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Investigation of Regularities of Formation and Propagation of Elastic Vortices in Surface Layers of Materials under Dynamic Contact Loading

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Abstract. On the base of computer-aided simulation by movable cellular automaton method regularities of formation of vortices in surface layers of materials under dynamic contact loading were investigated. It was shown that the dynamic contact loading leads to the formation of an elastic vortex in the area of contact interaction and its subsequent propagation in the volume of material. Direction of vortex movement essentially depends on the velocity of contact loading and value of the contact pressure, which are determined features of the interaction of the material surface and the counterbody (e.g. stress state of contact area).

INTRODUCTION

A significant and, in many cases, the leading role in material deformation belongs to rotational displacements that are manifested, in particular, in the form of rotation of the individual structural elements, such as grains or their conglomerates [1, 2]. In nanostructured materials, which are characterized by a large volume fraction of grain boundaries, the role of rotary displacement becomes crucial. The results of theoretical and experimental investigations indicate that the contribution of the rotary modes of deformation increases significantly under dynamic loading or dynamic change of stress state [3–5]. In spite of the a detailed study of the deformation mechanisms providing integral rotations of grains and their conglomerates, one of the fundamental factors that determine multiscale character of these mechanisms and conditions of their involvement into deformation process under dynamic loading, as a rule, is beyond of discussion. This factor is the elastic vortex motions in the material, which are formed at the initial stage of dynamic loading. Thus, the rotational modes of deformation play an important role at the dynamic surface (contact) loading of the material, which may be accompanied by severe plastic deformation of the surface layers and formation of damages [6, 7]. Therefore, the aim of this paper is investigation of the conditions of formation of elastic vortices in the area of contact interaction and peculiarities of their propagation in the bulk of material. The study was carried out on the base of computer-aided simulation by movable cellular automaton method [8–10].

MODEL DESCRIPTION AND DISCUSSION OF RESULTS

The study of the processes of formation and propagation of elastic vortices in the surface layers of material under contact loading was performed in 2D formulation. Fragment of contact area of surface layer of elastic-plastic material with rigid elastic indenter was considered. The mechanical properties of the material were close to properties of submicrocrystalline Grade-2 titanium (Fig. 1a).

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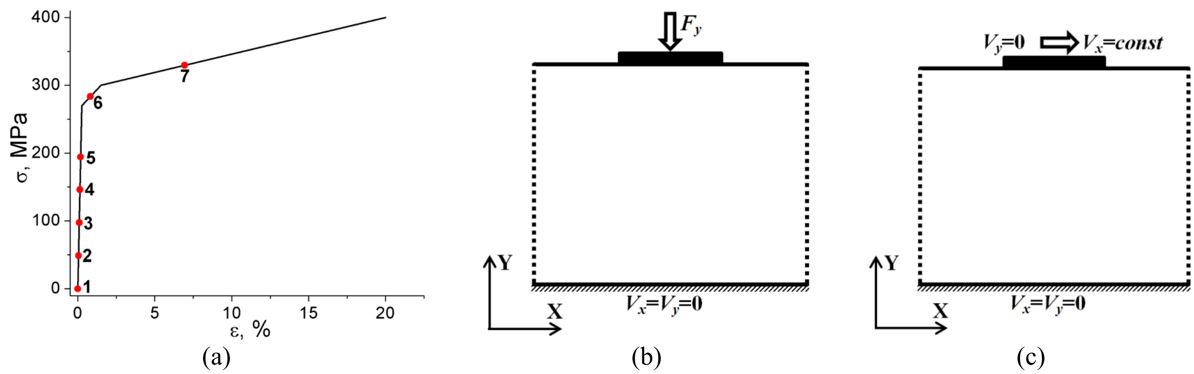


FIGURE 1. Response function of cellular automata of simulated material (a) and the loading scheme (b, c). Red dotes in figure (a) denote considered values of contact pressure σ_{cont}. Dash lines in figures (b, c) denotes periodic boundary conditions

Influence of a contact pressure and a velocity of indenter displacement on the formation and propagation of elastic vortices in the bulk of material were analyzed. Two stage loading scheme was used in the paper. In the first stage initial contact pressure σ_{cont} was set by means of applying a force F_y to the counterbody surface (Fig. 1b). In the second stage (after the establishment of force equilibrium in a simulated system) contact loading was performed by means of counterbody shifting along the sample surface with a constant speed V_x (Fig. 1c). Vertical position of the indenter was fixed at this stage ($V_y = 0$).

Analysis of the simulation results showed that the beginning of counterbody motion is accompanied by the formation of the elastic vortex directly under the contact surface (Fig. 2a). Direction of vortex rotational coincides with the direction of the shear displacement.

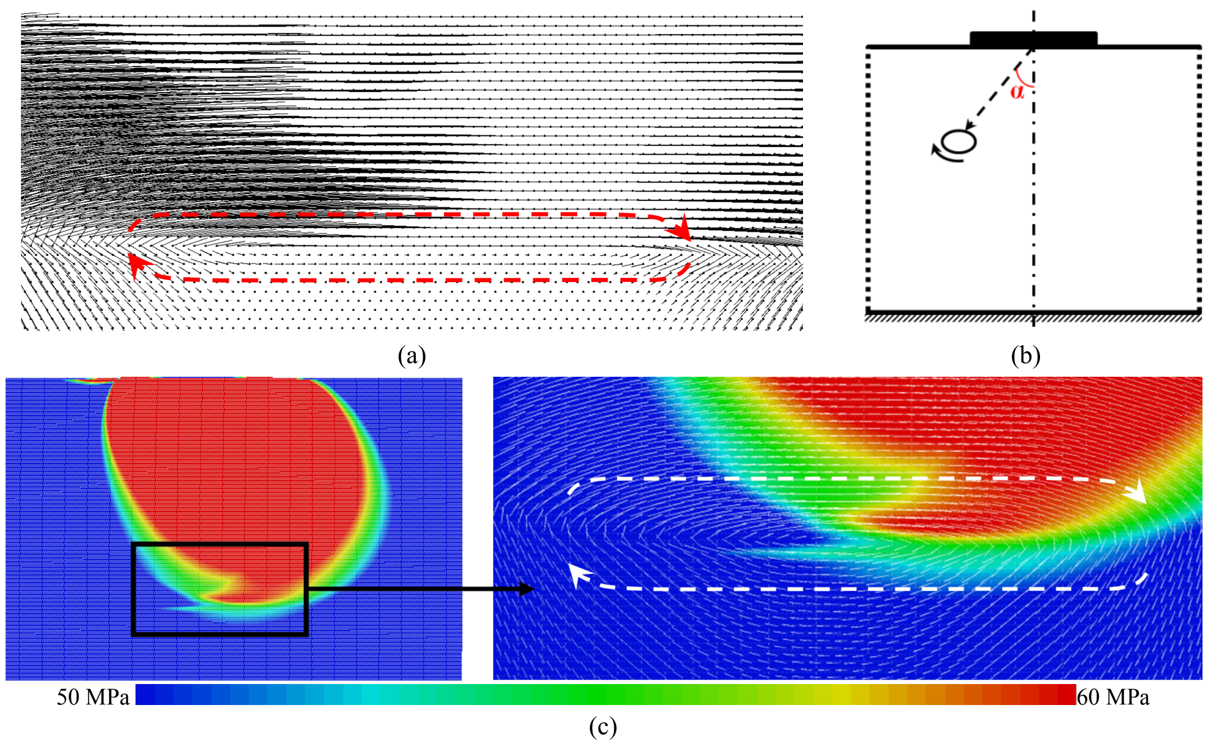
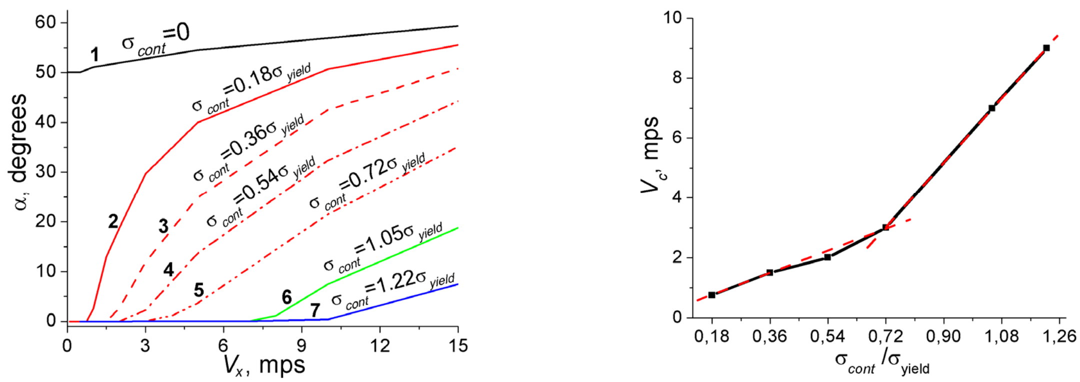


FIGURE 2. Velocity field in simulated sample at the moment of vortex formation (a); scheme of vortex propagation in the bulk of material (b); an example of the distribution of von Mises stresses in the area of the vortex location at $\sigma_{cont} = 0.54\sigma_{yield}$ (σ_{yield}—yield stress of the material) $V_x = 1.5$ mps. Red (a) and white (c) arrows indicate direction of vortex rotation



(a) (b)

FIGURE 3. Dependencies $\alpha(V_x)$ (a) and $V_c(\sigma_{cont})$ (b). In (b) red dash lines denote linear segments of dependence $V_c(\sigma_{cont})$

Formed elastic vortex propagates rectilinearly in the bulk of material at a certain angle α to the surface normal (Fig. 2b). In process of deformation concentration of shear stresses in elastic vortex increases (Fig. 2c), and its velocity quickly reaches the value of transverse elastic wave speed.

Analysis of the direction of the vortex motion showed the presence of dependence of the angle α (Fig. 2a) on the indenter velocity V_x and contact pressure σ_{cont}. At relatively low loading speeds vortex propagates deep into the material vertically ($\alpha \approx 0°$). At the same time, at higher loading speeds vortex propagates at a sufficiently large angle to vertical line. Figure 3a shows the dependences of the angle α (Fig. 2b) on velocity V_x, obtained for different values σ_{cont}. It can be seen that value of α almost linearly increases with V_x at $\sigma_{cont} = 0$ (curve *1* in Fig. 3a). At that in the considered interval of V_x change in the angle value is less than 10°. At the same time dependencies $\alpha(V_x)$ have a non-linear threshold character (curves *2–7* in Fig. 3a) at $\sigma_{cont} > 0$. At low speeds (below a certain threshold value V_c) formed elastic vortex propagates vertically ($\alpha \approx 0°$) in the bulk of material. When $V_x > V_c$ direction of the vortex motion begins to deviate from the vertical, and the value of α at high V_x could reach 50°–60°. V_c value depends on the contact pressure σ_{cont}. Figure 3b shows dependence $V_c(\sigma_{cont})$, which in generally could be approximated by two linear segments. The first of them corresponds to the range of contact pressures below the yield stress of simulated material (points *1–5* in Fig. 1a) and the second one corresponds to $\sigma_{cont} > \sigma_{yield}$ interval (points *6*, *7* in Fig. 1a). Thus, a substantial increase in the inclination angle of $V_c(\sigma_{cont})$ dependence takes place on passing through the yield stress of the simulated material.

Analysis of simulation results showed, that existence of above mentioned dependencies ($\alpha(V_x)$ and $V_c(\sigma_{cont})$) is associated with features of contact interaction of the surface of the simulated sample with the counterbody. Two interacting surfaces are characterized by a roughness whose value is determined by the size of movable cellular automaton *d* (Fig. 4). Dynamic tangential displacement of the counterbody leads to local increase in contact pressure (compression) in the "front" parts of the surface roughness (marked with red lines in Fig. 4) due to the inertia of the surface layer of the sample. At the same time the contact area in the "rear" parts of roughness (marked with green lines in Fig. 4) decreases. This process is accompanied by the formation of elastic perturbations in the area of contact interaction and by the formation of the vortex. Direction of vortex motion will be determined by the velocity of loss of contact of the "rear" parts of roughness and speed of adjustment (accommodation) of whole contact surface to the conditions of external action. Note that term "accommodation" means formation of a relatively smooth velocity field in the surface layer.

Thus, at low values of V_x material surface has time to adapt to the loading conditions. This is followed by the formation of the vortex. Its size is equal to the length of the contact zone. Horizontal position of vortex center corresponds to the position of the center of the contact zone, and the vortex propagates in the vertical direction. At the same time when $V_x > V_c$ "rear" parts of the roughness quickly lose contact with the corresponding areas of the sample surface (the sample surface does not have time to adjust to external loading). As a result, quite inhomogeneous complex velocity field is formed in the surface layer and the vortex is formed in the rear part of the contact surface. This determines direction of vortex motion under non-zero angle α.

Increase of σ_{cont} leads to increase in area of contact spot in the region of interaction of material surfaces with counterbody. Consequently, the value of necessary displacement of counterbody required for the loss of contact of "rear" parts of roughness increases.

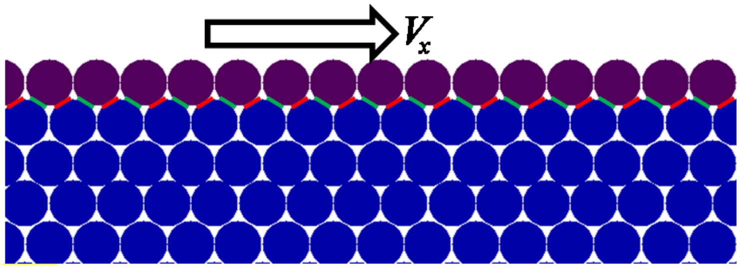


FIGURE 4. Example of structure of the contact surface. Red lines denote areas of compression and green lines denote areas of loss of contact with displacement of counterbody

Moreover, the increase in σ_{cont} leads to stress growth in the surface layer of the deformed sample and, accordingly, to increasing of the value of accumulated elastic energy in it. This provides more intensive accommodation of the material to external loading. The totality of these two factors leads to increase of the threshold velocity V_c with increase in the contact pressure (Fig. 3b).

In the case of $\sigma_{cont} > \sigma_{yield}$ a formation of areas of high compressive stresses takes place at the ages of contact surface (near the edges of counterbody). And these areas are in state of inelastic deformation. These plastically deformed areas are limited contact surface. This leads to even greater increase in the area of contact spots of the interacting surfaces, causes the formation of vertically propagating elastic vortices even at high velocities of the contact loading and, subsequently, to the increase in the inclination angle of $V_c(\sigma_{cont})$ dependence at high values of contact pressure ($\sigma_{cont} > \sigma_{yield}$).

CONCLUSION

On the base of computer-aided simulation using movable cellular automaton method peculiarities of formation and the dynamics of propagation of elastic vortices in the volume of material under dynamic contact loading was investigated. It is shown that the dynamic vortex structures are characterized by concentration of shear stresses and propagated in the material in front of the elastic perturbation caused by the dynamic contact loading. It is established that the direction of motion of the vortex (the inclination angle of the trajectory of its motion relative to the normal to the contact surface) is substantially depend on the velocity of contact loading. This dependence has pronounced threshold character. At speeds of contact loading below of a certain threshold value vortices can propagate deep in the bulk of material along the normal to the contact surface. At loading speeds above the threshold value direction of the vortex motion is deviated from the vertical. The value of this deviation depends on the rate of deformation of the contact surface and may reach 50°–60°. It is shown that the threshold value of the velocity at which the change in direction of vortex motion takes place depends on the value of contact pressure, contact surface roughness and the stress state of the contact area (elastic or inelastic deformation).

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