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Failure of metals I: Brittle and ductile fracture

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ABSTRACT

This is the first of three overviews on failure of metals. Here, brittle and ductile failure under monotonic loadings are addressed within the context of the *local approach to fracture*. In this approach, focus is on linking microstructure, physical mechanisms and overall fracture properties. The part on brittle fracture focuses on cleavage and also covers intergranular fracture of ferritic steels. The analysis of cleavage concerns both BCC metals and HCP metals with emphasis laid on the former. After a recollection of the Beremin model, particular attention is given to multiple barrier extensions and the crossing of grain boundaries. The part on ductile fracture encompasses the two modes of failure by void coalescence or plastic instability. Although a universal theory of ductile fracture is still lacking, this part contains a comprehensive coverage of the topic balancing phenomenology and mechanisms on one hand and microstructure-based modeling and simulation on the other hand, with application examples provided.

1. Introduction

Among the various damage mechanisms introduced in the preface, we begin by studying those associated with brittle and ductile fracture in metallic alloys. Brittle fracture includes both cleavage and intergranular fracture. Ductile fracture encompasses failure by cavitation or by plastic instability. The main objective of this article is to overview the methodologies that are based on the study of the mechanisms operating at a local, i.e. microscopic scale and, through a multiscale approach, on the transfer of this local information to the macroscale, that over which the performance of structural components as well as materials characteristics or "properties" are usually defined. Several reviews and books have been published on this subject (see e.g. Refs. [1–3]) but very few of them provide a comprehensive synthesis of the state of the art. In particular, a special effort is made here to incorporate the most recent developments in the theoretical and numerical modeling of both brittle and ductile fracture.

The methodologies referred to above fall under what is now called "the local approach to fracture", which has been largely developed for brittle fracture with the original Beremin model introduced in the late 70's and early 80's [4,5]. Brittle fracture has been reviewed recently by the authors [6]. In the present paper emphasis is laid on the latest developments, in particular those dealing with the multiple barrier models and the crossing of grain boundaries by cleavage cracks. This aspect of brittle fracture has a special importance when the materials are tested in the rising part of the ductile-to-brittle transition (DBT) curve. The topic of ductile fracture has also been independently reviewed by the authors in two separate monographs [6,7]. Another review by Besson [8] focused on modeling. While we defer to these reviews for many details, the main mechanisms and concepts are overviewed for completeness. In doing so, we lay emphasis on the latest developments adopting a narrative that seamlessly combines ductile fractures in structural components and metalworking. In addition, significant advances have recently been made in developing more robust models, which ultimately will reduce the many uncertainties associated with currently used models.

The influence of crack tip constraint and stress triaxiality on ductile and brittle fracture is of major importance for the assessment of structural integrity of many industrial components. This assessment is usually made by using linear and nonlinear fracture

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mechanics concepts. Compared with these concepts, micromechanical models developed in the frame of the local approach to fracture have the advantage that the corresponding material parameters for fracture can be transferred in a more general way between various specimen geometries. In the early version of the Gurson model for ductile fracture [9–11], crack initiation and propagation are a natural outcome of the local softening of the material due to void coalescence, which starts when a critical void volume fraction, f_c, is reached over a characteristic distance, l_c. In principle, the parameters f_c and l_c can be determined from rather simple tests such as tensile tests using smooth and notched round bars in combination with numerical analyses of these tests, or from micromechanical models. Similarly, the Weibull stress model originally proposed by Beremin [5] provides a framework to quantify the complex interactions among specimen size and geometry deformation level and material flow properties when dealing with brittle (cleavage or intergranular) fracture. The Beremin model in its simplest form also uses two parameters only.

The identification and determination of the damage parameters in the Gurson or in the Beremin model require a hybrid methodology of combined testing and numerical simulation. The full description of this methodology is out of the scope of the present paper. More details can be found elsewhere [6]. Here it is enough to say that, contrary to the classical fracture mechanics methodology, the local approach to fracture is not subject to any size requirement for the specimens as long as the same fracture phenomena occur.

This article is organized according to failure modes: cleavage, intergranular, and ductile fracture. In the part devoted to cleavage the early theories for this mode of failure are briefly presented first. Then more recent theoretical developments are presented and applied to ferritic steels and other metals with either a BCC or HCP structure. Intergranular fracture in ferritic steels is also briefly reviewed. Then, ductile fracture is presented in some detail.

2. Cleavage fracture

2.1. Preliminary remarks

Cleavage fracture preferentially occurs over dense atomic planes (See Table 1). Three fracture surfaces observed on ferritic steels are shown in Fig. 1a, b, c. These micrographs reveal that the orientation of cleavage facets, change when they cross sub-boundaries, twin boundaries or grain boundaries. Steps or ridges appear on the fracture surface to compensate for the local misorientation, in particular at grain boundaries. The crossing of grain boundaries by cleavage cracks is analyzed in more detail in the following. For BCC metals and in the case of mechanical twins, these steps look like indentation marks which are named "tongues" (Fig. 1c). In order to maintain the equilibrium of the crack front, the nearest steps gather to form a single step of higher height leading to the formation of "rivers" as observed in Fig. 1a and b. These rivers align with the direction of the local propagation of the cleavage cracks. On a macroscopic scale the surfaces of the cleavage facets tend to be normal to the maximum principal stress (mode I fracture).

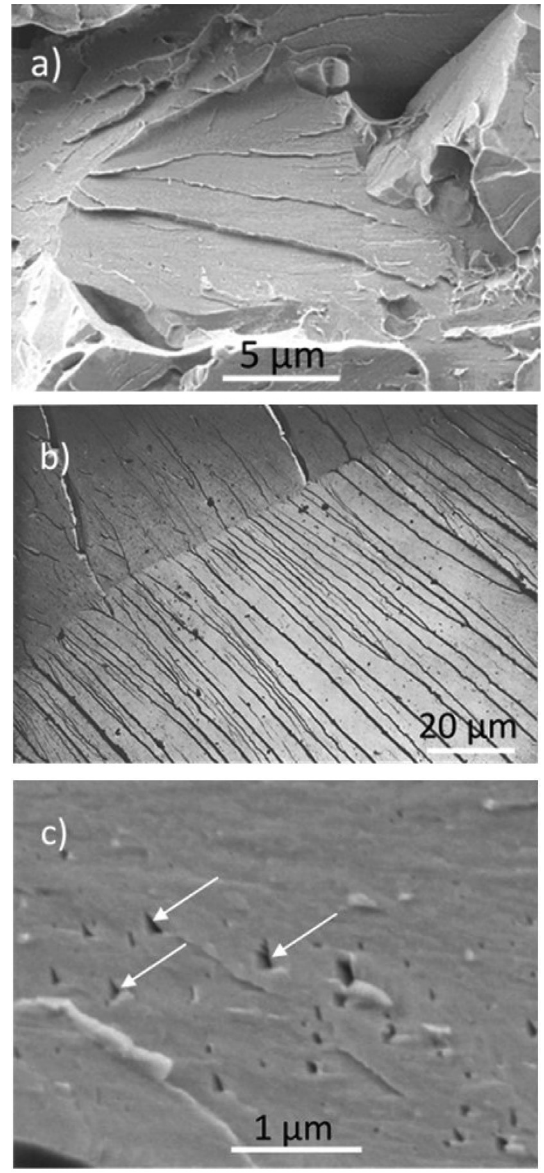

Fig. 1. Cleavage fracture surfaces (a) low alloy steel [439] – Rivers; (b) Polycrystalline zinc rivers originating from a grain boundary; (c) SEM micrograph showing the presence of "tongues" (indicated by arrows) formed at the intersection of the main (001) fracture plane with mechanical twins.

Intergranular fracture corresponds to another brittle mode of failure observed in polycrystalline metals. This mode of failure is often observed when the segregation of impurities such as P, As, S, etc … at grain boundaries takes place (See e.g. Ref. [12]). The transition between cleavage and intergranular fracture takes place when the ratio R_{CI} is lower than one [3]. This ratio is defined as

$$R_{CI} = 1.20 - \frac{\gamma_b}{2\gamma_S} \quad (1)$$

where γ_b is the free energy (per unit area) of the boundary and γ_S the free energy of a surface exposed by cleavage. Cottrell [13–15] has shown that, in pure metals, γ_b depends mainly on the macroscopic shear modulus, μ, whilst γ_S depends on the macroscopic bulk modulus, K. This means that the ratio R_{CI} can be written as

Table 1
Cleavage planes in various materials.

Structure	Cleavage plane	Some materials
BCC	{100}	Ferritic steels, Mo; Nb, W
FCC	{111}	Very rarely observed
HCP	{0002}	Be, Mg, Zn
Diamond	{111}	Diamond, Si, Ge
NaCl	{100}	NaCl, LiF, MgO, AgCl
ZnS	{110}	ZnS, BeO
CaF_2	{111}	CaF_2, UO_2, ThO_2