Specific features of the mechanism of small-sized solid particles penetration into a metal target

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Abstract. There was studied the process of solid objects with 50 radius penetration into aluminum solid bodies. Analysis of experimental results showed that the hydrodynamic model cannot be used as a basis for the penetration process description. It is shown that in case of small particles there occurs a specific mechanism of penetration.

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Introduction

One of the most important properties of the coatings is their adhesion with the basis metal. At conventional coating technology, the limiting adhesion characteristics are determined by the value of the adhesion energy. The value of this energy is usually much less than the cohesive energy of the coating material.

If to embed small particles of the coating material into a surface of the metal and firmly fix them mechanically (e.g., due to the forces generated by the elastic deformation), the particles falling within the metal surface can later interact with them. Due to this fact the coating strength at such their application will be determined by the cohesive energy of the coating material.

In this work we consider the process of penetration of solid spherical particles into the metal substrate. Possible mechanisms of penetration of small particles (50 µm), with high speed (about 3000 m/s) have already been objects of different studies (for example [1]), but until now this has not led to the creation of a satisfactory model of the penetration [2, 3].

Among the proposed models, the most popular model is the penetration of solid particles into the molten metal (the so-called hydrodynamic model). Besides the efficiency of using this model to describe the fast oversized models, the base for such popularity serves mainly the presence of molten metal remains in the track of the particle. However, in the work [4] there were expressed strong objections to the applicability of this model for description of small-sized particles penetration.

In this paper we investigate the role of the metal melting process and analyze the possibility of consideration of the hydrodynamic mechanism as the main one during the process of small-sized particles penetration into a metal target.

Description of the experiment

Table 1: Chemical composition and hardness of the powder ПР-Х11Г4СР

Ni %	Cu %	C %	Cr %	Si %	B %	Fe %	Mn %	The hardness of obtained Coating (HRC)
-	-	0.8	11	3	2.7	basis	4	<40

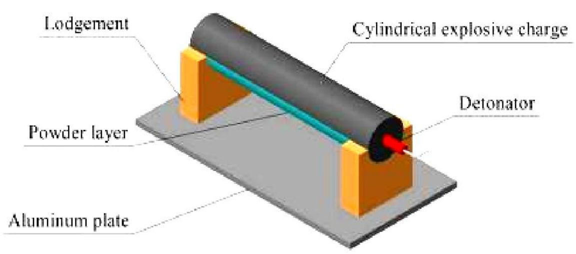

Fig. 1. Explosive device scheme

As percussion elements material there was used the iron-based master alloy powder ПР-Х11Г4СР, which is used for spraying and surfacing coatings resistant against corrosion, friction and abrasive particles wear. Alloy composition is given in Table 1.

One of the challenges faced by the authors is to identify the scale factor at impact interaction of solid spherical percussion elements. Some of the mechanisms that determine the penetration of percussion elements into the aluminum surface are presented in the works [5-8]. In the works [9, 10], there are given examples and considered models of anomalous implementation of microscopic particles at speeds over 1000 m/s. For obtaining the high-speed flows of micro particles, there can be used various explosive devices, described in the works [11, 12]. Experimental studies of particles throwing were carried out using explosive devices according to the scheme shown in Figure 1.

The charge has a cylindrical shape of 15 cm length and a diameter of 3 cm. As an explosive there was used a hexogen of bulk density enclosed into a thin paper membrane. There were used charges of 100 grams weight. On the side surface of the charge there was deposited a uniform layer of powder which was hold by a nitrocellulose lacquer. The charge is set on the lodgements horizontally at a height of 10cm above the aluminum plate – a 10 mm thick target. Charge was initiated by detonator mounted in the end wall.

Results and discussion

Photos shown on Figures 1 and 2 clearly demonstrate the presence of target's metal melting during the process of penetration. The presence of metal foam structure speaks even of its boiling. However, the amount of molten material is not enough to implement the hydrodynamic penetration mechanism. To prove this point, we calculate the maximum possible thickness of the layer of molten metal in front of the moving particle (melt layer thickness) in the above shown experimental conditions. In carrying out the upper estimate of the indicated value, it is sufficient to estimate the thickness of the metal layer in front of the particle, which temperature is above the melting point of the metal target. For this purpose we use the heat conduction equation

$$u_t(x,y,z,t) = a^2 \Delta u(x,y,x,t) + \frac{f(x,y,z,t)}{cq}$$

where $u_t(x,y,z,t)$ – the temperature field at the time instant t; c – the specific heat capacity; q – the mass density; $f(x,y,z,t)$ – the spatial density of the heat source;

$a = \frac{k}{cp}$ – is the thermal diffusivity coefficient; k – is the thermal conductivity coefficient.

We define an isothermal surface in front of the particle, which temperature is equal to the melting point of the metal base. Expression of this surface can be obtained, starting from the solution of the heat conduction equation, written in the form

$$u_t(x,y,z,t) = \iiiint \frac{P}{cp} G(x,y,z,t,\xi,\eta,\varsigma,\tau) \times u(x,y,z,t) f(\xi,\eta,\varsigma,\tau) d\xi d\eta d\varsigma d\tau, \quad (1)$$

where P – the thermal power, released during the particle moving inside the metal.

Function of the source G is determined by the expression:

$$G(x,y,z,t,\xi,\eta,\varsigma,\tau) = \left(\frac{1}{2\sqrt{\pi a^2 (t-\tau)}} \right) \exp\left(-\frac{(x-\xi)^2 + (y-\eta)^2 + (z-\varsigma)^2}{4a^2 (t-\tau)} \right) \quad (2)$$

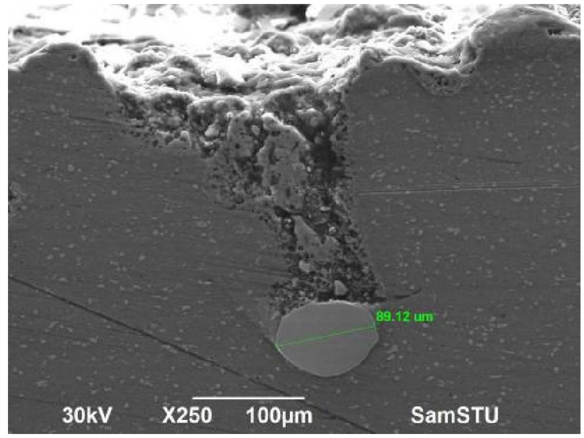

Fig. 2. Particle's track in an aluminum target

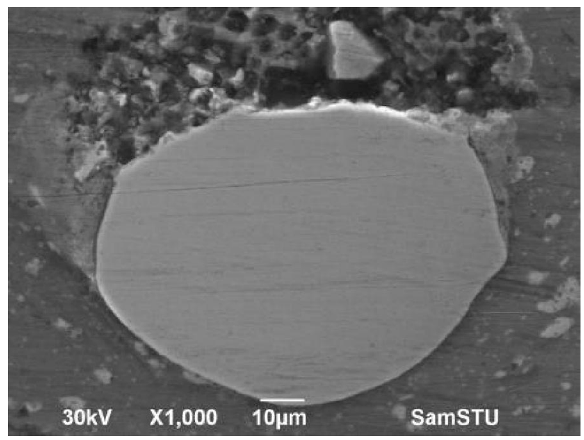

Fig. 3. Foam of molten aluminum in track

Let a spherical particle move perpendicular to the metal surface. We denote a fixed coordinate system and a coordinate system moving progressively along with the particle, respectively x, y, z and x', y', z'. We will direct axles z and z' along the direction of the particle velocity vector. The origin of the fixed system coordinates we will place on the metal surface at a point where the particle started its penetration into the metal at the time instant t_0. The origin of the moving system coordinates is located in the center of the particle. Then $x = x'; y = y'; z = z' + s(t - t_0)$

where $s(t - t_0)$ – the distance traveled by the particle inside the metal target.

If friction is the main source of heat, the distribution function of the heat source can be written as follows

$$f(\xi',\eta',\varsigma')=\delta\left(\sqrt{\xi'^2+\eta'^2+\varsigma'^2-R^2}\right)h(\varsigma'),$$

where R – a particle radius; δ – a delta function; h – a Heaviside function. Let us consider a uniformly accelerated motion with acceleration a and initial velocity v_0. Then, having accepted for $t_0=0$, for the fixed coordinate system we have

$$f(\xi,\eta,\varsigma,\tau)=\delta\left(\sqrt{\xi^2+\eta^2+\left(\varsigma-v_0t-\frac{at^2}{2}\right)}-R^2\right)h\left(\varsigma-v_0t-\frac{at^2}{2}\right) \tag{3}$$

Using the expression (1) and taking into account (2) and (3) for the temperature field we obtain the following

$$u(x,y,z,t)==\frac{P}{cq}\int_\tau\int_\xi\int_\eta\int_\varsigma\left(\frac{1}{2\sqrt{\pi a^2(t-\tau)}}\right)^3\exp\left(-\frac{(x-\xi)^2+(y-\eta)^2+(z-\varsigma)^2}{4a^2(t-\tau)}\right)\times$$
$$\times\delta\left(\sqrt{\xi^2+\eta^2+\left(\varsigma-v_0t-\frac{at^2}{2}\right)}-R^2\right)h\left(\varsigma-v_0t-\frac{at^2}{2}\right)d\xi d\eta d\varsigma d\tau$$

Further let us assume that the particle velocity is invariable within the time period required for covering distance of about the thickness of the layer of molten metal, and let us consider the moving coordinate system. This assumption leads to the following result

$$\xi'=\xi;\eta'=\eta;\varsigma'=\varsigma-v\tau,$$

where τ – is the time of penetration. For the temperature field in this coordinate system we have the following

$$u(x,y,z,t)==\frac{P}{cq}\int_\tau\int_\xi\int_\eta\int_\varsigma\left(\frac{1}{2\sqrt{\pi a^2(t-\tau)}}\right)^3\exp\left(-\frac{(x-\xi)^2+(y-\eta)^2+(z-\varsigma-v\tau)^2}{4a^2(t-\tau)}\right)\times$$
$$\times\delta\left(\sqrt{\xi'^2+\eta'^2+\varsigma'^2}-R^2\right)h(\varsigma')d\xi'd\eta'd\varsigma'd\tau \tag{4}$$

The molten metal layer has the maximum thickness in front of the particle, where $\eta'\approx 0$ and $\varsigma'\approx 0$ (assuming that the thickness is much smaller than the particle size). Therefore, to estimate the thickness of the top layer, it is sufficient to consider only this case. Then

$$\delta\left(\sqrt{\xi'^2+\eta'^2+\zeta'^2}-R^2\right)=\delta(z-vt-\varsigma')$$

Let us denote z_m that point z on the axis, where

$$u(z_m,t)=T_m,$$

where T_m – the temperature of melting. Considering the fixed layer thickness and using the notations $\Theta=t-\tau$, we obtain

$$T_m=\pi\frac{P}{cq}\int_0^\infty\left(\frac{1}{2\sqrt{\pi a^2\Theta}}\right)^3\exp\left(-\frac{(\Delta-vt)^2}{4a^2\Theta}\right)d\Theta \tag{5}$$

Numerical calculation, using this expression, gives the limiting value of the thickness of the melt layer in the conditions described above, at the order of several nanometers. Thus, in this case, the thermal conductivity has no effect on the process of particle penetration.

Conclusion

Insignificant value of thermal conductivity in the considered problem results in extremely thin layers of molten metal. Given the finite volume in which heat is released (e.g. by friction), this thickness amounts to the value in the order of grain size. Such a small value of the liquid metal thickness leads to too large values of viscous friction, to treat hydrodynamic mechanism as a defining one for particle penetration process.

Nevertheless, the presence of molten metal layer can play a big role in the process of penetration, namely the liquid metal in accordance with the law of Pascal generates an isotropic stress field. Then, using a small particle size and consequently large values of the pressure gradients, the metal may deteriorate due to the radial stresses.

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