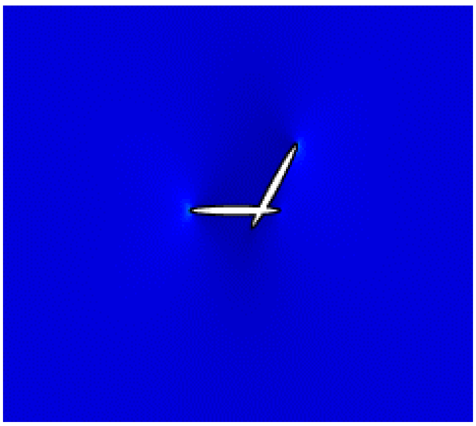

Fig. 4. Overlapping ellipses.

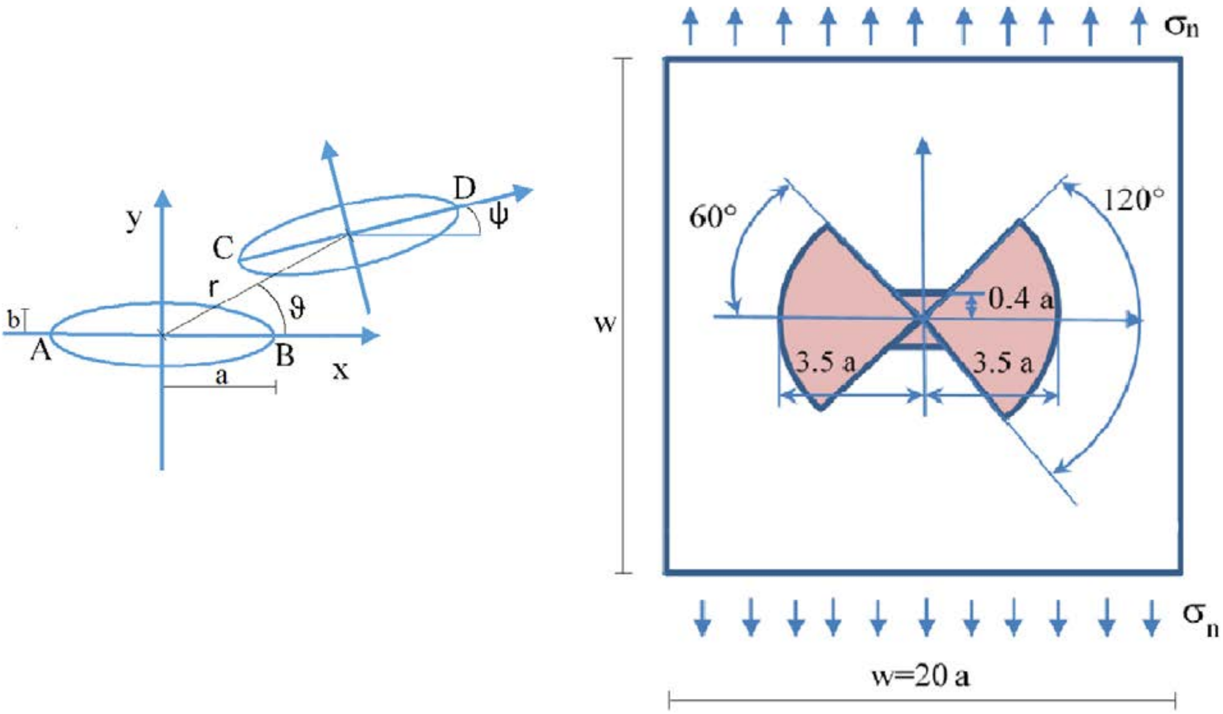

Fig. 5. Region where the presence of the second ellipse gives an increasing of $\sigma_\theta/\sigma_{max,w}$ greater than 10%.

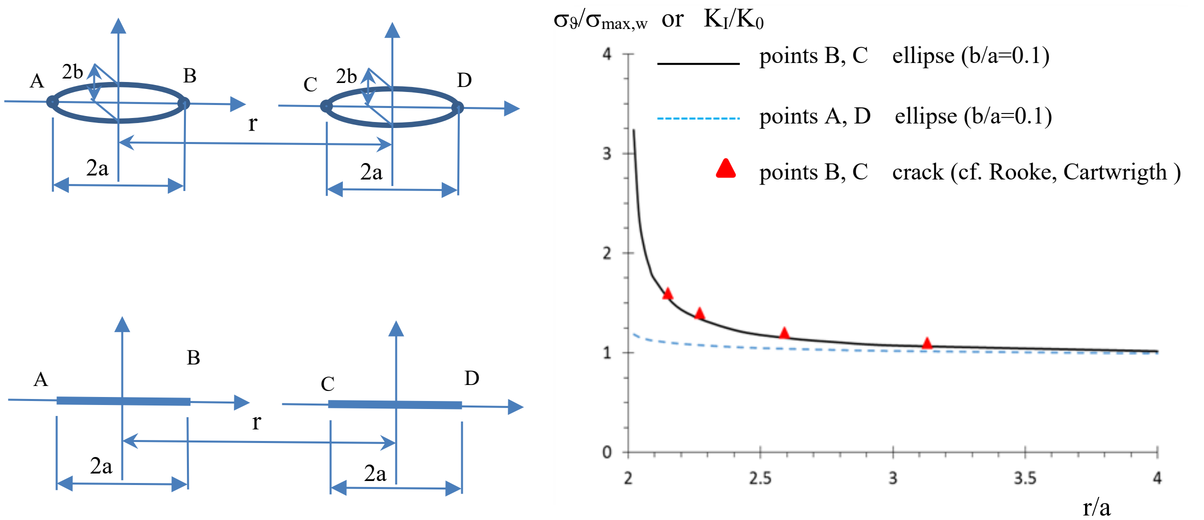

Fig. 6. Magnification factor for collinear ellipses or cracks in a sheet subjected to a uniform uniaxial tensile stress

4. Conclusions

This paper reports on some preliminary results for correlating the graphite microstructure morphology to stress concentration effects via a simplified geometrical description of the defects, chosen as a distribution of elliptical holes. It is well known that defects interaction may have a strong effect on stress concentration factors. In the literature, many authors focused on the impact of holes' eccentricities and relative dimensions on the interaction effect. The interaction effect depends on the eccentricities of the holes and on the distance between them (Kachanov (1993), Tsukrov and Kachanov (1994, 1997), Ting et al (1999), Ukadgaonker et al. (1993, 1995), Zhang et al. (2003)).

In this paper, we applied a parametric FEM analysis to calculate the effect of interaction on the stress concentration factor in a plate with two equal but arbitrarily oriented elliptic holes of given eccentricity (0.1) subjected to uniaxial traction. Our main result is the identification of a region, shown in Fig. 5, inside which the interaction effect gives an increase of the stress concentration factor larger than 10% when compared to Inglis's solution. The results obtained in this paper could be a first step towards the development of a procedure for estimating cast iron's fatigue strength accounting for the microstructure of the material.

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