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DUCTILE TEARING FROM INTERACTING SURFACE BREAKING DEFECTS

B. Bezensek and J.W. Hancock

Department of Mechanical Engineering, University of Glasgow, Glasgow, Scotland, UK

ABSTRACT

The interaction of coplanar surface breaking defects has been studied numerically and experimentally. Attention has been focussed on the behaviour of the re-entrant sectors which form as adjacent cracks coalesce in fatigue. Fatigue studies and numerical modelling shows that such sectors exhibit enhanced values of the stress intensity factor. The line spring technique [9,10] was used to analyse a series of evolving configurations, which originate from the interaction of two adjacent semi-elliptical cracks in monotonic loading. Under elastic-plastic conditions amplified values of J-integral were found in the re-entrant sectors, which also exhibit loss of crack tip constraint, as parameterised by T [7,8]. The numerical work is compared with ductile tearing experiments performed on a plain carbon–manganese steel. The experiments show that ductile tearing initiates from the re-entrant sector and the crack develops towards a bounding shape. The evolution of the shape of the coalescing defect in ductile tearing is initially similar to the development in fatigue. The conservatism of codified recharacterisation procedures is demonstrated for defects with re-entrant sector(s) in fatigue and ductile tearing conditions.

KEYWORDS

fatigue, fracture, crack interaction, coalescence, ductile tearing, recharacterisation

INTRODUCTION

Defects in real engineering structures frequently have complex shapes. Defect assessment procedures such as ASME, Section XI [1] and BS 7910 [2] recommend recharacterising the defect with a simple shape, which is amenable to analysis. Fracture mechanics assessments are performed for the recharacterised defect and structural integrity is assured when the recharacterised defect meets specified safety criteria. The validity of the procedure has been extensively studied in fatigue [3-5]. In fatigue adjacent surface breaking defects interact and form a single defect with a re-entrant sector, which exhibits accelerated crack growth rates [3]. The number of cycles in this stage may constitute a significant portion of fatigue life of the component, before the crack evolves into a bounding shape. The recharacterisation process is thus inherently conservative for fatigue. However for defects which fail in a brittle manner on the lower shelf, the presence of the amplified stress intensity factor values in the re-entrant sector presents significant concerns for the recharacterisation process [6]. The current work investigates the evolution of complex defects exhibiting a re-entrant sector in ductile tearing. Numerical analysis used the line spring concept [9,10] to evaluate crack tip parameters, including the J-integral and the non-singular T stress [7,8]. A related experimental programme studied the coalescence process in fatigue, ductile tearing and in brittle fracture [6] for defects with re-entrant sectors.

GEOMETRY AND TEST PROCEDURE

A rectangular plate of plain carbon-manganese steel defined as grade 50D in BS 4360, was machined to the geometry shown in Figure 1 and subject to three point bending. At the mid-length of the plate two coplanar notches were cut with a slitting wheel 70mm in diameter and 0.15mm thick. The two notches were used to initiate two surface breaking semi-elliptical cracks in fatigue. The evolving crack profiles in fatigue are schematically shown in Figure 2. These comprise seven configurations with neighbouring semi-elliptical cracks, seven coalesced cracks with re-entrant sectors and five bounding semi-elliptical cracks. The configurations are defined by the crack depth at the line of coalescence (position A). The current work considers the coalescence phase where the two adjacent crack tips merge to form a single crack with a re-entrant sector, as illustrated in Figure 2. The re-entrant sector initially has a highly concave profile which rapidly evolves to the convex shape of a bounding defect.

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The experimental procedure evaluated two sets of tests. In the first set the development of adjacent defects in fatigue was examined. The second set used fatigue crack growth to develop characteristic profiles with re-entrant sectors which extended by ductile tearing in three point bending.

NUMERICAL ANALYSIS

A finite element numerical analysis based on the line spring concept of Rice and Levy [9], extended to deformation plasticity by White and Parks [10] was employed to assess the fracture mechanics parameters for a series of coalesced profiles which form re-entrant sectors. The geometry was modelled by thick shell elements in ABAQUS [11] and the surface breaking crack was represented by non-linear line spring elements. The model was subject to displacement controlled three point bending. The material was represented with a Ramberg-Osgood power hardening law with a yield stress of 350 MPa, a hardening exponent of 9, a Young's modulus of 200 GPa and Poisson's ratio of 0.3.

Numerical results

The crack driving force was monitored through the development of the J-integral and is presented in Figure 3 for the shallowest part of the re-entrant sector and the deepest crack segment of the coalesced crack. J is normalised by the yield stress (Y) and the local ligament length ($t-a_{local}$). J is presented for a series of crack depths in the re-entrant sector for the same remotely applied load. The applied load is normalised with the limit load of an uncracked geometry (P_0). Amplified values of J are found in the re-entrant sector compared to the deepest crack segments for all applied loads favouring crack advance from the re-entrant sector.

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Crack tip constraint was quantified with the T stress [7,8] derived from the local bending moments and reaction forces in the line spring model. The interest was focused on the re-entrant sector which develops enhanced crack driving forces in elasticity and plasticity. Figure 4 presents T as a function of crack depth for the re-entrant sector. T is normalised with the yield stress and presented for five values of applied load, normalised with the limit load of the uncracked geometry. The magnitude of T depends on the extent of coalescence. Pronounced re-entrant sectors exhibit a compressive T stress in the initial stages of coalescence, indicating significant constraint loss. As the crack depth increases, T becomes more positive due to the bending dominated fields. Figure 4 shows that the T stress distribution saturates as the re-entrant ligament develops large scale plasticity.

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COALESCENCE IN FATIGUE

Fatigue crack growth tests were conducted at a frequency of 4 Hz and at a stress ratio of 0.1. The development of fatigue cracks was monitored with a “beach mark” technique. The processes of interaction and coalescence to form a bounding defect is presented in the fractograph of Figure 5. The spacing between consecutive beach marks in the re-entrant sector indicates accelerated crack growth during the process of coalescence. Use of the Paris fatigue crack growth law obtained from standard three point bend specimen, demonstrates that amplified values of the stress intensity factor exist in the re-entrant sector of the complex defect. Conversely the closely spaced beach marks in the deeper segment indicate reduced crack growth rates, until the re-entrant sector evolves into a bounding shape. The bounding crack then evolves towards a stable aspect ratio [12].

COALESCENCE IN DUCTILE TEARING

Ductile tearing tests were performed on two configurations, shown in Figure 6. These comprise a configuration with adjacent semi-elliptical defects before coalescence and a coalesced profile. The development of the re-entrant sector was monitored by heat tinting followed by a final brittle fracture after large amounts of stable displacement controlled ductile tearing. The test configurations are presented schematically in Table 1 with corresponding fractographs in Figure 6. Crack depths in the re-entrant sector and at the deepest segments are given in Table 1 for each tearing stage of the experiment.

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Extensive plasticity was observed in the re-entrant sector for both test profiles, followed by a stable ductile tear confined to the re-entrant sector, as indicated by a dark blue heat tint mark and a dark grey tear in Figure 6, followed by a brittle fracture. The remainder of the crack front underwent crack tip blunting and experienced only minor amounts of crack advance.

DISCUSSION

Analysis of the fatigue crack growth data confirmed the amplified stress intensity factors determined by the numerical analysis in the re-entrant sector. A numerical analysis of the development of plasticity on the upper shelf also showed amplified values of J-integral in the pronounced re-entrant sector. Experimental ductile tearing of a crack with a re-entrant sector showed substantial amounts of tearing in the re-entrant sector, agreeing with the line spring analysis and the experimentally observed rapid fatigue crack growth of the re-entrant sector. Constraint loss did not effect the tearing resistance in the moderate re-entrant sectors in bending dominated fields. The experimental studies show that in bending the shape of complex defects initially develop in similar ways for the distinctly different crack advance mechanisms of fatigue and ductile

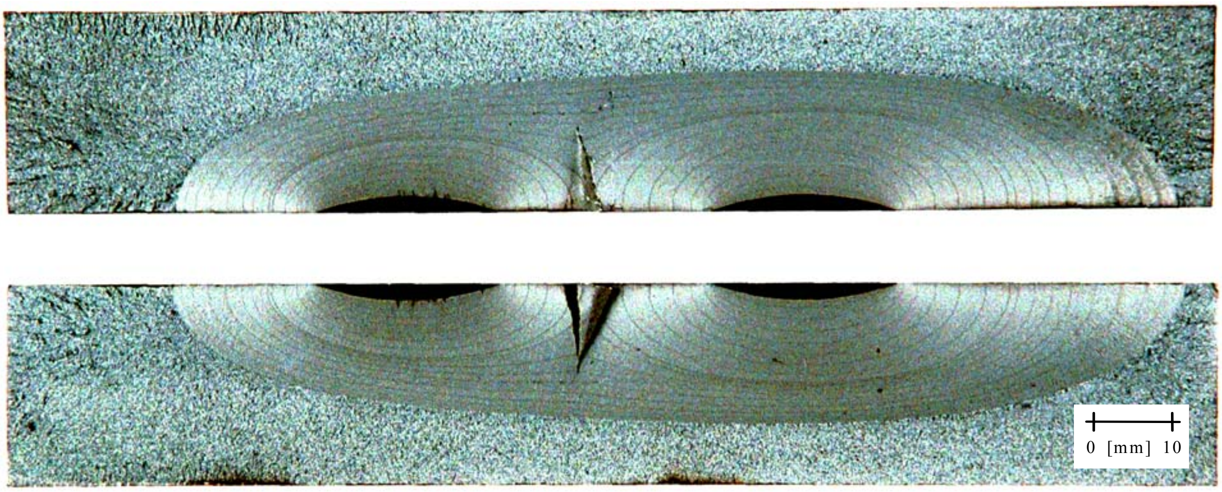

Figure 5: Coalescence in fatigue

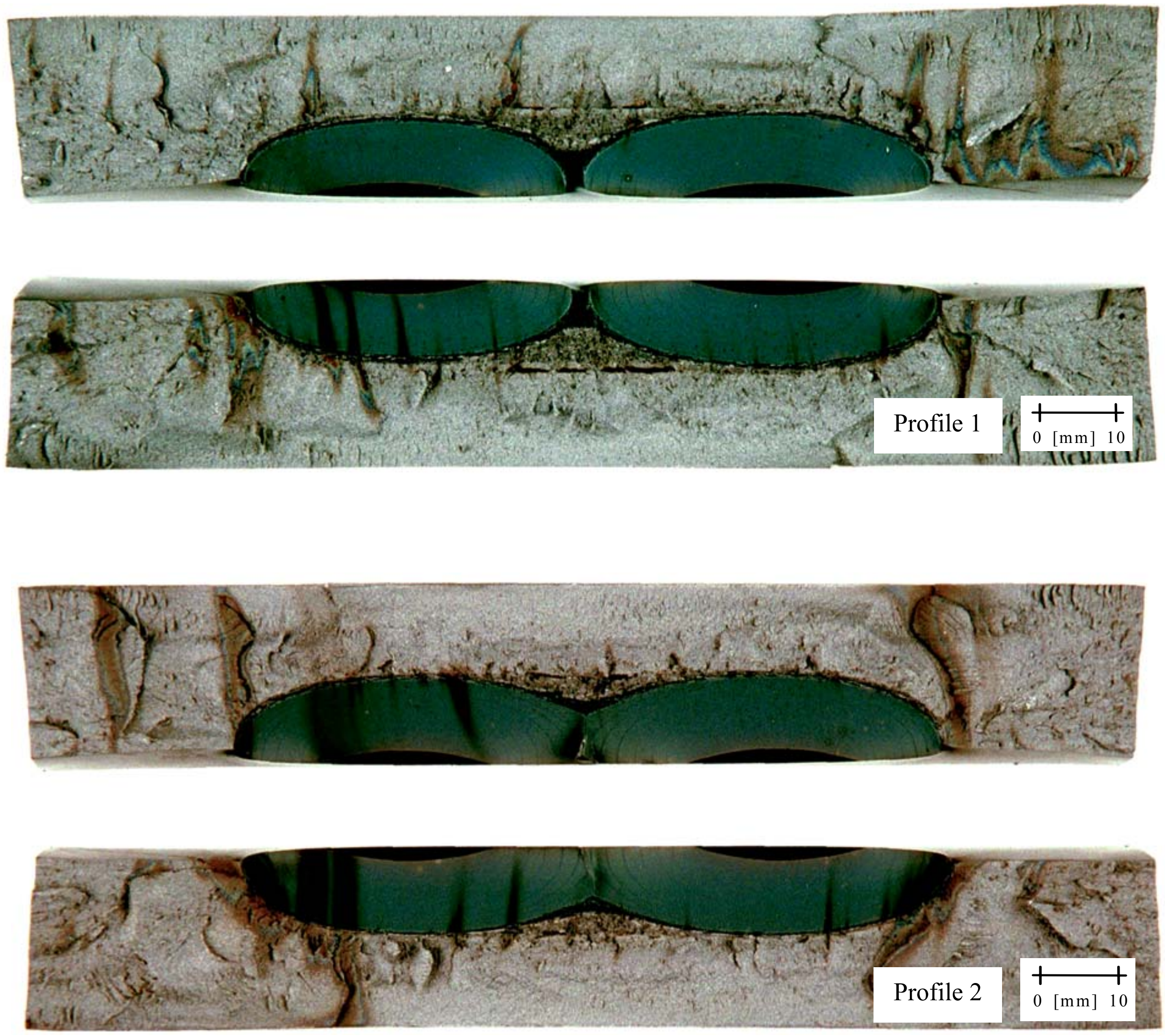

Figure 6: Coalescence in ductile tearing

tearing. Following the formation of a bounding defect of a low aspect ratio the major crack advance by tearing occurs near the free surface, in contrast to the fatigue where consistent crack advance along the crack front towards a stable aspect ratio was observed [12].

Codified recharacterisation procedure [1,2] for defects with re-entrant sectors recommends the evaluation for a bounding semi-elliptical defect. The conservatism of such procedure has been demonstrated for both, fatigue and ductile tearing. The coalescence phase amounts to the significant fatigue life of the component before the bounding profile develops. Although replacing the re-entrant crack with a bounding crack may incur premature repairs and expenses, the process is inherently conservative. Applying the recharacterisation procedure to cracks with re-entrant sectors in bending dominated ductile tearing is also conservative, since tearing starts in the re-entrant sector and the defect develops to the bounding shape of a recharacterised defect. For re-entrant cracks subject to conditions near the ductile-brittle transition regime a low fracture toughness was found [6] and a potentially non-conservative situation exists, when applying the codified recharacterisation procedure to such defects failing on the lower shelf.

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