INFLUENCE OF MICROSTRUCTURE ON THE FRACTURE INDUCED BY A HARD CUTTING INDENTER

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SOMMARIO

Il processo di indentazione nei materiali fragili e quasi-fragili è stato analizzato in passato da un punto di vista sia numerico che sperimentale. Occorre notare invece come, per gli stessi materiali, siano limitati i lavori in letteratura che abbiano affrontato lo studio del meccanismo di intaglio. Nel presente lavoro, vengono proposte alcune relazioni generali valide per il processo di indentazione ed intaglio nei materiali fragili e quasi-fragili, ottenute considerando diverse ipotesi a riguardo del meccanismo di collasso alla scala microscopica. La propagazione della frattura, nel caso di mezzo elastico-fragile omogeneo, è stati studiata mediante il *Metodo degli Elementi Finiti*, nel contesto della *Meccanica della Frattura Elastica Lineare* (LEFM). Viceversa, l'eterogeneità microstrutturale è stata presa in conto nelle simulazioni numeriche eseguite con il *Lattice Model*. Nonostante la realtà sia spesso molto più complessa dei modelli teorici presentati, lo studio fornisce interessanti suggerimenti al fine di ottimizzare la prestazione degli utensili da taglio.

ABSTRACT

The process of indentation of brittle and quasi-brittle materials has been investigated both from the experimental and the theoretical point of view. Quite surprisingly, only a few studies have tried to explain the mechanics of cutting due to an indenter which penetrates inside the material. In this paper, an attempt is made to find some general relations for the cutting process in brittle and quasi-brittle materials, under different hypotheses for the microscopic failure behaviour. Fracture patterns in homogeneous brittle solids are obtained by the *Finite Element Method* in the framework of *Linear Elastic Fracture Mechanics* (LEFM). On the other hand, microstructural heterogeneities are taken into account by the *Lattice Model* simulation. Although the reality is often much more complex than its theoretical model, the study provides interesting hints for improving performance of cutting tools.

1. INTRODUCTION

In the framework of Plasticity, the *Slip-Lines Theory* was developed to explain the collapse mechanisms of ductile materials under various kinds of contact loading [1]. The process of indentation is completely different in the case of brittle materials [2], and depends also on the shape of the indenter. When brittle materials are loaded by an
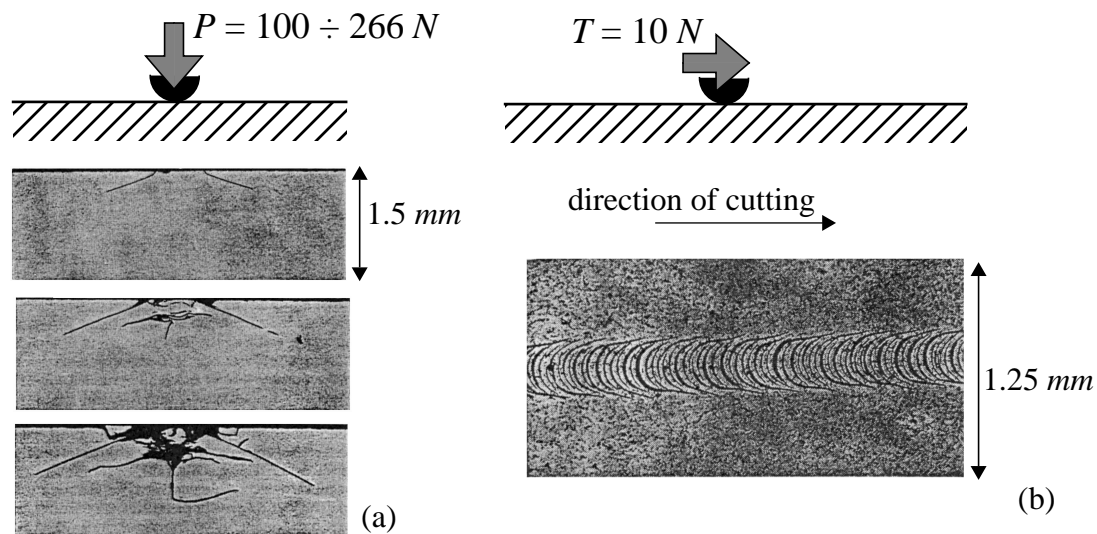
*igure 1: Experimental crack patterns in soda-lime glass under a blunt rigid indenter [3].
ransition from Hertzian cones to median vent cracks as the normal load is increased (a);
chevron-like crack patterns produced by a sliding tungsten carbide sphere (b).*

indenter, three different zones can be distinguished inside the material. Immediately below the wedge, an *hydrostatic core* develops, which is due to the high triaxial compressive stresses induced beneath the indenter. This zone may collapse only by *crushing* and *fragmentation* mechanisms, resembling the effects of strong impacts or explosions. Outside the compressed core, a surrounding zone of large strains develops due to the pushing action of the core. In this area, *tensile cracks* may be initiated starting from pre-existing flaws in the material. Outside this large area (whose size depends on the contact area, on the friction between wedge and base material and on the normal load F_n), the material behaves elastically, and the stress fields predicted by the linear theories can be considered valid.

Fracture patterns in brittle materials, under *blunt indenters*, usually start as ring surface cracks immediately outside the contact area. By increasing the normal load, these surface cracks evolve into the so-called *Hertzian cone cracks*, experimentally revealed by a multitude of tests on glass and other brittle materials (Figure 1a).

In the presence of *sharp indenters* (e.g. cones or pyramids), the high hydrostatic stresses beneath the tip provide different fracture patterns [3]. In any case, the splitting action of the confined core results in the propagation of an embedded *penny-shaped crack* below the indenter, whose extension is controlled by the size of the hydrostatic core. By increasing the load, the penny cracks evolve into the *half-penny* configuration, where the crack reaches the surface (Figure 1a). This was defined as the *median-vent* crack propagation.

On the other hand, fracture under tangential loading starts from behind the tool with respect to the cutting direction, where the highest tensile stresses are located (Figure 1b). Moreover, the fracture pattern depends on the interaction between normal and tangential loads and can evolve into the formation of chips.
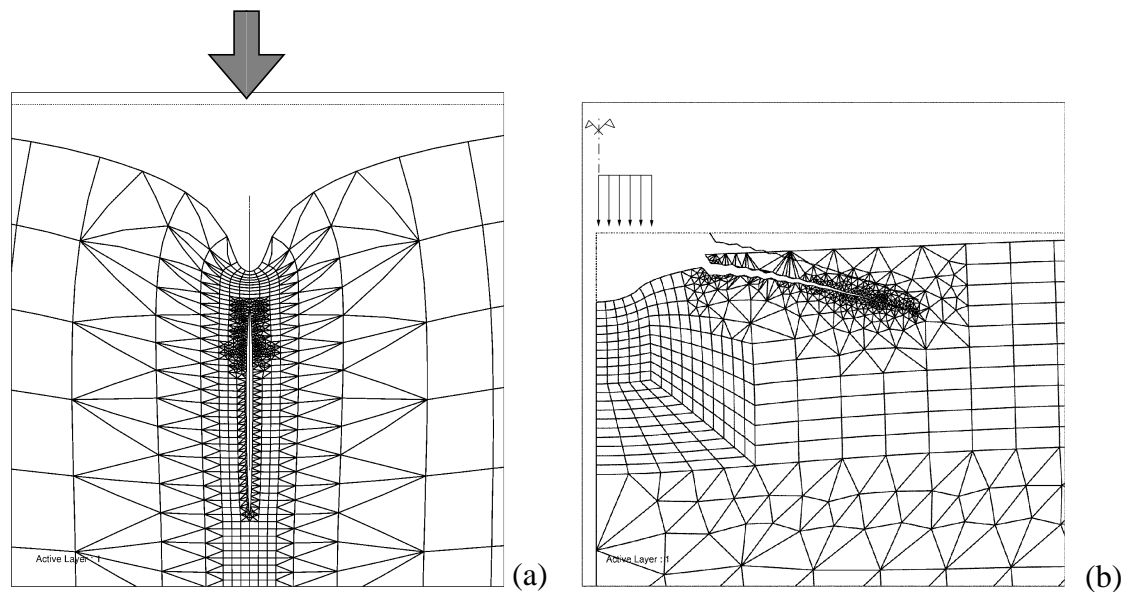
Figure 2: Deformed meshes with FRANC2D: sub-vertical crack propagation under vertical load (a); Hertzian cone crack (b).

Besides the basic patterns described before, other shapes of cracks may develop under indentation, depending on the loading rate, on the density of pre-existing flaws and on the presence of weak planes in the material microstructure.

The effects of material heterogeneity can be very important in the case of the so-called *quasi-brittle materials* (like concrete and many rocks). The role of microstructural disorder is essential because it provides a certain amount of 'ductility', which requires an *ad hoc* modelization of the fracture processes. The energy is consumed in the so-called *fracture process zone*, which is a wide zone around the main crack tips, where diffused damage comes into play. The extent of the process zone depends on the material microstructure and also on the size of the indenter.

In the following, the fracture process due to indentation and cutting is numerically simulated both in the case of brittle homogeneous microstructure and of disordered quasi-brittle microstructure. The *Finite Element Method* (FEM) can be effective for predicting fracture patterns in the homogeneous brittle case, whereas *Lattice Model* (LM) permits to take into account the presence of arbitrary levels of microstructural disorder.

2. INDENTATION AND CUTTING FRACTURE IN HOMOGENEOUS BRITTLE MATERIALS

The FRANC2D software [4], developed at Cornell University, has been used to simulate fracture in the homogeneous case.

Figure 2a shows the median vent crack propagation under a vertical load. Particular care must be taken in the choice of the initial defect, which must be placed under the load at a certain depth, in such a way that at least one fracture apex lays outside the hydrostatic
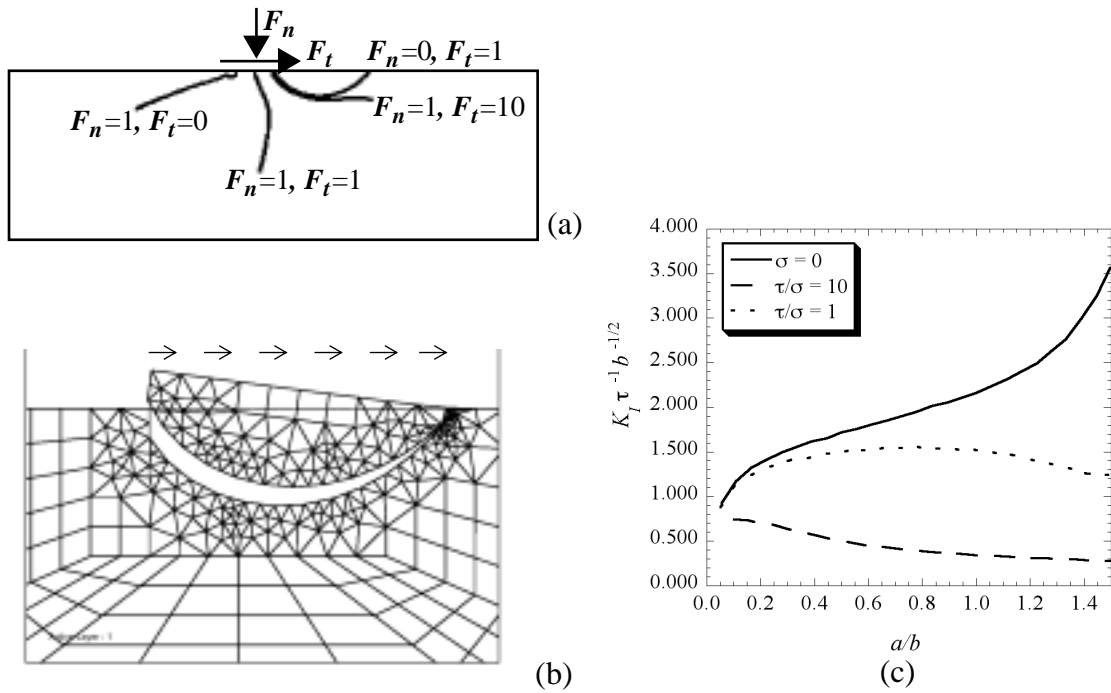
Figure 3: Cutting fracture patterns for different normal vs. tangential load ratios (a); deformed FRANC2D mesh relative to chip formation (b); normalised stress intensity

compressive core, with a positive stress intensity factor. The crack propagates in sub-vertical way, and no bifurcations can be detected. After the initial unstable propagation, fracture becomes stable, as soon as the stress field around the apex diminishes.

The classical *Hertzian cone crack* pattern is shown in Figure 2b. The problem has been simulated both in the plain strain and axis-symmetric case, taking advantage of the symmetry. A detailed study of the initial defect position has been carried out, emphasizing that fracture usually initiates from outside the contact area. While 2D simulations (plane-strain) predict unstable propagation, the 3D (axis-symmetric) simulations provide the well-known experimental stable propagation, also recoverable from a theoretical analysis [5].

In Figure 3a various cutting crack patterns are shown for different ratios of the normal vs. tangential load. As was also found by other Authors [6], when the tangential load prevails, the crack starts from behind the contact area with respect to the load direction, then turns upward (mixed-mode propagation) and can provide the formation and removal of a chip (Figure 3b).

In Figure 3c a nondimensional diagram is shown where the normalised stress intensity factor is plotted as a function of the normalised crack length (i.e., normalised with respect to the contact area). It is thus possible to observe the transition from the stable crack propagation (i.e. increasing stress intensity factor) in the case of indentation ($F_n \ll F_t$) to the unstable crack propagation in the case of cutting ($F_n \gg F_t$), confirmed experimentally by the sudden chip formation detected in brittle materials.

3. NUMERICAL SIMULATION OF CUTTING IN HETEROGENEOUS MATERIALS

In order to investigate the role of heterogeneity in quasi-brittle materials, numerical simulations of indentation by means of the *lattice model* [7] have been carried out. The lattice model is a discrete model of a solid material where the continuum is replaced by an equivalent beam or truss structure, the *lattice,* as shown in Figure 4. The main purpose of the lattice model is to achieve understanding of the fracture processes which occur at small scales and of the influence of the micro-structural disorder on the global behaviour of the material. A great advantage with respect to the classical codes based on fracture mechanics is that there is no need for an initial crack to be defined. Thereby, we do not need a positive stress-intensity factor K_I to ensure crack propagation.

Various microstructures have been investigated, by changing the aggregate size distribution, and the ratios between the mechanical properties of the material's phases. In this way, the role of disorder is evidenced.

The indentation process can be studied by imposing a vertical displacement to the loaded nodes. The damage level is denoted by the relative number (Δ) of broken bonds (N_{broken}). In Figure 4b the damage pattern is shown, and the Hertzian cone cracks can be easily recognised as well as the sub-vertical median crack under the indenter.
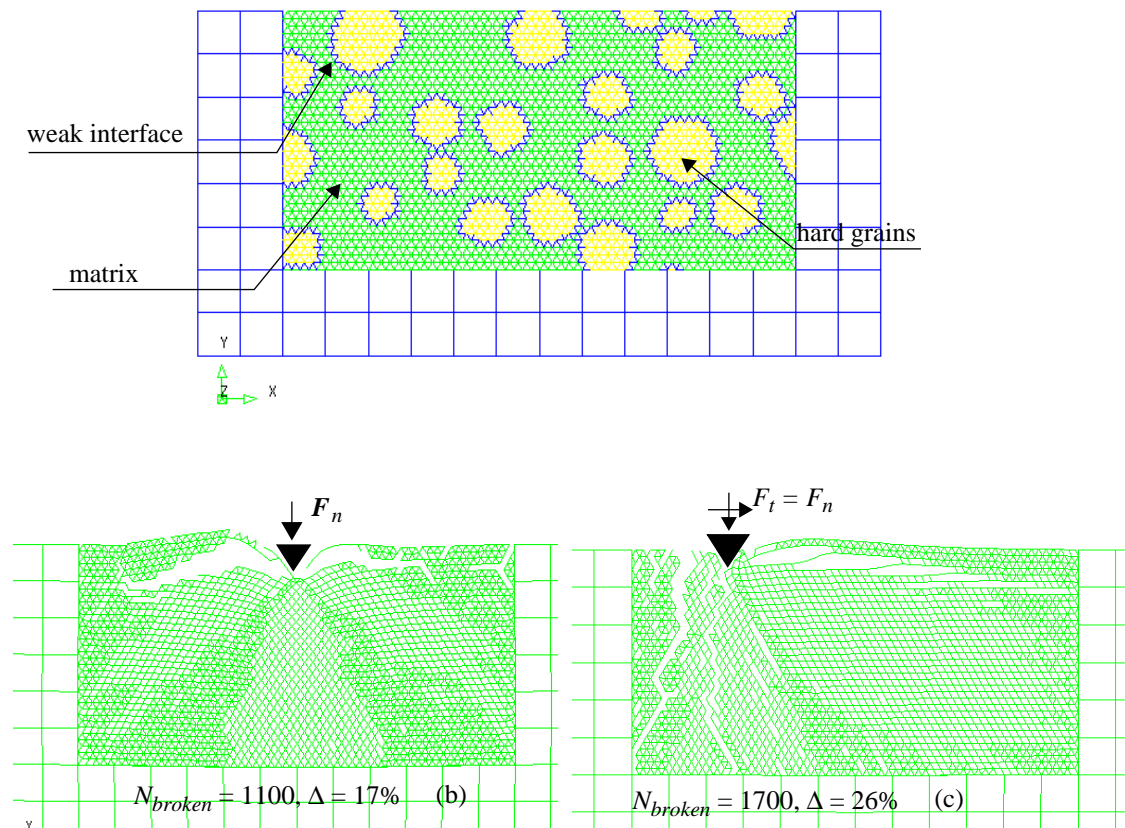

Figure 4: Three-phases coarse material adopted in the lattice simulations (a); Evolution of damage in the lattice mesh (coarse material) with increasing the indentation load F_n (b); lattice simulation of the ploughing action in a heterogeneous material (c).

The action of a ploughing indenter can be simulated by means of the lattice model, by prescribing vertical and horizontal rigid displacements to the loaded nodes. In Figure 4c the case of the coarsest microstructure is reported, where $F_t \approx F_n$. Since the cutting force is equal to the normal force, tensile stresses prevail behind the indenter, while a strong compressive field arises ahead of it. As suggested by the elastic stress field, cracks initially develop *behind* the indenter, in the form of vertical splitting fractures. Only when the material becomes significantly weakened in this zone, damage begins to spread inside the compressive field. However, due to the tension-governed fracture law, the lattice model cannot predict fragmentation within the compressed zone, and only surface delamination is observed in the last stages. Notice, however, the large amount of broken beams (due to the local splitting mechanism in the lattice network) along the maximum compression diagonal direction.

Contrarily to the FEM, within the lattice simulation no stress intensity factor is provided. Thus a consistent comparison between different microstructures must be carried out in terms of load-penetration responses, where the greater compliance of coarser microstructure reveals a greater energy dissipation (i.e. ductility) of quasi-brittle microstructures with respect to brittle homogeneous materials.

4. CONCLUSIONS

In the present work the cutting process in brittle and quasi-brittle materials has been simulated. With the help of the lattice model, the roles of material heterogeneity and diffused damage have been investigated. It has been shown that various mechanisms interact ahead of the indenter during the cutting process (i.e. plastic crushing and brittle chipping). Since the process is discontinuous, some characteristic lengths of damage come into play, related to the indenter's penetration, which provide size-effects on the cutting strength of the material. Theoretical arguments show that the so-called cutting strength S (e.g., energy spent per removed volume of base material) undergoes size-effects. In particular, its nominal volume depends on the depth of penetration according to Figure 5.
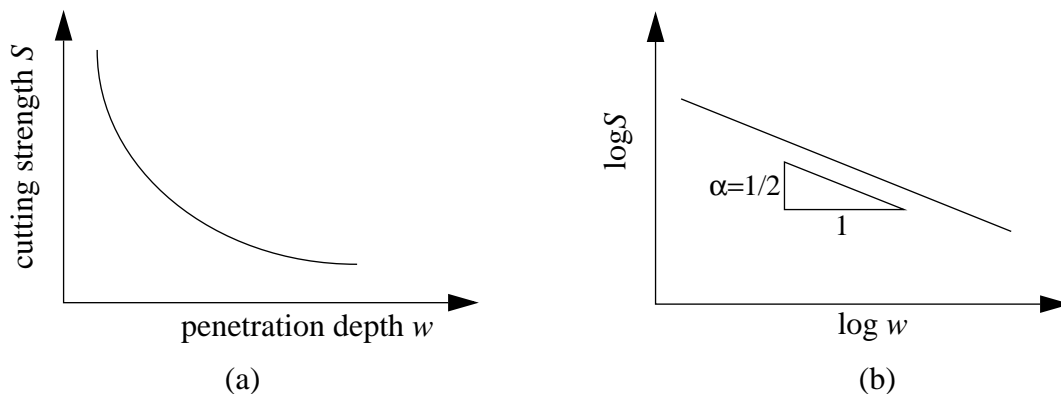

(a)   (b)

Figure 5: Size-effects on the cutting strength S according to LEFM (a);
bi-logarithmic diagram (b).

The slope of the curve depends on the interplay of the crushing and brittle chipping mechanisms ahead of the indenter (e.g. if LEFM holds, i.e. very brittle chipping, $\alpha=1/2$). Thereby, it can be concluded that the cutting performances could be significantly improved by reducing the crushing component and enhancing the chipping ability of the indenters, e.g. by increasing their sizes or the depth of penetration.

ACKNOWLEDGEMENTS

REFERENCES

1. Hill, R. *Mathematical theory of plasticity*, Clarendon Press, Oxford. 1950.
2. Lawn, B.R. and Wilshaw, R. *"Indentation fracture: principles and applications"*, J. Mat. Sci. 1975. **10**, 1049-1081.
3. Lawn, B.R. and Swain, M.V. *"Microfracture beneath point indentations in brittle solids"*, J. Mat. Sci. 1975. **10**, 113-122.
4. Bittencourt, T., Wawrzynek, P., Sousa, J., Ingraffea, A. *"Quasi-automatic simulation of crack propagation for 2D LEFM problems"*. Eng. Fract. Mech., 1996, **55**, 321-334.
5. Roesler, F.C. *"Indentation hardness of glass as an energy scaling law"*, Proc. Phys. Soc. London, 1955. **58**, 55-60.
6. Bower, A.F. and Fleck, N.A. *"Brittle fracture under a sliding line contact"*, J. Mech. Phys. Solids, 1994. **42**, 1375-1396.
7. Van Mier, J.G.M. *Fracture Processes of Concrete. Assessment of Material Parameters for Fracture Models*, CRC Press, Boca Raton. 1996.