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Theoretical study of the conditions and the mechanism of shear crack acceleration towards the longitudinal wave velocity

E.V Shilko[a,b,]*, S.G. Psakhie[a,c]

[a] *Institute of strength physics and materials science SB RAS, 634021, Tomsk, Russia*
[b] *Tomsk State University, 634050, Tomsk, Russia*
[c] *Tomsk Polytechnic University, 634050, Tomsk, Russia*

Abstract

The question about physically admissible velocity of dynamic crack growth is of significance to safety engineering as well as to earthquake dynamics. Recent researches including numerical simulations, experimental observations and the analysis of strong earthquakes have shown a possibility of propagation of shear cracks in supershear regime, namely at velocities comparable with dilatational wave speed. The present paper is devoted to the theoretical (numerical) study of some fundamental aspects of this problem. It is shown that development of a sub Raleigh shear crack is connected with a vortex traveling ahead of the crack tip at a shear wave velocity. The stress concentration area ahead of the crack tip revealed by different authors (Burridge, Andrews, Geubelle, Rosakis and others) is connected with this vortex. Acceleration of a shear crack towards the longitudinal wave velocity is concerned with formation of a daughter crack by the mechanism of shearing (the daughter crack is formed in the center of vortex). Analysis of sub Raleigh to intersonic transition has shown that development of shear cracks is self-similar and depends on dimensionless parameters.

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Keywords: brittle material; mode II fracture; vortex; stress peak; supershear rupture propagation; numerical simulation; MCA method

* Corresponding author. Tel.: +7-382-228-6971; fax: +7-382-249-2576.
E-mail address: shilko@ispms.tsc.ru

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1. Introduction

The question about physically admissible velocity of unstable (dynamic) crack growth is of significance to safety engineering as well as to earthquake dynamics. In the framework of conventional fracture mechanics analytical predictions a brittle crack cannot propagate faster than the Rayleigh wave speed. Nevertheless recent researches including numerical simulations, experimental observations and the analysis of strong earthquakes have shown a possibility of faster propagation of mode II cracks at velocities comparable with longitudinal wave (P-wave) speed.

A considerable number of reports regarding intersonic and supersonic shear crack propagation in full-scale systems (tectonic faults), laboratory experiments and computer-aided simulations (brittle or quasi-brittle materials) have been published in last four decades (Burridge (1973), Andrews (1976), Rosakis (2002), Abraham and Gao (2000), Geubelle and Kubair (2004), Hao et al. (2004), Broberg (2006) and others). Note that study of intersonic crack propagation is actual not only from fundamental point of view but has implication for some practical fields of application, for example, for building safety and seismic hazard (Rosakis (2002)). One of important conclusions concerning the seismic features of such earthquakes is that in the stable super-shear regime ground velocities and ground shaking durations can be much larger than in the classical sub-Rayleigh regime (Mello et al. (2010)). So, understanding of the mechanisms and conditions of intersonic crack nucleation and development is really important both mechanical and tribological problem.

An interest to this problem started form pioneering works of Burridge (1973) and Andrews (1976). Andrews first numerically showed main features of mode II crack propagation with use of finite element model. In particular he has shown that the rupture is initially propagating at a significant fraction of the Raleigh velocity and the stress peak appears in the crack tip at early stage of shear crack development. This stress peak propagates ahead of the rupture front at the shear wave velocity (a little bit faster than Raleigh velocity) and gradually becomes higher. It potentially can reach yield stress and induce fracture ahead of the shear crack tip (this secondary crack was later called a daughter crack by Abraham and Gao (2000)). This daughter crack propagates faster than the shear wave velocity. During the following decades a lot of experimental and theoretical results concerning supershear crack propagation regime were drawn. For example, Geubelle and Kubair (2004) showed that intersonic regime of propagation is achievable only for relatively short cracks, whose “shear strength” is higher than some fraction of the shear strength of intact material or interface. Different authors experimentally or numerically observed mode II crack propagation in intersonic regime in the whole range of length scales from atomic (Abraham and Gao_(2000)) to macroscopic scale. It is also important to note that supershear rupture is observed in elastic-brittle or quasi-brittle materials, while unstable crack growth in Sub Raleigh regime is inherent to materials with various rheologies.

Despite huge success in studying intersonic crack propagation and a number of theoretical and experimental results, some issues related to dynamics and conditions of mode II crack acceleration to intersonic velocity are still not fully understood. The present paper is addressed to the following aspect: how does the shear crack propagation and transition to intersonic regime look from physical point of view and why the stress peak ahead of the main crack is formed? The work is devoted to the theoretical study of aforesaid fundamental aspect of the problem. The study was carried out by means of movable cellular automaton (MCA) based numerical simulation. Note that the MCA method is a representative of particle-based numerical techniques, which treat the solid as an ensemble of bonded (or linked) interacting particles (Psakhie et al. (2001)). The MCA method combines mathematical formalisms of two well-know numerical methods: discrete element method and cellular automaton method. To study the problem the model of many-body interaction between movable cellular automata, which provide macroscopically isotropic linear-elastic response of particle ensemble, was used (Psakhie et al. (2013)).

2. Problem statement

The numerical study was carried out with use of the following two-dimensional model sample (Fig. 1a). It consists of two bonded parts. Plates have the same properties and are considered as isotropic, linear elastic and high-strength. The following mechanical properties of material of the plates were used in the study: Young modulus E=200 GPa, Poisson’s ratio ν=0.3, density ρ=5700 kg/m^3. Ideal bonding of the plates was assumed. This assumption means that thickness of the interface zone is much smaller than automaton (particle) size. In the framework of such assumption the only interface property taken into account is interface strength. In the MCA method the fracture is simulated by changing the state of the pair of interacting automata (particles) from "linked" state to "unlinked" state (in unlinked state only contact interaction between automata is possible). Condition of "linked to unlinked" switching is formulated in criterial form (Psakhie et al. (2013)). In the present study equivalent stress in interacting pair of automata was used as fracture criterion (detailed explanation of calculation of equivalent stress in the pair and of modeling fracture is presented in the paper by Psakhie et al. (2013)). The value of interface strength (250 MPa) was assumed to be much smaller than strength of plates themselves (2000 MPa).

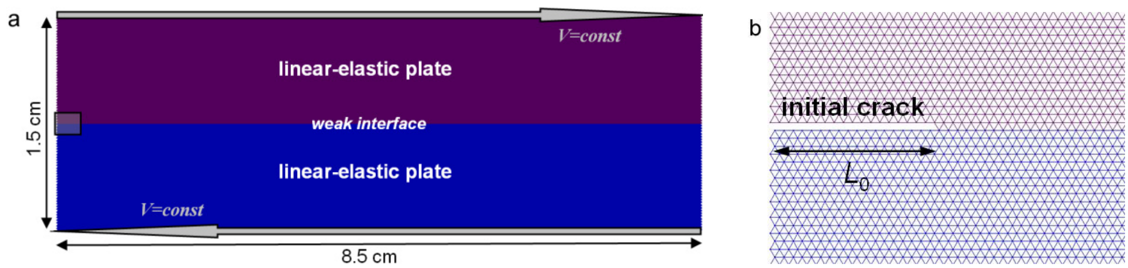

Fig. 1. (a) structure and scheme of loading of the model sample; (b) enlarged picture of small black rectangle in the left part of (a) containing initial interface crack.

Initial crack (precrack) was assigned by means of breaking the bonds at the interface (Fig. 1b). This implies the case of extremely narrow cracks (there is no gap between crack surfaces before loading). Shear loading is simulated by displacing of the upper and lower surfaces of the sample in horizontal direction with very low constant velocity (Fig. 1a). This imitates the condition of simple shear of the system. Periodic boundary conditions were used along the horizontal direction to avoid the influence of contortions at the side boundaries. Plane strain state approximation was used in described 2D model.

3. Simulation results and discussion

At the first stage of loading the initial crack is deformed elastically without growth. Fig. 2a shows an example of stationary field of particle velocities near initial crack during this stage. Velocity and displacement fields near the crack are contorted, while far from the crack they are homogeneous and correspond to direction of loading. Near the crack tip velocity distribution is vortex-like (it can be called a "protovortex"). Due to contortion of velocity field the crack being under shear loading becomes open. This can be seen in Fig. 2b showing vertical displacements of upper and lower surfaces of the interface near the crack. The area of valuable contortion ahead of the crack tip is nearly twice crack length. Note that crack normal component of stationary velocities near the crack tip and crack opening value increase with initial crack length and "protovortex" becomes more pronounced. Such kind of distribution determines many features of dynamics of subsequent crack development.

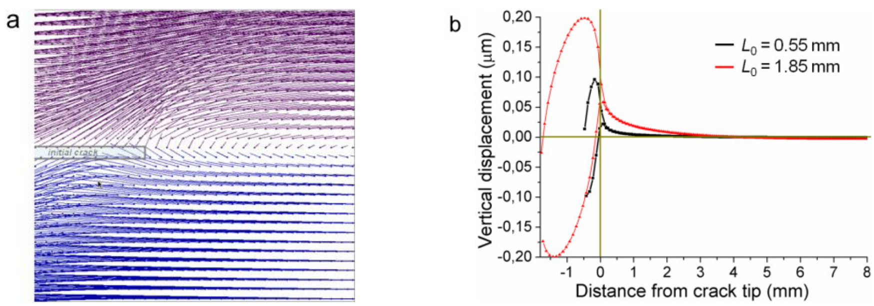

Fig. 2. (a) typical field of velocities of movable cellular automata near the right tip of the initial crack (in the right half of small black rectangle in Fig. 1a); (b) vertical displacements of the upper and lower interface surfaces near the right tips of the cracks with different initial lengths L_0.

At certain value of load (applied shear stress) the crack starts to develop in unstable regime. Described features of contortion of displacement field near the initial crack lead to formation of the vortex ahead of the crack tip already at the beginning of unstable crack growth (Fig. 3). The vortex is formed by the dilational mechanism proposed by O. Reynolds. There is a large gradient of velocities near the crack tip. This gradient gives birth to transversal displacement of material layers near the crack tip because material always tries to avoid change of its volume, and axial deformation always induces lateral displacements. Because of opposite directions of velocity gradients in the upper and lower areas near the crack tip the circular motion (or in other words, the vortex) is formed.

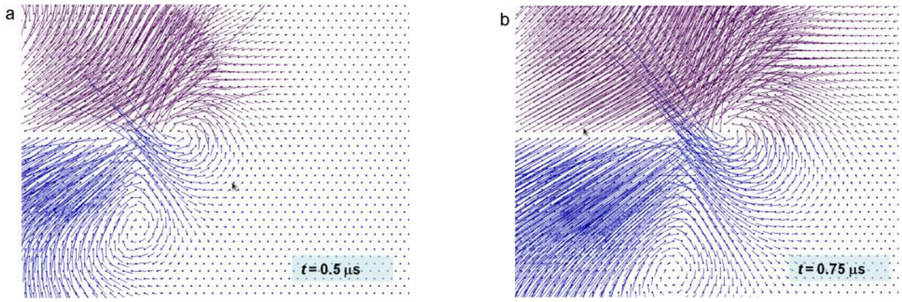

Fig. 3. Fields of velocities of movable cellular automata near the right tip of growing shear crack 0.5 μs (a) and 0.75 μs (b) after growth start.

Formation of such kind of vortexes in solids is typical and observed in the areas of strain rate gradient (Psakhie et al. (1997, 2014)). These vortexes can be considered as dynamic defects providing the condition of strain compatibility near the source of perturbation. The most important issue is that being initiated, such dynamic defects become self-dependent and develop according to their own laws. In considered problem the vortex travels ahead of the crack tip at a shear wave velocity. At the same time the crack develops at a velocity lower than Raleigh wave speed (in sub-Raleigh regime). Therefore during the course of propagation the vortex is gradually separated from the crack tip. The presence of strong vortex-like defect ahead of the crack tip indicates the concentration of shear stresses. This concentration is clearly seen in Fig. 4 showing distributions of equivalent stress near the crack tip at different time moments. The left boundary of localized area of stress concentration is attached to the center of vortex. Therefore during the course of vortex propagation this area moves away from the crack tip.

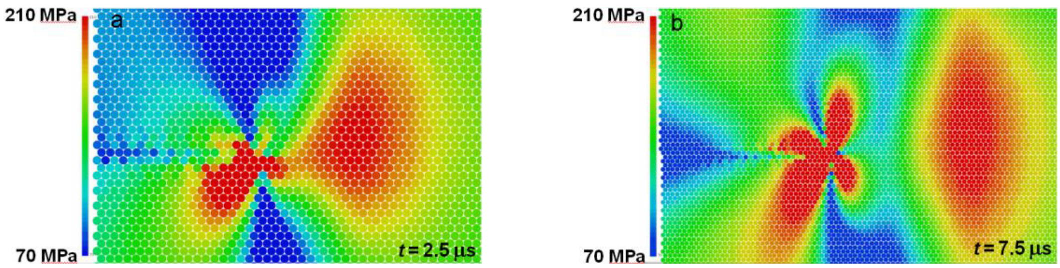

Fig. 4. Distributions of equivalent stress near the right tip of growing shear crack 2.5 μs (a) and 7.5 μs (b) after growth start.

Stress concentration in the localized area moving away from the crack tip can be clearly demonstrated by distribution of stress intensity at the interface ahead the crack tip (stress concentration at the interface is of the main interest within this study because it is the most weak part of the system and the path of crack propagation). As Fig. 5 shows, at the beginning stage of crack development the stress peak is formed at the segment of the interface attached to the crack tip and then moves ahead of the crack at a shear wave velocity. During the course of propagation its amplitude increases and reaches maximum value to the moment of separation of localized area of stress concentration from the crack tip. After that the stress concentrator moves independently and smears (this is accompanied by decrease of the amplitude of stress peak).

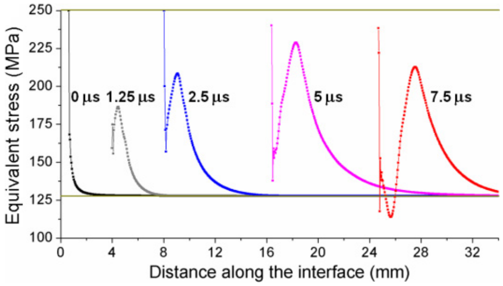

Fig. 5. Example of equivalent stress distributions at the interface ahead of the crack tip at different time moments after crack growth start.

Note that under the considered loading conditions the crack advances in self-feeding manner, namely by the expense of liberated and redistributed elastic energy (this energy was accumulated by the system at the initial stage of loading before crack growth start). Simulation results have shown that maximum achievable amplitude of stress peak at the interface as well as average velocity of crack propagation depend on the density of accumulated elastic energy. From Fig. 6 one can see that if the value of accumulated elastic energy is enough to provide reaching the value of interface strength by stress peak before separation from the crack tip, then the secondary crack appears at the interface at some distance from the crack tip (Abraham and Gao (2000)) called this crack a “daughter crack”). Note that this secondary crack nucleates in the center of vortex. Being initiated, the secondary crack then propagates at a velocity higher than the S-wave velocity and comparable with P-wave velocity.

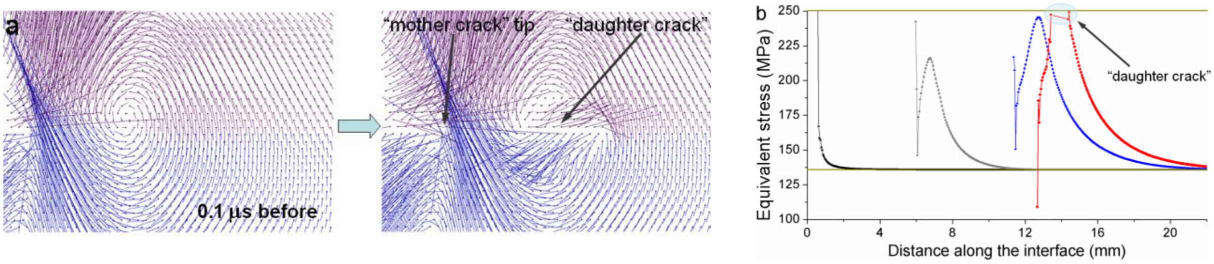

Fig. 6. Formation of the secondary crack (a) at the segment of the interface where stress peak reaches the value of interface strength (b).

It is important to note that the stress-strain state of material around the tip of the crack in sub-Raleigh regime of propagation is complex as it includes both components shear and tension. Therefore the mechanism of fracture in the crack tip is of combined nature with considerable contribution of mode I (tensile fracture). In particular the crack normal component of particle velocities in the crack tip is order of magnitude larger then crack parallel component. Fracture is accompanied by dynamic liberation of accumulated elastic energy in vertical layer of material surrounding the crack tip in the form of kinetic energy. The main part of this energy is concerned with transversal (crack normal) component. Large gradient of kinetic energy in this vertical layer surrounding the crack tip leads to intensive transfer of potential (elastic) energy ahead the crack tip by the mechanism of transverse elastic wave. This mechanism provides formation of above mentioned vortex and stress peak in its central part and explains propagation of this vortex at a shear wave velocity.

At the same time stress state of the place (segment of the interface), where the secondary (“daughter”) crack is nucleated, cardinally differs from the state in the crack tip. In the center of vortex shear stresses are dominating, while other components of stress tensor in this segment of interface are orders of magnitude lower. Therefore formation of a daughter crack takes place by the mechanism of shearing. In this case main part of liberated elastic energy transforms into crack parallel component of kinetic energy. So, the energy transfer ahead from the tip of new crack is realized mainly by longitudinal elastic wave (that is P-wave or compression wave). P-wave propagates much faster than S-wave. Therefore energy transfer ahead of a crack tip is faster and the crack takes a capability to accelerate towards the longitudinal wave velocity. Such a transition looks as a jump-like increase in crack velocity (Abraham and Gao (2000), Rosakis (2002) and so on). After coalescence of mother and daughter cracks the velocity of united crack stabilizes. This united crack propagates in steady-state regime at an intersonic velocity.

Finally it has to be reminded that supershear crack propagation was observed numerically or experimentally at different scales from atomic one (Abraham and Gao (2000)) to the scale of tectonic faults (Mello et al. (2010)). This means that the phenomenon of sub-Raleigh to supershear crack propagation regime transition is self-similar. The assumption of self-similarity of mode II crack propagation was first used by Burridge (1973). In the present study this assumption was verified by special calculations for scaled samples. The model sample shown in Fig. 1 was used as a basic one. It was scaled by multiplying the automaton and sample sizes by factors 0.01, 0.1, 10, 100 and so on. In such a case the initial length of precrack is scaled by the same factor. The most important result of these studies is that scaled samples demonstrate totally the same velocity and stress/strain fields at corresponding time moments from the time of crack start (i.e. at time moments scaled by appropriate factor). These results support the statement of self-similar nature of the shear crack propagation and transition to intersonic regime and indicate the presence of dimensionless parameter governing the condition of crack propagation transition to supershear regime.

4. Conclusions

Presented study shows that unstable development of mode II crack is connected with a vortex travelling ahead of the crack tip at a shear wave velocity. The stress concentration area ahead of the crack tip revealed by different authors is concerned with this vortex. Crack acceleration towards the longitudinal wave velocity is concerned with formation of a daughter crack in the center of vortex by the mechanism of shearing. Results of numerical study support analytically proposed statement of self-similar nature of the shear crack propagation and transition to intersonic regime and indicate the presence of dimensionless parameter governing the condition of crack propagation transition to supershear regime.

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