INFLUENCE OF MICROSTRUCTURE ON CLEAVAGE FRACTURE INITIATION MICROMECHANISMS IN STEELS

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ABSTRACT

Three different fracture initiation types related to low temperature brittle cleavage fracture of steels, are presented and available data on this subject is reviewed, thus proving that fracture initiation is a complex phenomenon. Microstructural features associated to each fracture initiation type are identified and the micromechanism involved is described, in terms of stress/strain control and general initiation localisation. Fractographs are included corresponding to blunt notch specimens. It is emphasised that the first cleavage nucleus forming feature in its own is not determinant and the surrounding microstructure (the matrix, void forming inclusions), can exert some coupled influence at the initiation stage by favouring or impairing fracture initiation. It is vital a sound knowledge of the cleavage initiation process as it has important implications in further metallurgical improvements and in the feeding of statistical fracture models.

INTRODUCTION

Brittle fracture micromechanisms is a key subject as it is the basis of further metallurgical improvements and feeds with physical basis statistical fracture models based on a local approach. In brittle cleavage fracture the initiation and the propagation stage have to be considered. It is believed that the propagation stage is stress controlled and there are some microstructural barriers which might stop an advancing crack. Smith [1] proposed a particle-crack initiated propagation controlled fracture criterion based on Mc Mahon et al.‘s findings [2] of carbide triggered fracture that can be applied to any brittle particle. As far as initiation concerns, this phenomenon is less well understood (statistical models lack of a proper treatment of this stage of brittle cleavage fracture).

The pioneering work of Mc Mahon and Cohen [2] demonstrated that coarse carbides cracked and provided crack nucleus for cleavage fracture. Later, cementite particle cracking was also observed in spheroidised 1.05 % C tool steel [3] and inclusions initiated cleavage fracture has been found in weld metal [4-6] and pearlitic steels [7], in an analogous way to that observed by Mc Mahon in coarse carbides. The wider use of Ti as a microalloying element has revealed that coarse TiN particles can initiate fracture as well.

The presence of coarse crack forming inclusions has made possible direct fractographic identification of initiation features and given new light to the micromechanisms of cleavage fracture, and consequently a good training in the skill of fracture initiation localisation. In cases where no inclusions are distinguishable the interpretation of cleavage initiation is arduous; fine experimental techniques and good skill is necessary. Tracing back river patterns and fracture surface etching have shown new initiation mechanisms related to debonded particles or hard phases. Also near notch root initiated fracture has been reported. This panorama requests a review of the to date available fracture initiation mechanisms. Regarding microstructure, not only the direct initiating feature is of relevance, as it has been shown, microstructural refinement can hinder inclusion cleavage triggering capability; in consequence, it follows that the matrix has also to be taken into account in initiation and not only in the propagation stage.

In cases where there is no microstructural feature to which the brittle fracture process can be related, dislocation mechanisms have been suggested [8-9]. To summarise, there is a rich variety of initiation mechanisms and it is difficult to state one only mechanism. Each of the following sections corresponds to one particular fracture initiation type:

- Brittle zone cracking initiated cleavage
- Particle or brittle zone debonding initiated cleavage
- Void driven cleavage initiation

It should be mentioned that this work is a result of many tests, and if not explicitly contrary mentioned it will always deal with blunt notch slow four point bending tests [10].

BRITTLE ZONE CRACKING INITIATED CLEAVAGE

Mc Mahon and Cohen [1] showed that coarse carbides in polycrystalline iron cracked in a brittle way and nucleated particle cracks that extended into the matrix as a microcrack. This work proved that opposed to previous dislocation based theories of cleavage nucleation in steels, brittle particles could provide a cleavage nucleus, by cracking subsequently to the onset of plastic deformation on the deforming matrix, and thus initiating the cleavage process. In recent years, considerable work has been performed in the area of fracture behaviour of TiN containing steels [11,12], in order to gain a better understanding of the brittle fracture process and evaluate the energy of the barriers preventing crack propagation [13,14]. As a consequence of these studies it can be stated that Ti containing non-metallic inclusions, (Ti,N) (Ti,N,Ca,S,Al,Mg,O) are easy crack nucleators which insert fast moving cracks which trigger brittle fracture by cleavage and promote the shifting of the DBTT curve to higher temperature values. A clear evidence of the potential of triggering brittle fracture is the large amount of secondary initiation sites that appear in the fracture surface on top of the general principal initiation site.

The reason of the microcrack forming ability of TiN brittle particles could be explained by its lower thermal expansion coefficient compared to the steel surrounding matrix [15]. This ensures trapping of the particle during the cooling from the hot working temperature to room temperature, making possible a raise in the circumferential stress around the particle by tessellated stresses [16] (favouring propagation in the matrix). And more over favouring a good bonding with the matrix, and thus enabling the load transmission from the matrix to the particle (favouring nucleation). There is strong evidence of (Ti,N) particle triggered fracture in many different microstructures in steels; bainite [17,18], ferrite-pearlite [11,12], martensite [18]. Figure 1 shows fractographs corresponding to (Ti,N) particle initiated fracture in the presence of these three microstructures.

Different mechanisms have been suggested in the literature through which the particle cracking is induced. Among these the most important are the fibre-loading mechanism [18,19], the dislocation pile-up mechanism [1], and finally the Weibull effect [20] related to the size of the particle (the bigger the more internal flaws). Further work is necessary to ascertain which is the one acting in the case of (Ti,N) or if it consists on a “mixture” of them. The knowledge of the mechanism is of vital importance in the temperature range where nucleation as opposed to propagation is the controlling or competing step.

Table 1 shows a summary of cracked inclusions responsible for fracture initiation reported in the literature. Inclusion initiated fracture has been reported in weld metals [4-6], in eutectoid pearlitic steel [7] and in the pressure vessel steel [22,23].

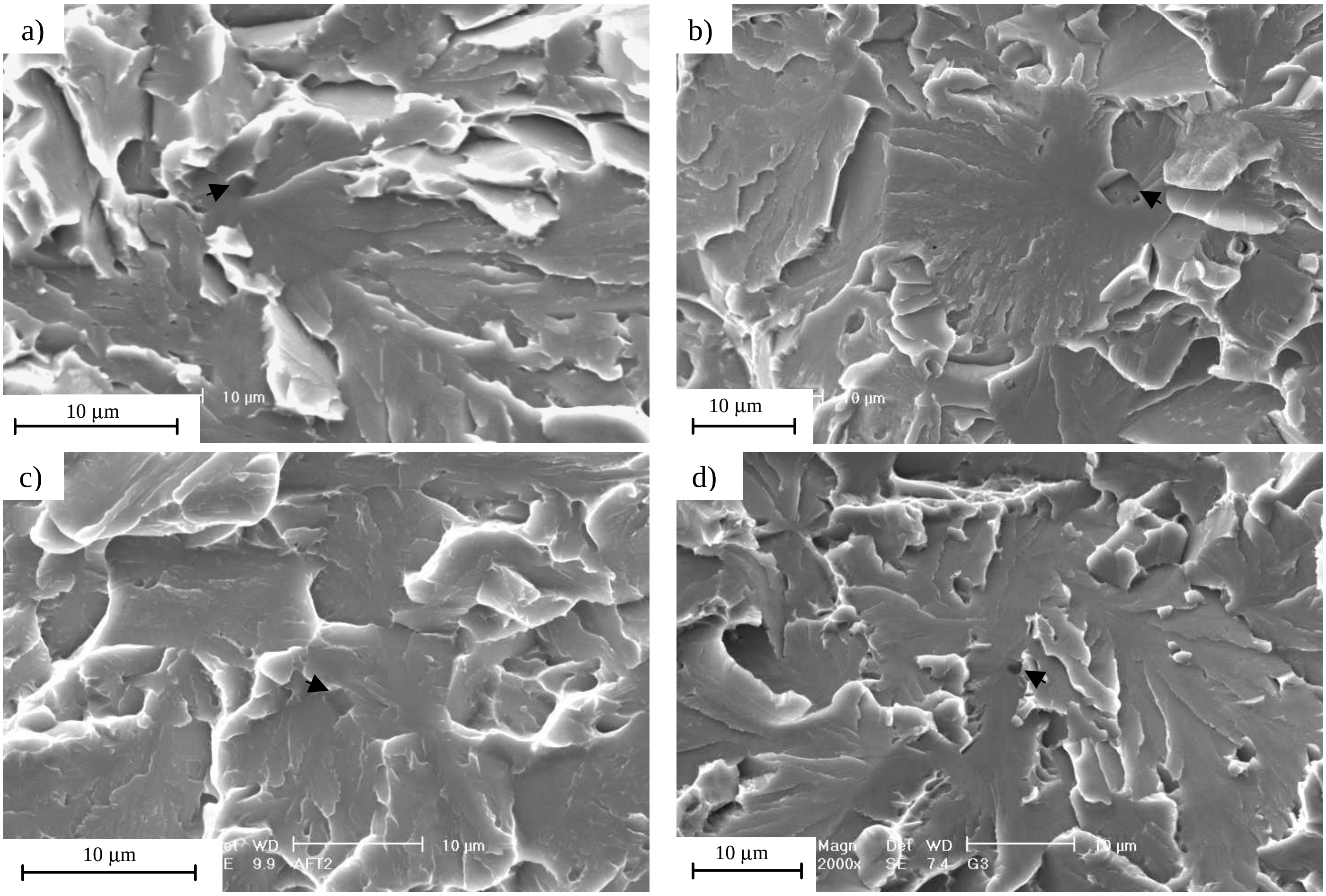


Figure 1: Broken TiN particle in the main origin of fracture in a four point-bending specimen in a) bainite, b) ferrite+pearlite, c) martensite and d) bainite.

TABLE 1

INCLUSION CRACKING INITIATED FRACTURE REFERENCES

Steel	Chemical comp.	Reference
Weld metal	Ca, Mn, Si, Ti, S, Al, K	Tweed and Knott [4]
2 ¼ Cr-1Mo weld metal (as deposited)	Ti, Si	Bowen, Ellis, Strangwood and Knott [5]
Weld metal	Mn,Ti, Si, S	Mc Robie and Knott [6]
Eutectoid pearlitic steel	Al, Ca, Si, Mn, Fe, (Ti)	Alexander and Bernstein [7]
Low carbon steel	Al_2O_3-MnO-SiO_2 Al_2O_3-MnO-SiO_2-CaO	Rodríguez-Ibabe [21]
A508 Class 3 steel	$M_{23}C_6$, TiC, MnS	Gibson, Capel and Druce [22]
A 533B steel	Mg/Ca/Ti (9µm) TiC (0.5-1 µm)	Franklin [23]

In a bainitic V microalloyed C-Mn steel [24] (similar in composition to that in Figure 1 a)), a small carbide has been found at the main initiation site. In this case in contrast to the Ti containing steel a second phase particle has caused the brittle fracture initiation.

There is a subtle difference between the latter carbide centred fracture initiation and the fracture in TiN containing steels. Fracture took place at a value of X/X_{max} (distance from the notch to the origin vs. distance to the notch of the peak tension) lower than in the case of TiN containing steels, in the zone of higher strain, which might imply a higher strain level for carbide cracking. It seems that in the absence of TiN the next most active nucleus of fracture can be a carbide.

Apart from particle cracking initiated fracture, hard phase-cracking initiated fracture also has been reported [25]. Figure 3 shows a small pearlite-colony initiated brittle fracture (in a Charpy testpiece) corresponding to a structural steel.

a) b)

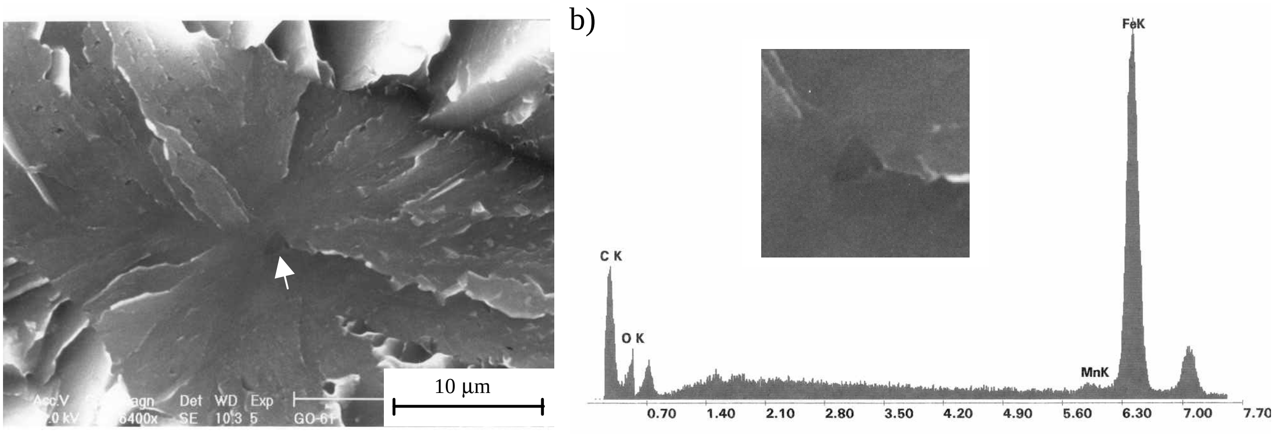


Figure 2: a) Fractograph of a broken 4PB specimen, showing a carbide in the fracture initiation. b) EDS analysis of the fracture triggering feature.

In the left hand of Figure 3 a fractograph of the brittle fracture initiation site is shown; cleavage fracture must have occurred in the junction between the two big facets (circle), although, no remarkable feature could be distinguished. Subsequent etching of the fracture surface has revealed a tiny pearlite colony where initiation was localised. It also should be noted that the first nucleus has formed at the neck of the pearlite colony where it has the stringer shape.

In the above paragraphs (see summary in Table 2) we have only focused in the nucleus of fracture (crack inserting feature); i.e. in the microstructural feature that triggers or forms a crack that will propagate in the way of a Griffith crack. This event (crack insertion) is a necessary condition, but doubts remain in the sense if it is the only and critical microstructural feature that controls brittle behaviour. The surrounding microstructure or the so-called matrix, has also been given importance in the way that its grain size or strength could exert some influence in the toughness properties. Its relevance is not limited to the brittle/ductile region where grain boundary could be the controlling barrier, but also in the lower temperature brittle regime.

Two evidences can be stated to account for the matrix properties. First, it is observed that the only and main nucleation origin of fracture exhibits not only a broken hard phase or particle in its centre but also the surrounding initial facet has a size greater than the average. Besides its orientation is close to the normal to the macroscopic fracture plane (the maximum tensile stress plane) [11,12]. This observation claims for a fracture mechanism where the weakest link, and later general initiation site is a zone composed of both a brittle zone (particle, or hard phase) and a big surrounding facet or effective grain.

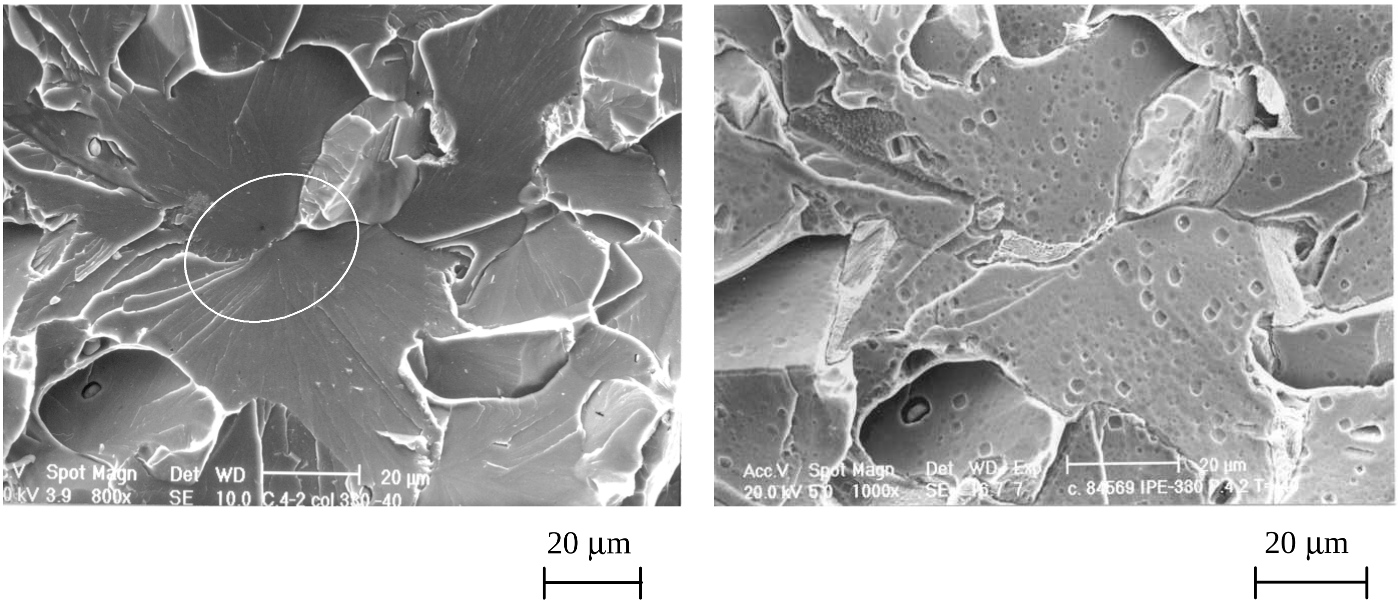


Figure 3: Small pearlite-colony initiated brittle fracture in a structural steel.

The second and more striking experimental result is the case of the brittle fracture behaviour of acicular ferrite in the low temperature regime in a TiN containing Ti-V steel. [26]. Acicular ferrite consists of a microstructure formed by a displacive transformation [27] in the same way as bainite, but composed of intragranularly nucleated ferrite whereas in bainite, ferrite is grain boundary nucleated. [28]. Acicular ferrite has the appearance of random laths of ferrite. In this case, surprisingly, TiN particles do not intervene in the brittle fracture initiation process and some other unknown mechanism acts [26]. Fracture appearance is different in the sense of the localisation of the cleavage initiation, (fairly close to the notch root) and the morphology of the spreading lines from the origin.

In consequence the presence of harmful brittle TiN particles may not be absolutely determinant in the fracture behaviour and mechanism, and the matrix could have the last word.

TABLE 2

FRACTURE INITIATION MECHANISMS AND RELATED MICROSTRUCTURAL FEATURES

BRITTLE ZONE CRACKING	PARTICLE	Inclusions (very harmful) Carbide (less harmful)
	HARD PHASE	Pearlite colony-island MA
PARTICLE OR BRITTLE ZONE DEBONDING	PARTICLE	MnS
	HARD PHASE	MA
VOID DRIVEN	NOTCH ROOT	Microvoids (tiny carbides)
	BETWEEN INCLUSION CENTERED VOIDS	MnS inclusion + MAC

PARTICLE OR BRITTLE ZONE DEBONDING INITIATED CLEAVAGE

Another kind of cleavage initiation mechanism is also related to particles or hard phases. Unlike the mechanism reported in the previous section its failure does not trigger the fracture process directly, but the subsequent load transfer, as it will be shown below.

Davis and King have found direct fractographic evidence of fracture initiation in areas between two closely spaced blocky MA particles in intercritically reheated coarse grained HAZ of high-strength low-alloy (HSLA) steels [29]. The proposed mechanism consists on the debonding of two particles (from the surrounding material). The region between the debonded particles is constrained and subjected to high local stress that can cause a microcrack to form. It should be mentioned that this kind of fracture initiation has been reported especially in welding and dual-phase steels where hard and soft phases are coupled.

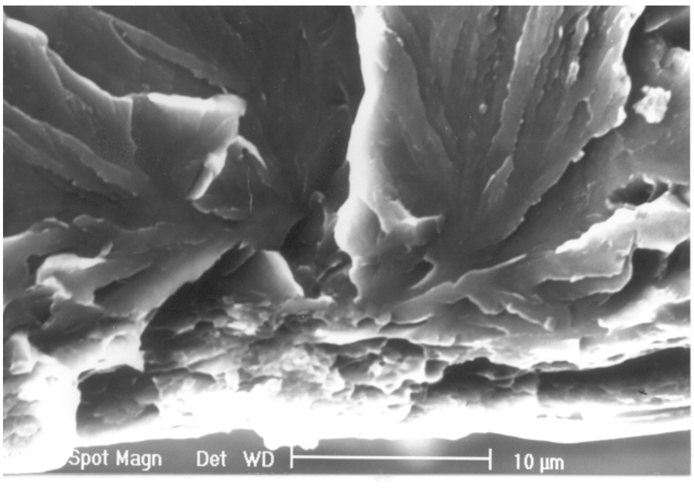
Several reasons have been proposed for debonding: a) low interfacial energy between the particle and the matrix, b) unrelieved transformation stresses (in MA).

The same occurs in the case of MnS inclusions [30, 31], (see Table 2 for different debonding initiated fracture). As Baker et al. [30] have argued these inclusions have a low interfacial energy and consequently debond when the material undergoes some plastic deformation. This last feature, (plastic deformation) has been proven to be a necessary precursor for debonding. Davis and King in a further paper [32] have proved (in blunt notch specimens) that the attainment of a critical level of strain was required, as it follows from the close position of the initiation point in relation to the notch root at a distance smaller than the peak stress.

Zhou and Knott [33] have also observed inclusion-debonding (MnS, (CN)Nb and silicate inclusions) related fracture initiation in a lath martensite microstructure. These authors proposed that a possible model for the fracture process is that the autotempered carbides around them crack to provide cleavage nuclei, the critical stage of fracture being the propagation of these cleavage nuclei into the matrix.

VOID DRIVEN CLEAVAGE INITIATION

In the absence of potent crack nuclei sources as brittle particles (TiN, aluminates, silicates…) cleavage fracture initiation in blunt notched specimens, is postponed to higher values of applied load and thus greater size of the plastic zone [17,24]. In most cases the “general initiation site” is systematically either close to the notch root, or even at it. In a previous work [17], the brittle fracture behaviour of a bainitic steel was studied; in this case neither inclusions nor carbides were found at the origin of fracture. None the less a group of small microvoids in thumbnail shape seems to be the origin of cleavage fracture as shown in Figure 4. It consists on brittle cleavage fracture but in its origin ductile micromechanisms have emerged and it is this bundle of microvoids which causes the initial flaw that propagates in a brittle way.



10 μm

Figure 4: Fracture initiation at the notch root. (preceded by microvoids formation)

It has been suggested [17] that as opposed to the first section mechanism (brittle phase cracking), fracture in this case is strain controlled rather than stress controlled. The stress-strain history of the general initiation sites in a Ti containing steel and in a Ti free steel of similar bainitic microstructure and chemical composition is shown in Figure 5. The dashed line represents the point where fracture has occurred. It is important to note that (TiN) particle initiated fracture in the Ti containing steel occurs far from the notch (125 µm) where s_{11} is highest as opposed to the case of the Ti free steel, in which case fracture initiates at the notch root. Particle initiated fracture occurs at a moment where s_{11} is still growing where as microvoid caused fracture occurs in a region of stress (s_{11}) reaching saturation. Regarding e_{11}, the level of (necessary) strain is much higher for the microvoid driven cleavage initiation, both because the notch root undergoes always the maximum strain and the fracture event occurs at a higher applied load (s_{nom} / s_o). This argument supports a strain-controlled fracture.

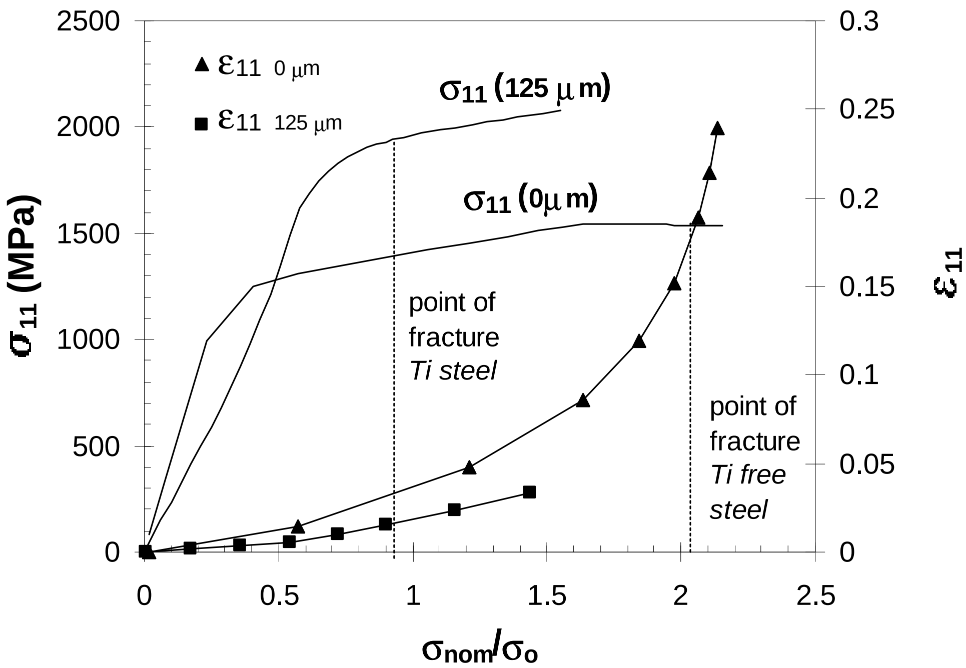


Figure 5: Evolution of s_{11} and e_{11} in the fracture initiation site in a TiN containing steel (brittle zone cracking initiated cleavage) and in similar Ti free steel (microvoid driven cleavage initiation).

Knott [34-35] has also reported inclusion centred ductile voids causing cleavage fracture by the fracture of MAC phase in between these voids in precracked testpieces. In this case voids are bigger than the microvoids shown in Figure 4. This last fracture is similar to that formed in between debonded particles cited in the previous section. Table 2 collates the microstructural features related to this fracture initiation type.

This fracture initiation type should not be confused with the cleavage fracture ahead of a ductile front, in the fibrous to cleavage fracture transition. When cleavage takes place ahead of a ductile front, cleavage can initiate at a position remote from the front, in the same way by any of these three initiation types.

CONCLUSIONS

To summarise it is evident that cleavage fracture initiation can follow different micromechanisms, each one related to a critical parameter(s) (stress, strain, combinations of both). The resulting mechanism is an outcome from the interaction between inclusions, second-phases and the main microstructure in the matrix (see Table2).

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