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Creation of unstable zones in metals under dynamic loading

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Abstract—The process of creating unstable rapidly heated and cooled zones of a plastically deformed metallic material under the process of realisation of super-deep penetration is described. Parameters, sizes, lifetime and proportion of such zones in the bulk of a target material was established and evaluated.

Almost all of the works devoted to explosive treatment of metallic materials use schemes in which an explosive charge contacts with the target. The values of loading impulses achieved in such cases vary within the limits from 2 to 50 GPa, excluding axisymmetric schemes in which on the axis pressure impulses exceeding 100 GPa can be achieved. As a rule, the duration of loading in all of these cases does not exceed 10 μs.

The scheme which is traditionally used to realise a super-deep penetration effect (SDP) [1–3] is based on a different principle, Fig. 1. An explosive accelerator with an aluminium liner filled with powder and placed at the bottom part of the explosive charge creates a high-speed dense gas-powder flux the parameters of which can be widely changed within an acceleration process. The average density and velocity of the flux are determined in the limits from 0.5 to 7 g cm^{-3} and from 1 to 3 km s^{-1}, respectively. As shown by calculations [4] and experimental data [5], the duration of loading in this case varies from 100 to 500 μs, the pressure impulses generated by the flux in the target have a substantially variable character and their intensity achieve 10–15 GPa.

An experimental investigation of metallic targets treated by a gas–powder flux generated by an explosive acceleration (Fig. 1), allowed one to detect a new complicated phenomenon, the investigation of which is still too far from completion. Application to the investigation of SDP of almost all the known methods of investigation of solids such as chemical and X-ray structural analysis, visual and electron microscopy, neutronography and microprobing together with a traditional method of measuring physical and mechanical parameters of solids and theoretical modelling made it possible to observe a sequence of features that differ SDP from the well-known effects accompanying the processes of the collisions of solids. These are:

- SDP is observed only under the conditions of interaction of a high-speed dense flux of powder particles with a metallic target;

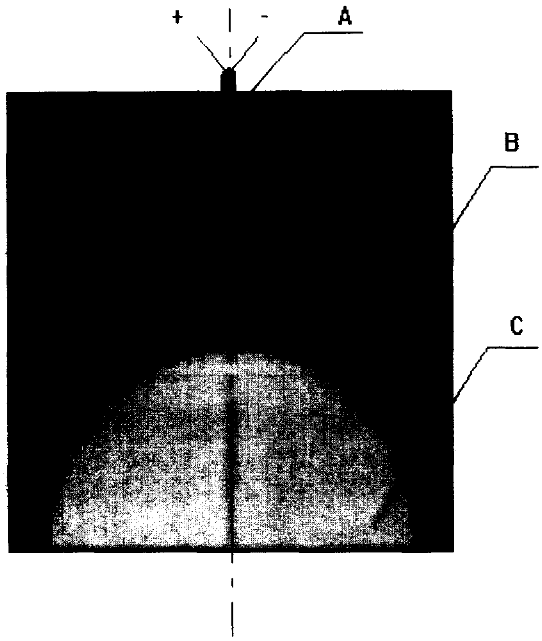

Fig. 1. An explosive accelerator of a powder particle flux. (A) an initiator; (B) explosive charge; (C) powder.

- SDP is accompanied by penetration of a portion of the particles of the flux to the depths not exceeding 10^3–10^4 of the initial sizes of powder particles (calibre). The total portion of penetrating particles does not exceed 0.1%.
- interaction between a metallic target and a penetrating particle has a plastic character, the level of plastic deformations is extremely high near the axis of particle motion and becomes smaller on moving away from this axis. At a distance of 2–3 diameters from the axis of the motion of particles (Fig. 2), the plastic influence becomes negligibly small. A portion of the material located near the axis of particle

NOMENCLATURE

c	concentration of inserted material
c_p	specific heat of a target [J (kg·K)$^{-1}$]
d	particle diameter [m]
L_m	latent heat of melting [J kg^{-1}]
q	specific heat of flux [J (m^2·s)$^{-1}$]
r	radius vector starting from the path of particle motion [m]
t	current time [s]
T	current temperature [K]
T_m	melting temperature of a target [K]
T_o	inital temperature of a target [K]
$\dot{T}_h$	rate of heating [K s^{-1}]
$\dot{T}_c$	rate of cooling off [K s^{-1}]
U	average velocity of particle motion in the target under a steady-state process [m s^{-1}]
V	total volume of a target [m^3]
V_z	volume of a target occupied by thermal zones [m^3].

Greek symbols

δ_i	thickness of zone of thermal influence [m]
δ_m	thickness of a melted zone [m]
δ_T	total thickness of thermal zone [m]
λ	heat conductivity of a target [J (kg·s·K)$^{-1}$]
ρ	target density [kg m^{-3}]
τ	total duration of loading [s]
τ_c	characteristic time of cooling [s]
τ_{ch}	characteristic time of interaction between a moving particle and target material [s]
τ_m	characteristic time of target material melting [s]
τ_{us}	total time of thermal process in thermal zone sections [s]
χ	thermal diffusivity coefficient of a target [m^2 s^{-1}].

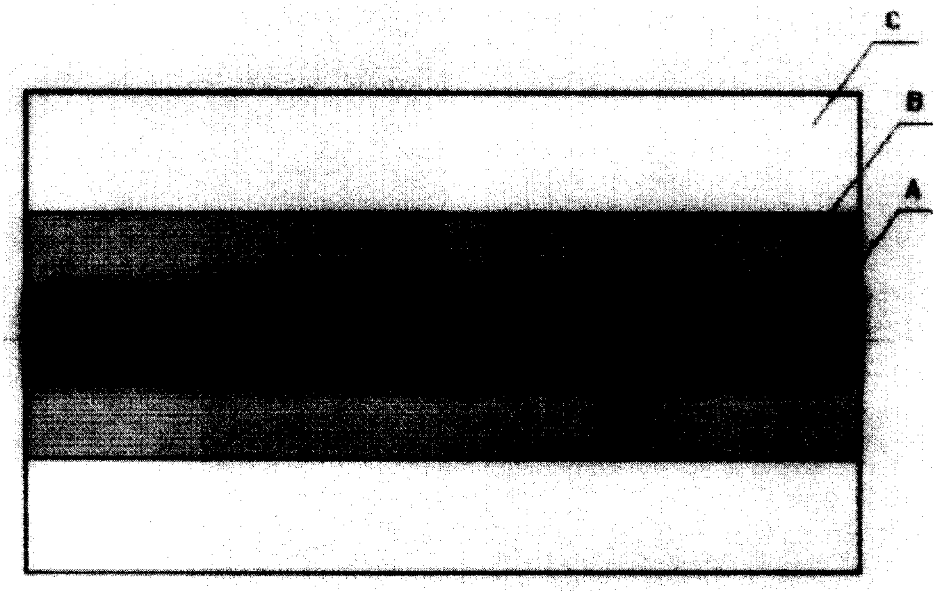

Fig. 2. Structure of plastic deformation of the target material near the particle path. (A) Material completely losing its crystalline structure; (B) plastically deformed material; (C) non-deformed material.

motion almost becomes negligibly small. A portion of the material located near the axis of particle motion almost completely loses its crystalline structure, Fig. 3 (on the left). This fact is confirmed by the respective radiographs, Fig. 3 (on the right).

- channels (Fig. 4), formed in the target by penetrating particles close (collapse) completely. The process of channel closing after the passage of particles is the result of a high pressure generated in the target by the powder flux. Under the action of this pressure the 'walls' of the channel formed in the target by the particle start to move toward the axis of the motion of particles and the channel finally collapses. This fact substantially distinguishes SDP from all the other processes of the penetration of solid particles into solids. The paths of particles in the target can be detected afterwards only by means of a special etching technique that allows one to remove pre-

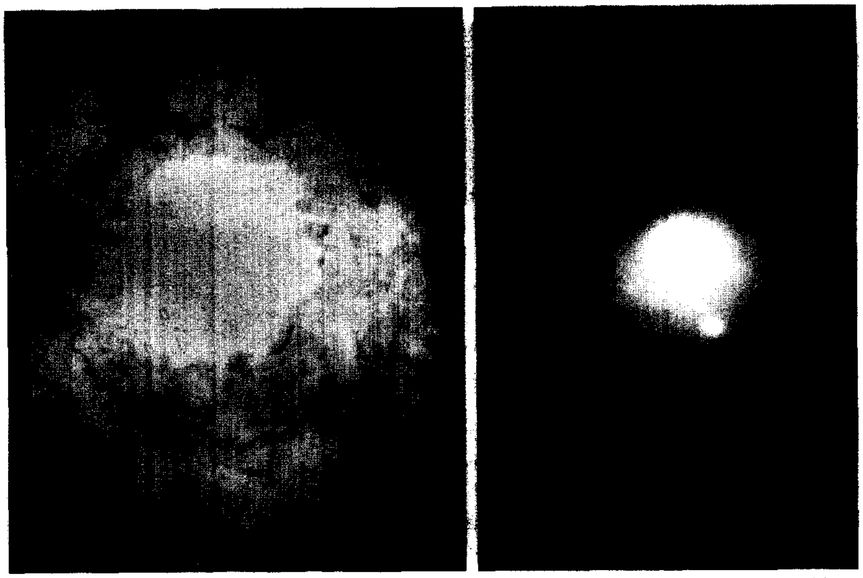

Fig. 3. Zone situated closely to the path of penetration at a depth of about 7 mm after etching under translucent microscope (left). Radiograph of this zone (right). Steel treated by SiN particles.

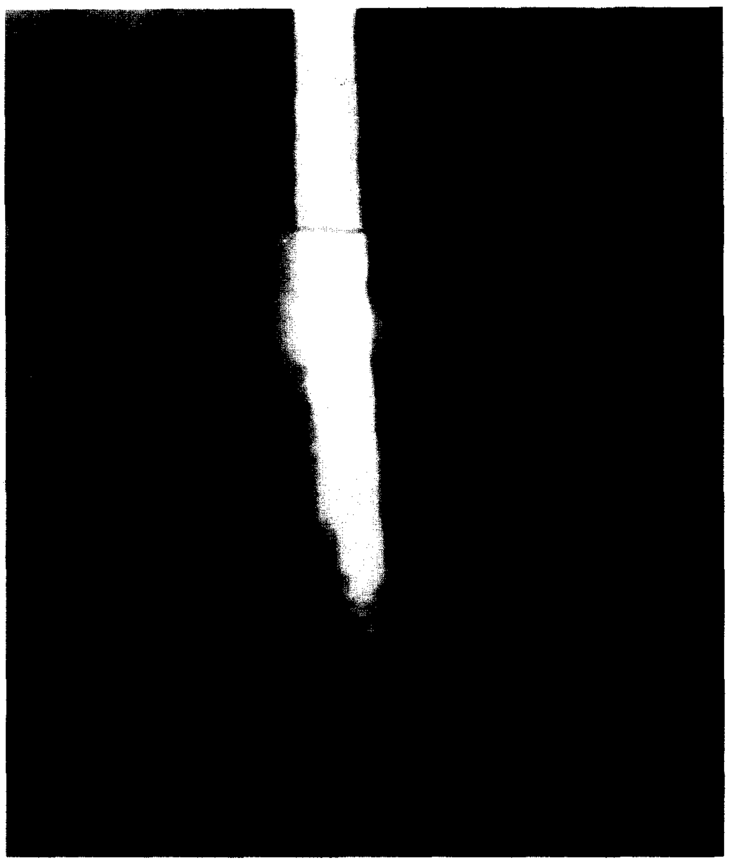

Fig. 4. Channel and the rest of SiN particle in the steel target treated by the SiN particles at a depth of about 12 mm.

dominantly plastically deformed zones of the target material. Remains of the penetrating particles that were finally caught by the target material can be often found at the ends of such paths (Fig. 4).

The model of SDP developed in the work frame of the complex investigations of SDP is based on the analysis of the energy balance of the process. The experimentally established plastic character of the interaction of particles with metallic targets allows one to state that the energy of every separate particle is insufficient for penetration into the target to the depth of 100 and greater calibre (it is easy to show that this energy would suffice only for penetration to the depth of about 40–50 calibre even under assumption that the strength component of the target resistance force can be neglected). Consequently, SDP is characterised by the fact that a portion of penetrating particles must receive an additional energy that would be sufficient for overcoming the target resistance. The only source of this additional energy in the present scheme can be the energy of an explosive charge of the accelerator depicted in Fig. 1. By means of the flux of particles created by the accelerator the explosive energy is transferred to the target (when the flux is retarded on the surface of the particle) and is accumulated by the target structure as an energy of the pressure field. There is a special mechanism of transfer of this energy to the particles and, due to this, some particles can penetrate the target to super-deep depths. This mechanism is described by the authors in their special works [6, 7]. It is based on taking account of the process of the collapse of channels formed in the target by penetrating particles during their motion after the passage. The model allows one to establish that a certain small portion of penetrating particles gets such a quantity of energy which allows them to move in the target with an almost uniform velocity during the whole time of the interaction of the target with the flux. As a result, this allows the particles to achieve the depths that can be defined as super-deep. One of the results of the SDP model [6, 7] which is essential for the present work is the fact that under the pressure generated by particles of about 10–15 GPa an average velocity of steady motion of particles is determined by the value $U = 0.6$–$0.7\ \mathrm{km\ s^{-1}}$ for an average duration of the process of about $\tau \approx 10^{-4}$ s [5–7]. The characteristic time of the interaction of a moving particle with the target material $\tau_{ch} = d/U \approx 3*10^{-8}$ s exceeds (or is comparable with) the characteristic time of target melting

$$\tau_m \approx \frac{2}{3} C_p \lambda \rho \frac{(T_m - T_o)^2}{q^2} \tag{1}$$

where

$$q \approx \rho \frac{U^3}{2} \tag{2}$$

ρ, c_p, λ, T_m, T_o is the density, specific heat, thermal conductivity, melting and initial temperature of the target, respectively. For Fe and Ti for the above defined U the value of τ_m will be respectively $0.211*10^{-9}$ s and $0.139*10^{-9}$ s. The total zone of heating will be

$$\delta_T = \delta_m + \delta_i \tag{3}$$

where

$$\delta_T = \frac{q}{L_m \rho}(\tau_{ch} - \tau_m) \tag{4}$$

L_m is the latent heat of melting and

$$\delta_i = \sqrt{\chi \tau_{ch}} \tag{5}$$

where χ is the thermal diffusivity, $\chi = \lambda/(c_p \rho)$. For Fe and Ti, $\delta_m \approx$ e 8.31 and 4.82 μm, $\delta_i \approx 0.73$ and 0.48 μm and $\delta_T \approx 9.04$ and 5.3 μm, respectively, for particles with the initial diameter $d \approx 20\ \mu$m. After its penetration every particle left a long ($\approx 10^3 d$) and thin ($\approx \delta_T$) zone of heat treated material, the so-called 'thread'. The rate of heating of this zone is

$$\dot{T}_h \approx \frac{(T_m - T_o)}{\tau_{ch}} = \frac{U(T_m - T_o)}{d}. \tag{6}$$

Immediately after the passage of the particle the thermal zone that contacts with the 'cold' material of the target (not touched by the interaction between the particle and target material) starts to cool off. This cooling is described by the equation

$$\frac{\partial T}{\partial t} + \mathbf{U} \cdot \nabla T = \chi \Delta T \tag{7}$$

since

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\partial T}{\partial t} + \frac{\partial y}{\partial t}\frac{\partial T}{\partial y} + \frac{\partial x}{\partial t}\frac{\partial T}{\partial x} + \frac{\partial z}{\partial t}\frac{\partial T}{\partial z} = \frac{\partial T}{\partial t} + \mathbf{U} \cdot \nabla T \tag{8}$$

the rate of cooling is

$$\dot{T}_c = \frac{\mathrm{d}T}{\mathrm{d}t} = \chi \Delta T = \chi(\nabla \cdot \nabla T). \tag{9}$$

For a steady motion, when the change in temperature with depth is negligibly small, and $T = T(r)$ and $\nabla = \partial/\partial \mathbf{r}$, we have

$$\nabla T = \frac{T_m - T_o}{\mathbf{r}}. \tag{10}$$

and

$$\nabla \cdot \nabla T = \frac{\partial}{\partial \mathbf{r}}\left(\frac{T_m - T_o}{\mathbf{r}}\right) = -\frac{T_m - T_o}{\mathbf{r} \cdot \mathbf{r}}. \tag{11}$$

Finally the rate of cooling is

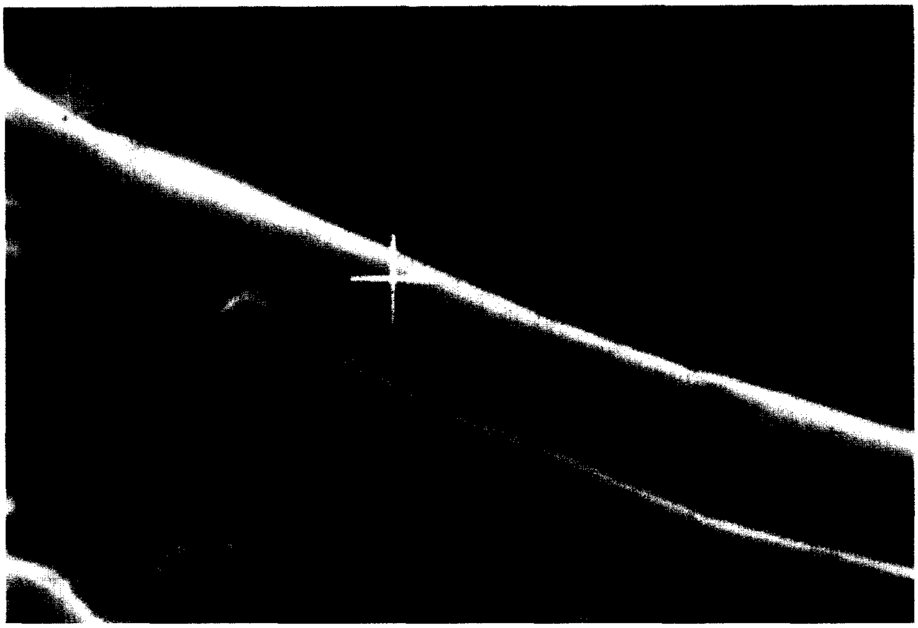

Fig. 5. Zones of mixing of the target and particle material and heat influence in the steel treated by NiB_2 at a depth of about 6 mm.

Fig. 6. Steel treated by TiB_2 at a depth of about 7.5 mm. Inclusions with non-recognised composition.

$$\dot{T}_c \approx -\chi \frac{T_m - T_o}{\delta_T^2} = -\frac{\delta_i^2}{\tau_{ch}\delta_T^2}(T_m - T_o)$$
$$= -\left(\frac{\delta_i}{\delta_T}\right)^2 \frac{U(T_m - T_o)}{d}. \quad (12)$$

Since $\delta_i < \delta_T$, the numerical value of the cooling rate is always smaller than of the rate of heating. For Fe and Ti, $|\dot{T}_c/\dot{T}_h| \approx 0.078$ and 0.091 and $\dot{T}_h \cdot \approx 5.3 * 10^{10}$ K s^{-1} and $5.8 * 10^{10}$ K s^{-1}, respectively.

Such zones of thermal influence near the paths of the motion of particles were detected experimentally, Fig. 5. Investigation of these zones shows that after the passage of a portion of particles their material loses its crystalline structure characteristic for the initial target. Moreover, an intensive chemical interaction between particles and target material was observed. An X-ray structural analysis allows one to detect in these zones some compositions of the target and inserted material, but some inclusions were detected that differed substantially from compositions of the particle and initial material of the target (Fig. 6).

The ratio of the volume of such zones to the total volume of the target material can be determined if the concentration c of the inserted substance is known

$$\frac{V_z}{V} \approx \frac{3}{2} c \left(\frac{\delta_T}{d}\right)^2. \quad (13)$$

Thus, it can be considered as established that in realisation of SDP thin zones of the target material stretched along the direction of the flux of particles are formed near the paths of penetrating particles (Fig. 5), that were subjected to intensive heat and plastic influence. The reasons of their appearance, time and method of their existence and chemical composition allows one to characterise them as unstable zones of active chemical interaction and mixing of a target and inserted material under the conditions of fast heating and cooling which take place under high pressures accompanying SDP effect. The total time of the existence of such a zone is

$$\tau_{us} = \tau_{ch} + \tau_c.$$

As it can be seen from equation (1) $\tau_c \approx \delta_T^2/\chi$. For the Fe and Ti $\tau_{us} \approx 4.57 * 10^{-6}$ and $3.65 * 10^{-6}$ s, respectively.

Heating (annealing) of a target after an explosive loading makes it possible to obtain a more stable material, since it leads to the re-crystallisation of amorphosized zones of the target, but the chemical composition of some inclusions appearing after SDP loading cannot be determined by traditional methods (micro X-ray structural analysis or translucent electron microscopy). This field of knowledge requires further investigations and, in our opinion, can be very interesting.

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