ON THE STRUCTURE OF PLASTIC AND DAMAGE ZONES IN DIFFERENT MATERIALS AND AT VARIOUS SCALES

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ABSTRACT

The regularities of the formation and structure of plastic and damage zones in structural materials of different types are considered. Our own experimental investigations of the plastic zone structure in metals and extensive literature data analysis are used as the basis for identifying general and particular features of the development of localised damage zones in various materials and at various length scales differing by several orders of magnitude. A single zone of severe deformation (the fracture process zone) is formed at the tip of a crack or a notch in a material in the brittle state. We show that the process of fracture in ductile and quasi-brittle materials is accompanied by the formation of at least of two localised zones characterised by different degrees of deformation and damage: the inner fracture process zone (FPZ) of severe deformation, and the outer, plastic zone (PZ) or damage zone (DZ) where the degree of damage or deformation is lower. It is the presence of the outer zone of moderate deformation and damage (PZ or DZ) that gives rise to the appearance of the size effect. We consider the structure of crack tip zones (FPZ, and PZ or DZ) in materials other than metals, namely, in rubber toughened polymers, concrete, and rocks. We discuss that the fracture properties of different materials are determined by the mechanisms of damage accumulation in the crack tip zones and by the transition from low constraint (plane stress) to high constraint (plane strain) conditions near the crack tip. Although the mechanisms of damage accumulation in different materials may differ, we suggest that in all cases the disappearance of the outer zone (and hence the lack of size effect on strength) is a consequence of the presence of material hardening (as opposed to softening).

1 INTRODUCTION

Plastic and damage zones are the ‘response’ of the material structure to the loading conditions. Therefore the regularities of the initiation and development of plastic and damage zones in different materials are a central topic of fracture and damage mechanics, and the experimental evaluation of their size and shape is an important means of clarifying the fracture mechanisms and of validating the models for energy dissipation during fracture. Many researchers concerned themselves with the experimental methods of plastic and damage zone visualisation, and the procedures for interpreting these observations. We analysed these results with the aim of understanding the general features of the zone formation process that govern the fracture kinetics and size effect in different materials.

2 PLASTIC ZONES IN METALS

Extensive studies of plastic zones in metals in the late 60-s – early 70’s of last century established the relationships between the size and shape of the plastic zones and the stress state of the material under monotonic and cyclic loading and led to the development of fracture models that took account of the localised plastic deformation (Hahn and Rosenfield [1], Hahn et al [2], Broberg [3], Broek [4], Yokobori [5], Taira et al [6]). The concepts of ‘hinge-type zone’, ‘45-degree shear zone’ and ‘fracture process zone’ (FPZ) were introduced to describe the formation of the regions of intense deformation and damage in the vicinity of a tensile crack, and also to distinguish of the monotonic and cyclic plastic zones under fatigue loading conditions.

The data of Hahn et al [1,2] demonstrate that two plastic zones are formed at the tip of a ductile crack both under cyclic and static loading. These ideas were developed further (Botvina et al

[7,8], Klevtsov et al [9,10]) in application to the plastic zones in metallic materials under monotonic, cyclic and impact loading within a wide temperature range. X-ray diffraction methods used for this purpose relied on the evaluation of peak broadening that depends on the distortion of the crystal lattice, thus characterising the extent of deformation within the plastic zone. In order to measure the variation of plastic deformation with depth under the fracture surface the collection of X-ray data was used intermittently in combination with chemical layer removal. This allowed the evaluation of the dependence of the plastic zone width on the crack length and the loading conditions, and the study of the morphology of the plastic zone as a function of the prevailing stress state. The following conclusions were made:

- The mechanical behaviour of the metallic specimen is governed by two connected parameters: the size of the plastic zone (or, more precisely, by the ratio of the plastic zone size to the specimen thickness), and the degree of distortion (plastic strain) within this zone.
- Two distinct zones form in the vicinity of the crack tip: the inner zone (FPZ) of highly deformed material, and the outer surrounding zone (PZ) of weak plastic deformation.
- The ductile-brittle transition is connected with the disappearance of the outer zone of weak plastic deformation when the temperature is lowered and reaches the critical transition temperature. Similar effect may arise as a consequence of increasing the specimen thickness or decreasing the material toughness while maintaining the temperature unchanged.
- The conditions for the disappearance of the outer zone of weak plastic deformation coincide with the well-known requirements for the valid determination of the plane strain fracture toughness.

The identification of the two types of deformation zones at the crack tip provides important insight into the mechanism of energy absorption during fracture. The smaller zone of intense deformation (the fracture process zone) is the region where decohesion actually occurs and is a necessary pre-requisite for material separation. The larger zone of less intense deformation, on the other hand, is identified with the process of energy dissipation by inelastic deformation, and is not directly related to the process of material separation: it is coincidental, in that it arises due to stress concentration near a notch. The increase in the size of this outer zone of lower deformation promotes energy dissipation, therefore increasing the apparent toughness of the material and ductile behaviour. Conversely, the absence of the outer zone means that energy dissipation is restricted to the minimum needed for actual material separation, and that the external appearance of the fracture surface corresponds to brittle behaviour.

The detailed study of the structure of plastic zones in low carbon steel by metallographic methods (Botvina et al [11]) showed that they contain single cracks of transgranular and intergranular type, as well as clusters of microcracks. The microcrack density increases significantly in the fracture process zone at the crack tip. The coalescence of these microcracks leads to the initiation and development of the main crack (Korsunsky and Botvina [12]).

The kinetics of local plastic deformation at the level of inhomogeneities and inclusions were investigated by Tetyueva et al [13]. Plastic zones arising at the tips of elongated sulphide inclusions having the length of 0.5mm in steel were studied by the method of microhardness. Specimens of low alloy tube steel were subjected to hydrogen charging under tensile load using different exposure periods. To delineate the shape and size of the plastic zone microhardness measurements were performed along lines extending from the tip of the inclusion in several directions in relation to the sulphide axis. The results allow two plastic zones with different degree of hardening to be identified at the inclusion tips. This is similar to the formation of two deformation zones (inner intense deformation zone, and outer weaker deformation zone) at the tip of a macroscopic crack under tensile loading. It is interesting to note that the outer, more weakly deformed plastic zone disappears after the maximum exposure period corresponding to the highest degree of embrittlement, reflecting the reduction in the amount of energy dissipation during fracture. This change in size of the plastic zone is accompanied by a change in its shape. The narrow elongated plastic zone at the inclusion tip, more characteristic of the low constraint, plane stress conditions is replaced by the ‘butterfly’ shape that is more typical of the high constraint, plane strain conditions. This change in the plastic zone shape may therefore be connected with the change in the local material yield properties as a result of hydrogen embrittlement. This observation highlights the fact that a correspondence may be established between the ductile-brittle and plane stress-plane strain transitions, on the basis of the difference in energy dissipation during fracture. It is also worthwhile noting that the characteristics of the plastic zone pattern are preserved across several orders of magnitude.

3 DAMAGE ZONES IN POLYMERS

Two distinct zones of plastic deformation near the crack tip were found during fracture testing of two rubber-modified epoxy matrices with different toughenability (Arias et al.[14]) using the double-notch four-point-bending technique which allows one to observe the damage zone at the surviving notch after specimen fracture develops from another notch. The damage zones were studied by the methods of transmission optical and electron microscopy.

The rubber-modified epoxies differed in their chemical structure and, as a consequence, in terms of their glass transition temperature and yield stress. The first epoxy (to which we shall refer as H-type) exhibited higher values of glass transition temperature and yield stress, and lower values of the critical stress intensity factor. The stress-strain curve of the H-type polymer manifested strain hardening at relatively small strains. Due to the flexibility of polyether chains present in structure of the second epoxy (to which we shall refer as S-type), the glass transition temperature and yield stress of this polymer were lower than for the H-type, but the plane strain fracture toughness, K_{1C}, was higher than that for the H-type epoxy. S-type polymer undergoes significant strain softening after yielding and manifests a plateau stress persisting to relatively high strain.

The difference in the fracture characteristics of the two polymers can be related to the different situation near the crack tip. Namely, a single damage zone (fracture process zone) was found at the crack tip in the H-type epoxy, while two damage zones were observed in the S-type material, namely, the inner zone immediately in front of the crack tip extending by about 100 µm, and the outer zone containing a large number of dilatation bands. The predominant mechanism of deformation in the first zone was cavitation of rubber particles followed by void growth and induced shear yielding of the matrix. The dilatation bands in the second zone did not cause massive shear yielding of the surrounding matrix and contained arrays of cavitated rubber particles within dilatation bands. The researchers (Arias et al [14]) suggested the following stages of damage accumulation: cavitation, void growth with simultaneous formation of dilatation bands within the second zone, and massive shear yielding by overlapping of dilatation bands in the first zone. The formation of the localised dilatation bands of high shear strain is a result of strain softening of the epoxy matrix. Eventual hardening imposes a limit on the strain achieved.

The damage zone in the H-type epoxy revealed only the region of cavitated particles near the crack tip. However, void growth and the formation of dilatation bands was not found. Fracture surface of specimens was smooth and mirror-like.

These changes in the damage zone structure are similar to those in metals tested above and below the critical temperature of brittleness. Indeed, in the case of polymers the two zones also form in the ductile state; the disappearance of one of them leads to a decrease in the fracture toughness and the appearance of smooth fracture surface corresponding to the brittle or quasibrittle state of this epoxy. The results of this paper suggest that it is the hardening response of the material responsible for the ductile-to-brittle transition that also gives rise to the necessary plastic deformation constraint for the disappearance of the size effect.

4 DAMAGE ZONES IN QUASIBRITTLE MATERIALS

The fracture of quasi-brittle materials such as concrete is accompanied by the formation of localised zones of microcracking near the crack tip. The analysis of the morphology of these zones concerned many researchers in the context of energy dissipation on microcracking, and the associated effect on the apparent material toughness.

Various authors distinguished at least two zones containing different level of damage, that occupy different locations relative to the crack tip. For example, Mihashi [15] observed the formation of two distinct fracture zones with closed and opened microcracks during fracture of concrete. Closed microcracks appear in the region close to crack tip, while open microcracks arise in front of this region. Fracture occurs in three stages: (1) the formation of the initial microcrack zone; (2) the development of the main crack which is accompanied by the growth at its front of the zone of closed microcracks, and further out in front of it of the second zone with open microcracks; (3) further propagation of the main crack is accompanied by extension of both damage zones.

Wittmann [16], on the other hand, suggested a different fracture sequence. He distinguished an inner microcracking zone with interacting microcracks and an outer zone that surrounds the inner one and contains isolated microcracks. This concept of multiple fracture zones is analogous to that noted above for metals, for which strongly and weakly deformed plastic zones can be identified near the crack tip under all types of loading. However, in contrast with metallic materials, plastic deformation in concrete is virtually absent, and the two zones that arise are only characterised by microcracking.

The results of estimating the acoustic emission (Otsuka [17]) also confirm that fracture of concrete is connected to the formation of two damage zones at the crack tip.

5 FRACTURE PROCESS ZONE IN ROCKS

Hoagland et al [18] presented an early detailed study of the process of damage zone development around a machined slot in rock. The authors showed that during initial loading of the specimen, even under nominally elastic conditions, a localised microcracking zone is formed near the tip of the slot. Further loading results in the formation of a larger zone, although no crack propagation as yet has taken place at this stage. Once again, it is possible to distinguish two zones at the tip of the crack: the inner zone with high microcrack density, and the outer zone, where the microcrack density is lower.

6 DAMAGE ZONE NEAR FAULTS IN THE EARTH CRUST

Fault is usually defined as a discrete planar surface which accommodates slip in the earth crust. However, observations of natural faults show that they have complicated structures and do not correspond to this simple idealisation. According to Scholz [19], the growth of experimentally induced shear fracture is accompanied by a complex breakdown process including the interaction and coalescence of mode I microcracks. This differs from the propagation of tensile brittle fracture and cannot be fully described using linear elastic fracture mechanics models. The idealised fault zone structure consists of the process zone, the cataclasite zone and the shear zone (Scholz et al [20]).

For faulting in the brittle state the cohesion zone was thought to be equivalent to the process zone, containing tensile microcracks that appear prior to the fault tip propagation. Microfracturing within the process zone near the fault tip starts when the stress reaches a critical dilatancy stress of about 50% of the initial yield strength. The degree of microfracturing in the outer zone remains low at this stage.

6 MODELS OF LOCALISED DAMAGE ZONES

Classical models for the description of the localised inelastic deformation processes at the crack tip are those due to Barenblatt [21] and Dugdale [22]. These models were originally formulated and applied to the analysis of fracture in polymer and metal sheets. However, the insight provided by these approaches was so valuable that the application of these models was successfully developed for other materials, such as concrete (Hillerborg [23], Bazant [24], Karihaloo [25]).

Cowie and Scholz [26] developed a plane strain cohesive zone model of fault growth. Their treatment is also based on the Barenblatt-Dugdale approach and provides solutions for stress and displacement distributions associated with faults. The model introduces a critical shear displacement for inelastic deformation that develops within a cohesion zone near the tip. In this zone the shear strength falls from an initial yield stress value to the residual frictional strength of the fault. The displacement distribution predicted by this model differs from the parabolic variation typical of the linear elastic fracture mechanics models, in that the displacements taper off gradually toward the fault tips. This finite taper, or crack opening angle, ensures that the stress concentration in the vicinity of the fault tip is finite and limited to the initial yield stress value.

The proposed model was confirmed by the detailed studies of the structure of the microfracture process zone near the fault tip conducted with the evaluation of the zone size and the variation of the crack density within the zone as a function of distance from the fault (Vermilye and Scholz [27]). In this analysis, as in all models of the Barenblatt-Dugdale type, the inelastic deformation is thought to be confined to the plane of the fault. The model assumes that this inelastic deformation occurs entirely within the plane of the fault, i.e. no deformation outside the fault plane is considered.

7 CONCLUSIONS

The review of localised fracture processes in different materials and at different scales shows that certain general features, such as the two damage zones, hardening and constraint effects and brittle-ductile transitions are present in all material types and at all scales. Improved understanding of strength scaling and size effects requires detailed analysis of crack tip damage zones. This is particularly relevant for quasi-brittle materials, where outer zones of distributed damage are usually very large, perhaps due to the lack of material hardening and constraint.

Further analysis of fracture processes and size effects in various materials requires the development of the ability of the models to incorporate the differences in the hardening response, the development of two zones of damage accumulation, and the influence of deformation constraint on the shape of the near tip zones.

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