FRACTURE PROPAGATION IN CAST IRONS

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The nature of the stress - strain functions which occur at contact loading in brittle materials of constrained brittleness are considered and attention is focused on the case when fraction are caused either by a predominantly tensile mode or by shear at large plastic strains. The fracture properties of the cast irons have been studied by strength measurements of controlled contact deformation and direct observation of cracks propagation under variable amounts of triaxiality. The analysis provides a explanation of the fractographic nature of crack fields in the contact damage. Acoustic emission (AE) was monitored during continuous deformation up to the failure and there was a strong increase in root-mean-square (rms) AE level during deformation as a function of failure modes.

INTRODUCTION

Cast irons are widely used because of their excellent machinability, ability to damp vibration, excellent wear resistance, and the case with which they can be cast into complex shapes as automotive engine blocks, gears, flywheels, brake disks and drums. Brake disks of motor vehicles are heavily charged safety parts, which are usually manufactured of low or middle strength cast iron with lamellar graphite. This at first glance astonishing fact is due to excellent properties of cast iron with respect to heat conduction and damping behaviour. Surfaces of break disks in service are commonly subjected to concentrated loads, which can introduce localised structural damage and can degrade the strength or erode the surface. Depending on the contact geometry, individual cracks may initiate from pre-existing flaws in structure or from precursor "plastic" deformation. Cast iron bulk strength depends both on metal matrix and graphite precipitation whereas contact strength depends chiefly on matrix and only in a small degree on graphite precipitation. On the other hand AE characteristic depends primarily on graphite precipitation characteristics as has been discussed by Speich et al (1).

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The purpose of the work reported here. was to investigate the fracture behaviour of brittle materials of constrained brittleness in contact loading based on a methodology proposed by Lawn and Wilshaw (2). The advent of indentation fracture mechanics has provided a fundamental basis for analysing the apparently complex deformation/fracture response to controlled contact events. In this paper we examine more systematically the role of triaxility on the nature of the subsurface deformation - macrocrack damage. using acoustic emission.

EXPERIMENTAL PROCEDURE

The tests were performed on cast iron from induction furnaces of 20 and 100 kg capacity with lamellar graphite in perlitic matrix (carbon equivalent C_{eq}=2.7÷3.7 , strength levels ranged from 200 to 300 MPa and Brinell hardness from 150 to 220 HB). The graphite structure tended to rosette formation (IB3-3). Tests bars of 32x300 mm were cast and from them specimens for mechanical testing as well specimens for contact loading were turned out. Four cylindrical disk models were analysed, each 30 mm in diameter. with thickness to diameter ratios (t/D) of 0.1, 0.5, 1.0 and 2.0. AE during contact loading tests were measured. The sensor was applied to the specimen through an acoustic wave guide with a diameter of 4 mm and length 20 mm. A piezoelectric resonant transducer with a resonant frequency near 200 kHz was used for all tests. The state of cracking and the acoustic emission AE under loads up to 300 kN for disk models and automobile ("Audi-100") brake disk (diameter 257 mm, main thickness 13 mm) were studied (Fig. 2).

RESULTS AND DISCUSSION

Failure modes. Depending on circumstances contact fracture in brittle materials may occur in one of several different modes. The most commonly applied strength criterion for brittle materials is the maximum tensile stress criterion in which the material is assumed to fracture when the principal tensile stress reaches a critical value. However, when the state of stress is triaxial the maximum tensile stress criterion gives poor results (Fig. 3). The loading paths of test include indentation test (denoted by IT), uniaxial compression test (UC). uniaxial tension test (UT) and diametrical compression test (DC). High triaxiality occurs in contact loading because of the constraint of the surrounding elastic material, the plastic deformation induces internal stresses, the plastic zone acts as a compressible hydrostatic core and there is sufficient strain hardening for singularity(Fig. 1a). The stress state in the spherically deformed region is triaxial, which tends to promote fracture for cast irons due to reduced plastic flow. In all casies the fracture is brittle, intercrystalline, but differences can be seen between different stress states. For UC test, specimens fails in shear mode as shown in Fig. 1b, the failure mode is different from that of cast iron under indentation test. For DC, fracture surface orthogonal to the direction of maximum tensile strain. In indentation test with various contact geometry (sphere, cones) beneath the indenter one takes the material to behave as an outwardly expanding "core", exerting a uniform hydrostatic pressure on its surrounds; encapsulating the core is an ideally "plastic region", within which flow occurs according to some simple yield criterion; beyond the plastic region lies the elastic "matrix"(Fig.1a). The plasticity somewhat relieves the tension locally about the contact area (whose dimension is now determined by the load, indenter shape, and material hardness). The inclusion debonding cracks were radial features, for which the tangential stresses are of most importance (Fig. 4a,b). The indenter shape (sphere, cone, pyramid) is likewise important, because various contact indentation angles produces various level of contact deformation; e.g., a sharp indenter produces a more highly concentrated field which is generally more likely to produce fracture. Blunt indenters on the other hand, rely on the critical load necessary to spontaneously from a Hertzian cone crack from the precursory ring crack as the basis for determining fracture toughness. Generally, a deformation zone surrounds the indenter contact area and deformation processes and inhomogeneities are generally responsible for nucleating cracks in structure metals (Fig. 4c,d,e).

Strength data. The cracking due to elastic-plastic contact of brittle materials by rigid indenters has been analyzed in detail (2). The more recent analyses are based on the observation that the driving force for crack formation is provided by a residual stress field which results from mismatch in the elastic and plastic deformations beneath the contact site. The stress field associated with this deformation field has been discussed by Evans (3) and Johnson (4). A spherically symmetric stress field can be associated with a pressurised, expanding spherical cavity, for which an analytical solution is found. From detailed fracture mechanics studies of such cracking, it can be shown that the extent of fracture can be used to determine fracture toughness for extremely brittle materials (glasses and ceramics). In our experiments such cracks are not as well developed, but we may nevertheless use the formulation to gain a crude estimate of K_c. The formulation for the sharp indenter is

$$K_c = \lambda (\cot\theta)^{2/3} \left(\frac{E}{H}\right)^{1/2} \frac{P}{C^{3/2}}, \qquad (1)$$

where θ - indenter half - angle, E - Young's modulus, P - indenter load, H - material hardness = $P/\alpha_0 a^2$, α_0 - indenter constant, a- characteristic dimension of the indentation, C - the cracks size (the radial length of the cracks measured from indentation), λ - experimentally determined constant independent of indenter/specimens system and plastic deformation in contact. =0,0032. The mean level of deformation is determined by the indentation angle, described by Vasauskas and Baskutis (5). Plastic deformation is 0 % for the ideally infinite indenter 180°, 0.2 % for 160°, 16 % for 120°, 70 % for 60°, etc. For sharp indenter ($2\theta<120°$) we take H=1750 MPa and E=0.95×10^5 MPa. Taking P=70 kN and C=9×10^{-3} m (Fig. 4) we calculated K_c=8,95 MPa $m^{1/2}$. This is a reasonable value for a gray cast iron.

After a certain level of plastic deformation is achieved, local fracture occurs. Indenters of angle less than the critical value (between ~100 to 120 deg, depending on the brittleness) produce a cutting type of strain field (Fig. 3). In all tests ultimate strength correlates with stresses of maximum levels of rms AE and of failure (Fig. 5). At the beginning of loading only small amount of energy is released up to 0.75 of failure load. In this phase of loading micro - cracks in cast iron matrix are originating and they start to propagate. For the higher loading level an abrupt increase in the energy rate for cast iron specimens is observed up to failure. Under indentation the time varies from 10 s to 30 s, under compression from 10 s to 50 s, under diametrical compression from 20 s to 40 s. AE is not related to the process of cracking up to a certain stress limit. Under compression shear is initiated at very low stresses.

CONCLUSIONS

The present study has demonstrated that the types of contact fracture occurring in brittle materials of constrained brittleness are strongly dependent on the geometric details of the contact indentation. For cast iron damage at the contact loading included the irreversibly deformed zone directly under the indentation and a radial/median crack system, which sizes becomes the main factors for fracture propagation. The measurement of the AE signals creates new possibilities of better recognition of damage process of cast iron and analysis of amplitude and frequency of AE spectrum enables assessment of fracture mode.

SYMBOLS USED

K_c = fracture toughness (MPa $m^{1/2}$)
E = Young's modulus (MPa)
H = hardness (MPa)
C = crack length (m)
P = load (N)
a = indentation dimension (m)
$\sigma_{1,2,3}$ = principal sresses (MPa)

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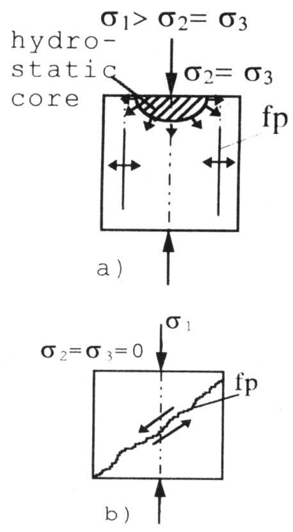

Figure 1. Failure modes: a)indentation, b) compression, fp - fracture planes

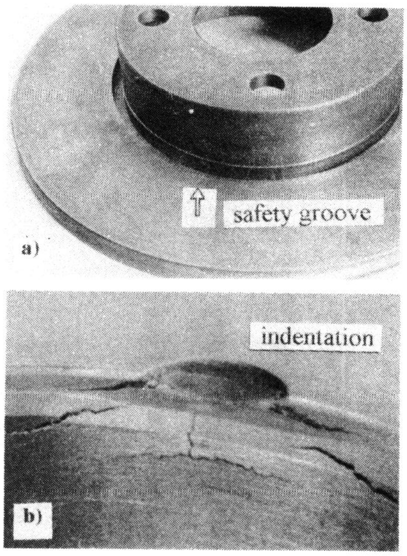

Figure 2. Fractured brake disk (a); crack system for safety groove (b)

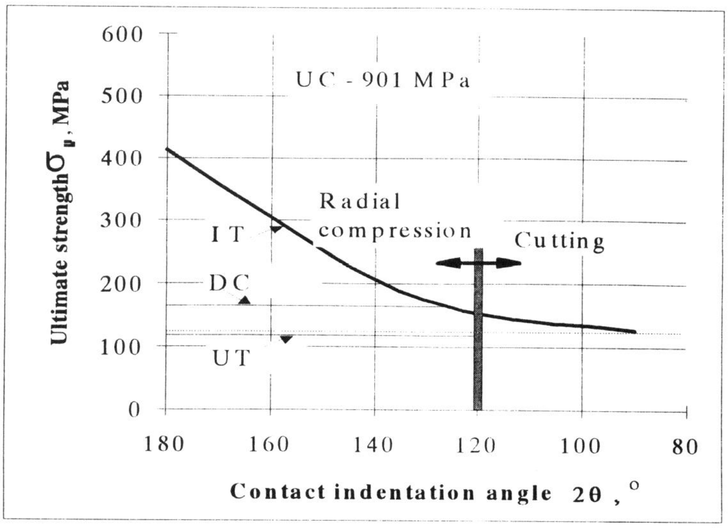

Figure 3. Failure strength at various stress paths: IT - indentation, UT - uniaxial tension, UC - uniaxial compression, DC - diametrical compression

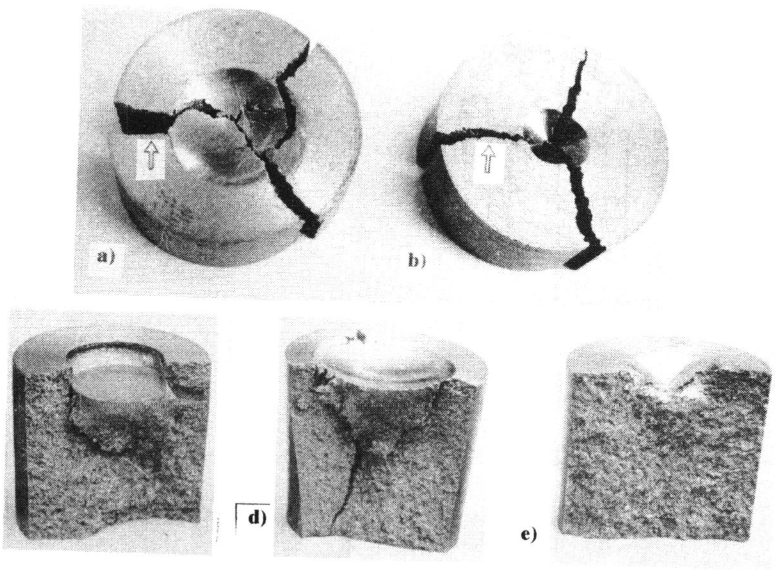

Figure 4. Cracks on sphere (a) and cone (b) indentation, arrows stands for the initiation first crack; specimen cross sections: c) flat punch, d) sphere, e) cone

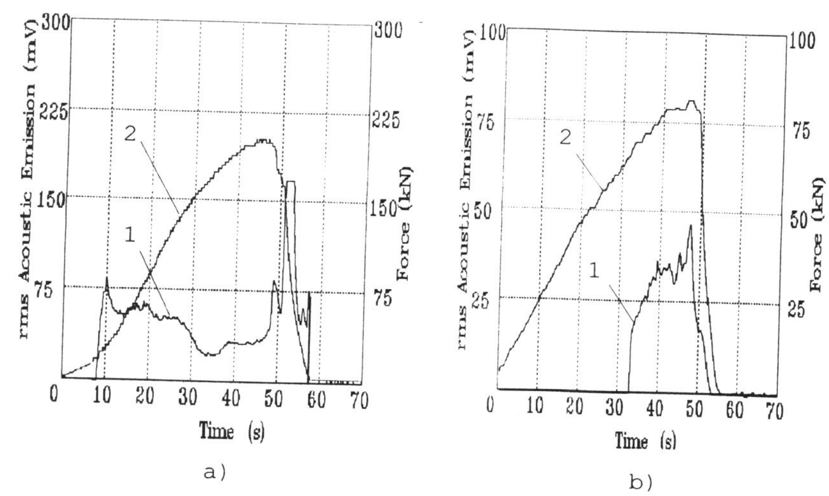

Figure 5. Acoustic emission (1) as a function of load (2) and stress state:
a) uniaxial compression; b) cone indentation