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G. G. Sih

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A criterion of plasticity flow for polycrystals at mesoscale level

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Abstract

The traditional yield criteria of plasticity such as Mises, Tresca, etc., make use of averaged macro parameters. while mesomechanics consideration is based on the physical notion of plastic deformation mechanisms. They may involve the development of plastic shears on the surfaces and interfaces of internal structure elements involving stress concentration and relaxation. A criterion of plasticity flow is proposed; it is based on the stress-strain state in a cell of computational grid as well as in the neighboring cells. An algorithm describing the plastic shear generation at the interfaces and surface and the progressive propagation of the plastic shears over the crystal is developed. Test calculations of the crystal behavior under tension are made performed and the results are presented.

1. Introduction

A traditional approach for describing the transition of elastic to plastic flow [1] is to use stress criteria expressed in terms of macroscopic quantities. They are mostly phenomenological models. referred to most frequently are the Mises and Tresca criteria. It is assumed that some combination of the stresses would reach a limit corresponding to yield in uniaxial tension. Such an approach is tolerable for solving engineering problems of a macroscopic nature, where material heterogeneity does not play an important role. The approach is not adequate for describing the plastic deformation mechanisms at the mesoscale level. where the stress and strain state is essentially heterogeneous. That is the local state of affairs may differ significantly from that in the bulk.

A physical mesomechanics approach has been advanced in [2,3]. The material under loading is assumed to undergo nonequilibrium multi-stage self-organizing states. The material bonding forces are so large that shear stability loss takes place nonuniformly throughout the specimen. Plastic flow is regarded as successive loss of shear stability at the different scale levels, i.e., micro, meso and macro [3]. At the microscale level, shear stability loss occurs in localized zones of crystalline lattice. This leads to dislocation generation. At the mesoscale level shear stability loss may prevail in local mesovolumes where shear bands may form. They are regarded as the dominant defects at the mesoscale level and appear near stress concentrators [2,3]. Stress relaxation in the local zones follows as a result of plastic flow development.

2. Numerical simulation of mesoscale plastic flow generation and development

A material when loaded is initially elastic until plastic shear appears at the grain boundaries or surface where local effects are present and stress relaxation [2-7] take place. An algorithm will be developed to describe the process.

Other feature occurring at the mesoscale level is discontinuity of micro shears resulting in the restriction of deformation of meso structure elements [2-4]. This should be included in the formulation of a criterion that accounts for transition from an elastic to a plastic state.

To describe plastic flow at the mesolevel, a system of equations in two-dimensions for a barotropic medium shall be solved numerically by the finite-difference method [1]. They includes the equations of motion

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} = \rho \dot{U}_x, \qquad \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = \rho \dot{U}_y \tag{1}$$

and equation of discontinuity

$$\frac{\dot{V}}{V} = \frac{\partial U_{xx}}{\partial x} + \frac{\partial U_{yy}}{\partial y} = \dot{\varepsilon}^T_{xx} + \dot{\varepsilon}^T_{yy} \tag{3}$$

The constitutive equations are given by

$$\dot{\sigma}_{xx} = -\dot{P} + \dot{S}_{xx}, \qquad \dot{\sigma}_{yy} = -\dot{P} + \dot{S}_{yy}, \qquad \dot{\sigma}_{xy} = \dot{S}_{xy} \tag{4}$$

were σ_{ij} and ε^T_{ij} are the components of the total stress and strain tensors, respectively. Note that U_i are the components of the particle velocity vector; ρ is the material density and V is the specific volume. The dot indicates time derivative. Pressure P is defined by a barotropic state equation [8]. The assumption is acceptable for stresses up to 10 GPa. Relations between the deviatoric tensors of stress and strain are given by

$$\dot{S}_{xx} = 2\mu\left(\dot{\varepsilon}^T_{xx} - \frac{1}{3}\frac{\dot{V}}{V} - \frac{1}{2\eta}\left(1 - \frac{\sigma'_0}{\sigma}\right)S_{xx}\right)$$

$$\dot{S}_{yy} = 2\mu\left(\dot{\varepsilon}^T_{yy} - \frac{1}{3}\frac{\dot{V}}{V} - \frac{1}{2\eta}\left(1 - \frac{\sigma'_0}{\sigma}\right)S_{yy}\right) \tag{5}$$

$$\dot{S}_{xy} = 2\mu\left(\dot{\varepsilon}^T_{xy} - \frac{1}{2\eta}\left(1 - \frac{\sigma'_0}{\sigma}\right)S_{xy}\right)$$

It is assumed that the instantaneous response of material to loading is elastic. Stresses relax as plastic flow develops. Note that η is the relaxation function; it depends on the effective stress and plastic strain

Experimental data obtained in [2-7,8] indicate that plastic shear is generated mostly at the free surfaces and interfaces. Dislocations then move from the boundaries, lining up and forming different structure elements such as cellular structures, blocks, etc. Dislocation flow arises from mesoscale deformation; it consists of shear band, Lüders band meso fragment rotation and shear [2-3,9]. Accounting for plastic shear generation and effects of interface surface, an algorithm is developed for elastic-plastic behavior of a computational grid cell. Each computational cell is regarded as cellular automaton that can be in an elastic and/or plastic state. The state of each computational grid cell is determined by the stress-strain state in the cell as well as in the neighboring cells, according to the following algorithm:

- A computational grid cell becomes plastic state when the applied stress reaches a critical value σ_{cr}. This depends on the type of structure element. It may be a grain boundary, grain body or matrix/inclusion boundary.
- Plastic shears are generated by surfaces and interfaces. They may include grain boundaries, matrix/inclusion interface etc. This follows after the onset of yielding of the grid cell.
- A grid cell unrelated to surface or interface becomes plastic and generates plastic shears. This should occur in at least one of the 8 neighboring cells. The plastic strain built-up should exceed a critical value ε^{p}_{cr}. If one of the requirements does not fulfill, a cell is regarded to be elastic.
- If an internal stress reaches the theoretical shear strength, the material in is said to loss shear stability. The grid cell turns into plastic state independent of the neighboring cell states.
- Material response to unloading is elastic.
- Those cells that have turned plastic, deformation should accumulate until elastic unloading takes place. Stress in the cells relaxes up to a threshold value according to some relaxation relation determined from physical or phenomenological consideration. For each time step of loading, a process of redistribution of elastic and plastic portions of the total deformation takes place.
- After elastic unloading, plastic deformation may continue as additional load is applied.

3. Results and discussion

Calculations are made to test material behavior for physical properties close to those for AL6061-T6 alloy. A qualitative description of plastic flow at the mesoscale level will be given. Critical stresses and plastic strains as well as relaxation times could not be validated until more test data are made available.

Zones located on the crystal surface may vary in size while the critical stresses may be lower then those for the basic material, Fig. 1. The may be referred to "zones with reduced strength" (ZRS). At first, the generation of plastic strain was permitted to take place on the specimen surface and the remaining grid cell turn from elastic to a plastic state based on the algorithm.

As yield continues, elastically deformed elements adjacent to the plastic zones become plastic. Elliptically-shaped bands of localized plastic strain are thus formed as in the experiments [2-4,9]. These bands formed on the ZRS at the opposing surfaces start to move perpendicular to tension axis towards the middle of the specimen, Fig 1. The plastic strain in the other ZRS stops to grow at the early stage of loading. This is due to stress relaxation when plastic strain is developed at the leading bands of localized plastic deformation

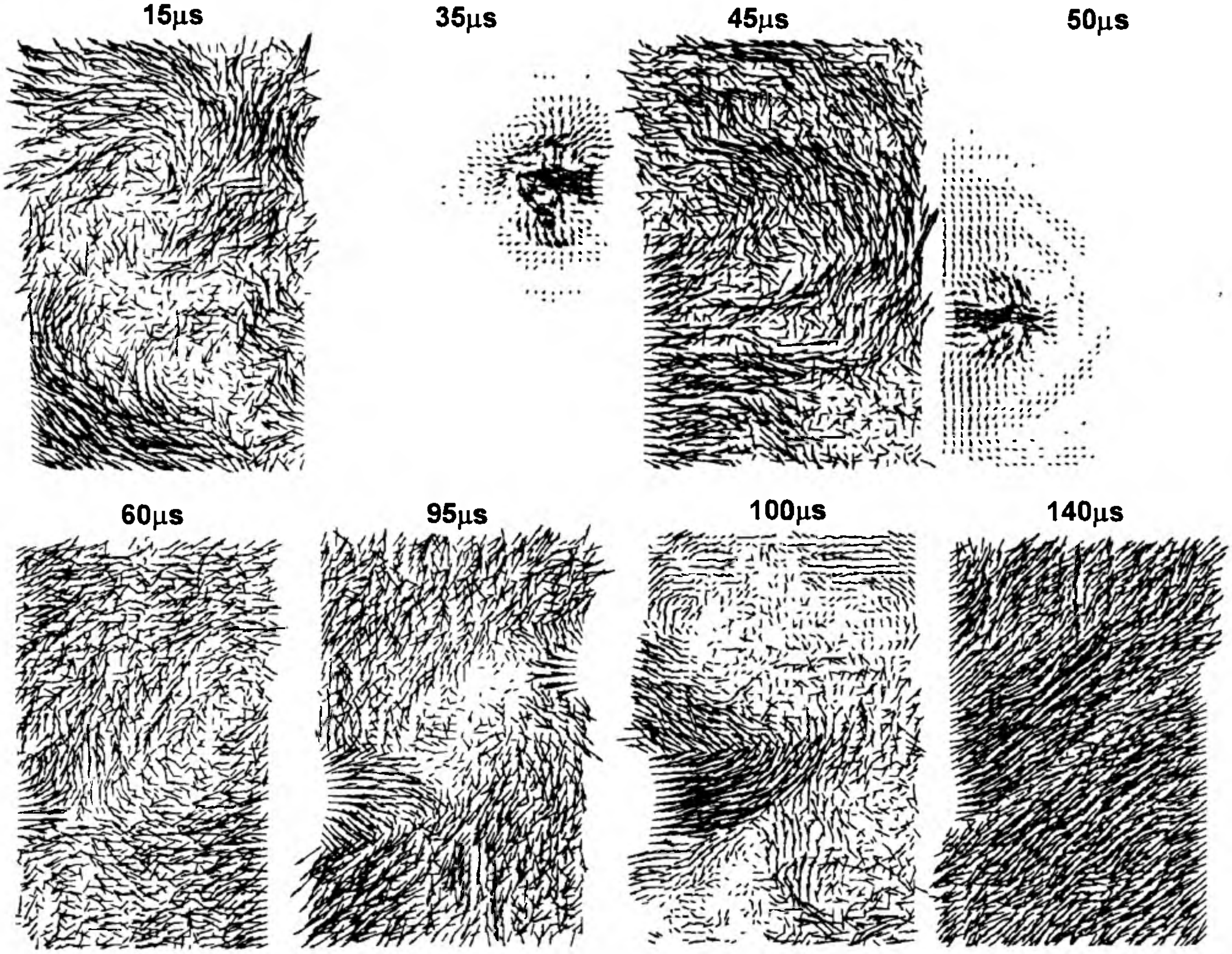
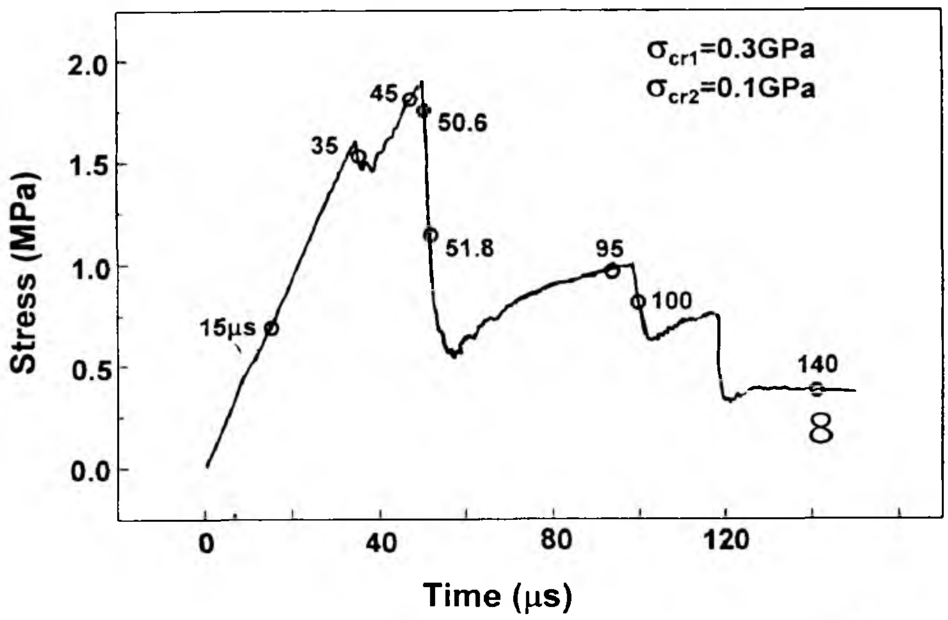
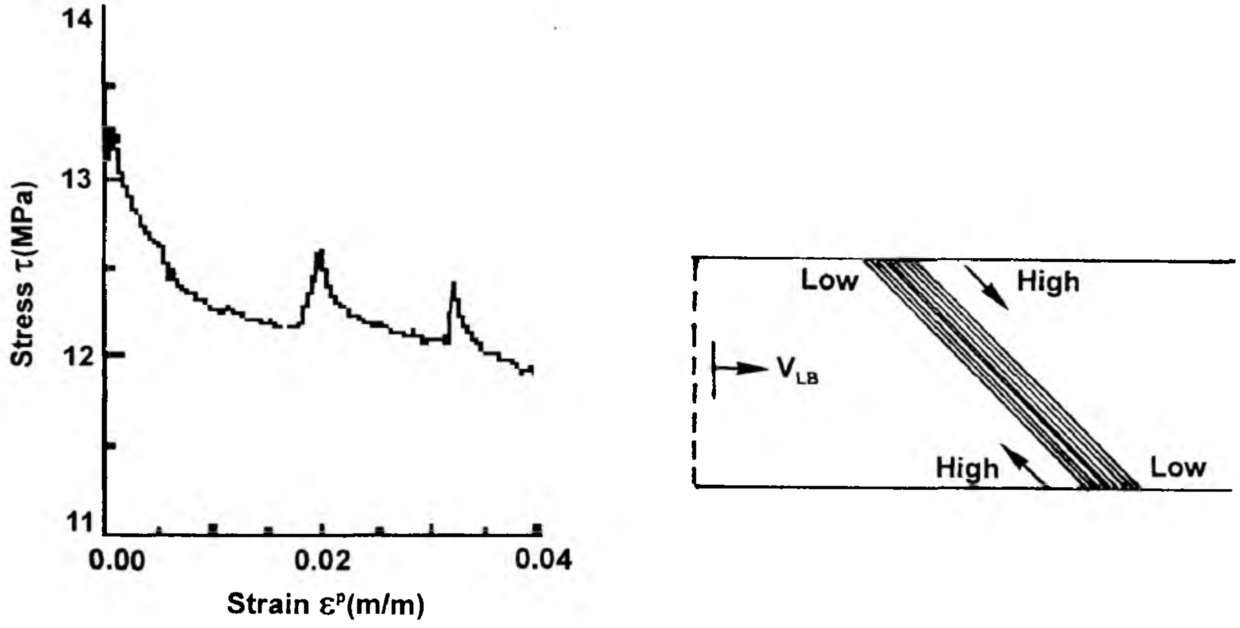


Fig. 1 Particle velocity field under tension

The shear bands move irregular with high speed at the plastic fronts from the ZRS. Plotted in Fig 2 is the time-dependent stress averaged over the grid cells Marked on the curve are those states shown on Figs 1 and 3 Comparing the results presented in Fig 1, 2 and 3, it is possible to conclude that development of plastic strain in one of the bands corresponds to the average relaxation stress on the time-dependent stress curve. The particle velocity fields covering the specimen are nearly homogeneous. This indicates that the on the specimen curvature about the tensile axis depends on the average stress increments, Figs 1 and 2 As the plastic fronts near the middle of the specimen are scaled down, Fig 2, the bands of localized plastic strain merge into a localized band directed towards the tension axis at approximately 45° Refer to Fig 1 for t = 95 and 100 μs) Finally, the time-dependent stress curve flattens out This corresponds to the specimen separating into two fragments (see Fig. 1



(a) Time-dependent stress under tension with $\dot{\varepsilon} = 72c^{-1}$



(b) Stress-strain curve [9] for Cu based alloy

(c) Plastic shear and Luders band (LB) formation [9]

Fig. 2 Mechanical behavior of base material and ZRS

for t = 140μs). Similar curves for average stress relaxation have been obtained in [9] for Cu-Al alloys, Fig. 2(b). Also shown in [9] are results for the Lüders bands that originate at the opposite specimen surface and then propagate toward each other as bands of localized plastic strain, Fig. 2(c).

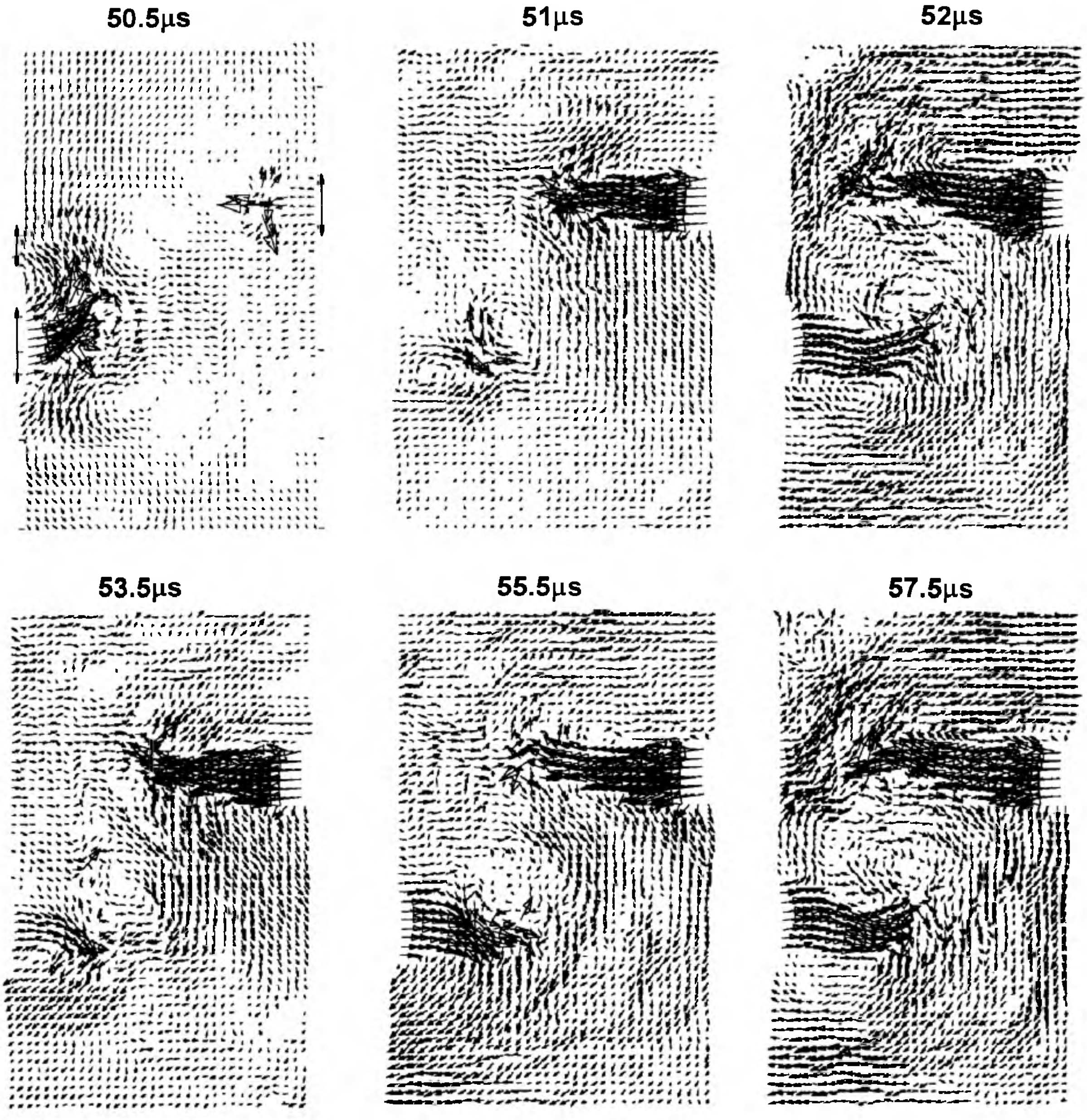


Fig. 3 Particle velocity fields corresponding to the intensive relaxation of average stress

Consider the particle velocity (Fig. 3) and stress (Fig. 4) fields in relation to the stress relaxation expressed by the time-dependent stress curve, Fig. 2(a). Stress relaxation in a band of localized plastic deformation results in generation of an elastic release wave. It propagates as spherical front through the elastically deformed material, causing a relaxation. Periods of band movement can be retraced from the dynamics stress pattern, Fig. 4. Depending on the physical-mechanical characteristics and relaxation times, the plastic deformation develops with the bands moving from opposite surfaces. The process is illustrated in Fig. 4. There is a stress concentration in elastically deformed region adjacent to the plastic front. The stress in the cells increases until the strain and stress yield criteria are satisfied simultaneously. Refer to points 1 and 3 of the algorithm mentioned above. Hence forth, the stress relaxation begins at the rate determined by a relaxation function up to a threshold. After the stress has relaxed, the band movement retards and stops. To continue the band movement, it is necessary that the level of plastic strain on the band front and stress in the elastically deformed cells adjacent to the plastic front would reach their respective threshold values. The same applies to the opposite surface.

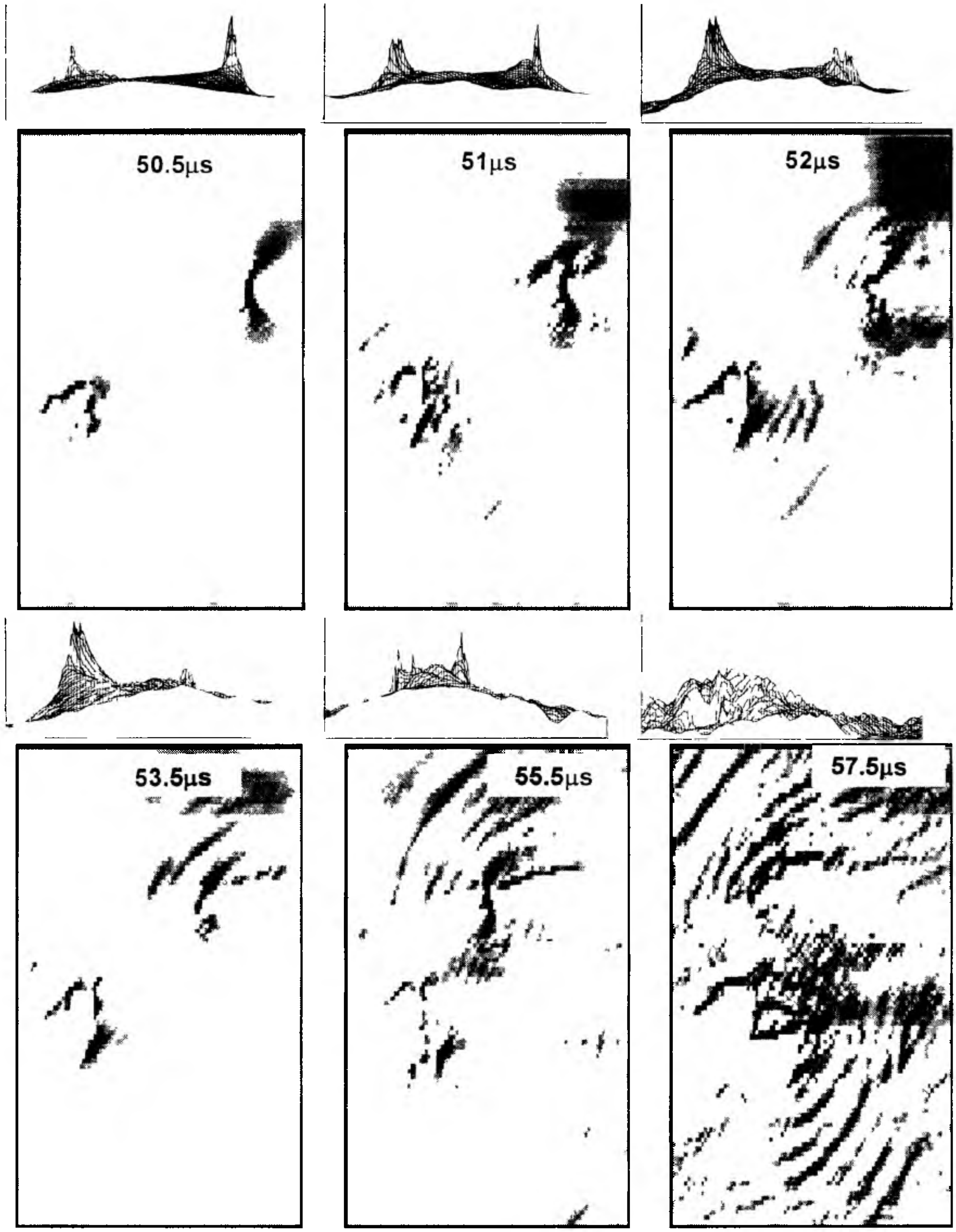


Fig 4 Time sequence of stresses on normal plane to tension

Plastic fronts near the middle of specimen, change of band movement direction and velocity fields are reflected by the progressive curvature change of the specimen axis, Fig. 3.

4. Conclusion remarks

According to the yield criterion proposed, plastic shear originates on the surface and interface; it then propagates from the boundaries into the crystal covering the entire specimen. Plastic shear cannot originate from the inside,except in the case when the stress in a local area reaches the theoretical shear strength. This could correspond to interfaces inside the body. Plastic shears could be generated by interfaces form bands of localized plastic deformation. The band would move provided that the prevailing plastic strain reaches a critical value. That is a stress concentration could yield a localized plastic front. Dislocation flow could also enhance the movement of the band [3,4]. other factors that would affect such movement could be identified upon further investigation.

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