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CRITICAL LOADING PARAMETERS FOR THE DEVELOPMENT OF ADIABATIC SHEAR IN TITANIUM

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An increase in deformation normally leads to metal strengthening, which is connected with a reduction in the travel of mobile dislocations and an increase in defect density with a fixed amount of strain. However, with explosive and high-velocity impact experiments under different loading schemes (always with the presence of a free surface) there is a change in deformation mechanism from uniformly distributed shear to clearly nonuniform shear with formation of "adiabatic shear bands." The intensity of plastic flow in the bands is much greater than in the basic material, which leads to additional warm-up of the deformed region, its weakening, and as a consequence to its more active deformation in the band. The governing role of adiabatic shear in processes of high-velocity punching, formation of spalling, high-speed cutting, and stamping, was demonstrated in [1-4].

In order to study the nature of adiabatic shear and a credible solution of applied problems it is very important to consider the question of critical parameters for high-velocity loading leading to a change in deformation mechanism. In the known works on adiabatic shear there is no systematic study of this type, which is connected with the complexity of the experiments. For this purpose there are a number of procedures: radial disintegration of a tube under the action of explosive loading from the direction of the internal surface [2] and shock loading in shear [4]. In the present work a simple procedure is suggested making it possible to change the loading parameters over wide ranges.

Shown in Fig. 1 is the scheme for carrying out the experiment. The plate of test material is thrown by a smooth-bore gun or by means of an explosive charge (at velocities greater than 1100 m/sec) at a massive substrate. The angle of impact prescribes the amount of shear deformation to $\tan\gamma$. With prescribed deformation time the process may be controlled by changing the flight velocity of the thrown plate. To a first approximation the impact velocity v is proportional to the shear deformation rate. In view of the importance of this question, a series of special experiments was carried out for measuring by means of a pulsed x-ray emitter the dimensions of the transition zone with different impact velocities. In order to avoid welding by explosion, in some of the experiments a thin fluoroplastic or polyethylene film was placed on the impact surface, and no marked effect of the film on deformation within the volume of the thrown plate was noted. Impact velocity and angle were controlled by means of the standard procedure of charged needles.

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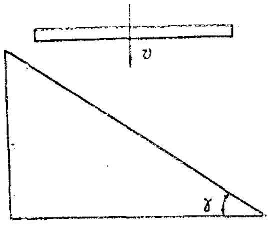

Fig. 1

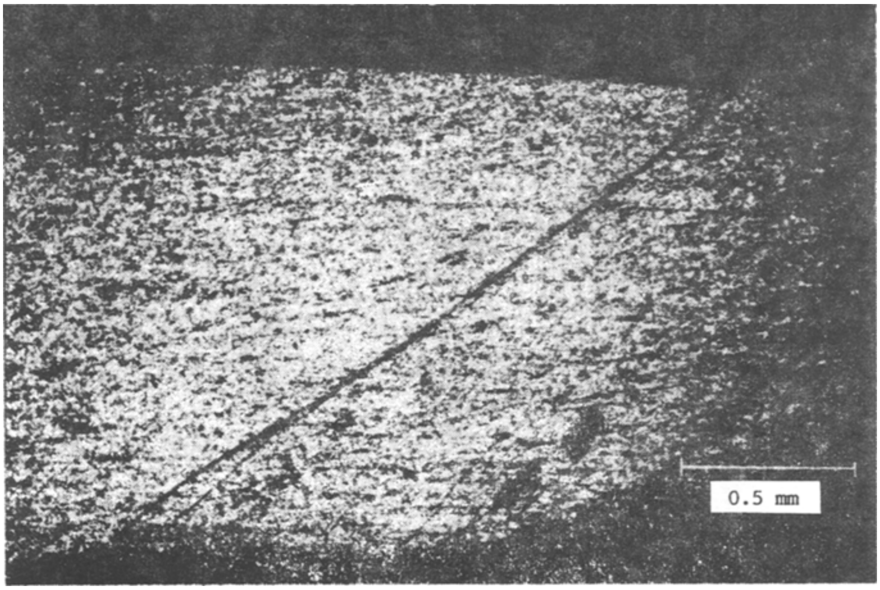

Fig. 2

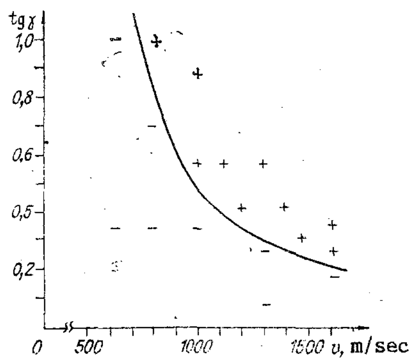

Fig. 3

A series of tests was carried out by this scheme on titanium VT-1-0 in the as-supplied condition (initial hardness HV = 180 kg/mm^2, grain size 0.02 mm) with a plate 2 mm thick. Deformed specimens were cut in the longitudinal direction in an electric-arc machine. The presence or absence of an adiabatic shear band was checked metallographically in polished and etched microsections. Shown in Fig. 2 is the structure of titanium with an adiabatic shear band after loading with parameters γ = 30°, v = 1000 m/sec. Broad, comparatively rare bands run right through the plate, and the amount of shear of the band reaches 0.3 mm. The angle at which the band runs normally corresponds to the calculated impact angle, and with large impact angles the picture is distorted by material flow along the impact surface. The distance between bands, and hardness in the matrix depends on the amount and rate of deformation. Currently a systematic study of these dependences is being carried out.

Presented in Fig. 3 are the first of the results obtained, i.e., critical impact parameters for development of adiabatic shear in titanium VT-1-0; the curve separates regions with presence and absence of an adiabatic shear band (experimental data are marked by plus and minus signs respectively). Thus, a changeover from uniform deformation with high velocity shear strain to adiabatic shear is governed by two loading parameters: the amount of deformation and impact velocity (deformation rate).

The existence of this dependence points to the following sequence of deformation development. In the first stage there is comparatively uniform development of plastic deformation throughout the volume. With an increase in strength there is an increase in defect density, and the distance of travel for mobile dislocations decreases. The changeover to the adiabatic shear stage occurs at a level of strengthening when intense development of shear along some band at considerable distances with surmounting of existing barriers requires less increase in flow stress than follows from extrapolation of the deformation of shear. Changes in microhardness indicate that with a prescribed amount of deformation, strengthening increases with an increase in impact velocity, then it emerges into saturation with the start of development of adiabatic shear.

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CONSIDERATION OF VISCOSITY DURING SUBSONIC PENETRATION OF A SOLID BODY INTO ISOTROPIC BARRIERS

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In solving the problem of the reaction of solids with isotropic barriers during their impact, one of the main questions is determination of the penetration resistance of the solid into the barrier. Currently in calculating this resistance as a basic phenomenological approach use is made of the hydrodynamic anomaly in accordance with which the penetration resistance in the plastic region is assumed to be equivalent to the resistance of an ideal liquid.

In domestic practice during determination of the force of resistance in the case of subsonic impact there has been widespread use of the so-called two-term equation of the Leningrad Physicotechnical Institute (LETI) suggested in [1] based on this analogy. According to this relationship force of resistance to penetration is written in the form

$$R = -F\left[H_d + k\frac{1}{2}\rho v^2\right], \quad (1)$$

where H_d is dynamic hardness determined by experiment with impact velocities $v \sim 10$ m/sec; v is local penetration velocity; ρ is barrier material density; k is shape coefficient for the body, assumed to equal 1.0 for a body with spherical head; F is body cross-sectional area. Similar relationships were derived in [2]. For supersonic impact velocities in working out penetration use is made of modifications of the Lavrent'ev—Neuman hydrodynamic theory [2-4].

At the same time, as has been established by experiment [5], the majority of ductile materials behave beyond the yield point as a ductile liquid. It was shown in [6] on the basis of numerical modelling of the penetration process for a deformed body into a barrier

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that the effect of viscous resistance, without force at the initial stage of penetration, will predominate in the final stage of deep penetration.

In view of this it is desirable to have an idea of the resistance of penetrating body taking account of Newtonian viscosity for the barrier material. It may be obtained by proceeding from the following basic assumptions.

1. The penetration process is quasisteady (transition processes are ignored).

2. Forces of penetration resistance are only distributed at the front surface of the body (a cavern forms behind the body).

3. Distribution of the force of resistance at the front surface of the body is the same as with uninterrupted flow around it during movement in a viscous liquid; deviations from this distribution in the vicinity of disruption lines of the barrier material with the surface of the penetrating body are ignored in view of the smallness of the contribution of the force of resistance in this region to the overall amount of resistance.

Proceeding from these assumptions, we take the structure of the expression for the total force of resistance

$$R = R_1 + R_2(\dot{v}) + R_3(v), \tag{2}$$

where R_1 is the static comonent of the resistance to penetration, depending on the shape of the penetrating body and the strength characteristics of the barrier material (hardness); R_2 is the inertial resistance component, depending on the adjoining mass of the body and its acceleration; R_3 is the dynamic comonent of resistance with quasistationary (steady) movement.

Furthermore, by analogy with an expression for the force of resistance on introducing a solid into soil [4], we assume that the dynamic component of resistance may be presented as

$$R_3(v) = bv + cv^2. \tag{3}$$

Expression (3) corresponds to retention of the first two terms of a series in the expansion of $R_3(v)$ into a Taylor series.

As a rule, values of coefficients b and c in expressions of type (3) are established by experiment. Besides this there is a real possibility of determining them on the basis of theoretical solutions. With this approach an experiment is only necessary in order to check the proposed dependences and it may be carried out in a much reduced volume.

Subsequently we shall limit ourselves to consideration of a body with a spherical head. In this case for the static component of the penetration resistance we write

$$R_1 = -FH_M, \tag{4}$$

where H_M is Meyer's hardness [7].

The inertial component of the resistance may be obtained if we use the Bussinesq solution [8, 9]. As is well known, according to the Bussinesq solution the resistance of a sphere of radius a moving forward with a prescribed velocity v(t) into a limitless region filled with viscous liquid is

$$R = -6\pi\mu a v\ (t) - \frac{2}{3}\pi a^3\rho\frac{dv}{dt} - 6\sqrt{\nu\pi}\,\rho a^2\left[\frac{v}{\sqrt{t}} + \int_0^t \frac{dv}{d\tau}\frac{d\tau}{\sqrt{t-\tau}}\right], \tag{5}$$

where μ is dynamic viscosity coefficient; $\nu = \mu/\rho$ is kinematic viscosity coefficient.

Since according to the original assumptions the penetration process is considered to be quasisteady, and the force of resistance of the front surface is the same as with uninterrupted flow around a body, from expression (5) for the inertial comopnent of resistance we have

$$R_2\left(\frac{dv}{dt}\right) = -F\frac{1}{3}\rho a\frac{dv}{dt}, \quad F = \pi a^2. \tag{6}$$

An expression also follows from relationship (5) for the linear component of dynamic resistance. However, since the dynamic component of resistance should be determined with an accuracy to squared components, the Bussinesq solution is inadequate. Therefore, in order to find the dynamic component of resistance use is made of the Ozeen solution [8].

It is well known [8] that axisymmetric flow of a stream of viscous liquid around a body is described, proceeding from the generalized Stokes' equations, by the potential of velocities ϕ and functions χ which satisfy the equations

$$\Delta\varphi = 0, \quad \Delta\chi - \frac{v}{\nu}\frac{\partial\chi}{\partial x} = 0,$$

where $\Delta = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial x^2}$ is Laplace operator; r is radius in a cylindrical coordinate system; x is coordinate along the running stream; v is stream velocity. At the body surface the "attachment" condition should be fulfilled $v_n = v_s = 0$ (v_n and v_s are normal and tangential components of velocity), and at infinity the condition for damping of perturbations introduced by the body into the stream $v_x = v$, $v_r = 0$ should be fulfilled.

In considering flow of a stream around a sphere it is natural to change over to dimensionless spherical coordinates

$$x = R_c a \cos\theta, \; r = R_c a \sin\theta$$

(a is sphere radius).

Keeping to the details of obtaining solutions which are given in detail in [8], it is noted that with an accuracy up to Re^2 ($Re = va/\nu$ is Reynolds number) the functions sought ϕ and χ may be presented (with $R_c \sim 1$) in the form

$$\varphi = \sum_{n=0}^{\infty} A_n \frac{P_n(\cos\theta)}{R_c^{n+1}}; \tag{7}$$

$$\chi \approx -v + B_0\left\{\frac{P_0(\cos\theta)}{R_c} - \frac{\mathrm{Re}}{2}[P_0(\cos\theta) - P_1(\cos\theta)] - \frac{1}{2}\left(\frac{\mathrm{Re}}{2}\right)^2 R_c\left[\frac{2}{3}P_2(\cos\theta) - 2P_1(\cos\theta) + \frac{4}{3}P_0(\cos\theta)\right]\right\} + \tag{8}$$

$$+ B_1\frac{1}{R_c}\left\{\frac{P_1(\cos\theta)}{R_c} + \frac{\mathrm{Re}}{2}\left[\frac{2}{3}P_2(\cos\theta) + \frac{1}{3}P_0(\cos\theta)\right]\right\} + B_2\frac{P_2(\cos\theta)}{R_c^3} + \ldots,$$

where $P_n(\ldots)$ are Legendre polynomials [10]; $P_0(\cos\theta) = 1$; $P_1(\cos\theta) = \cos\theta$; $P_2(\cos\theta) = 1/2[3\cos^2\theta - 1]$. Constants A_n and B_n are determined from the boundary conditions (with $R_c = 1$)

$$v_{R_c} = -\chi\cos\theta + \frac{1}{\mathrm{Re}}\frac{\partial\chi}{\partial R_c} + \frac{1}{a}\frac{\partial\varphi}{\partial R_c} = 0; \tag{9}$$

$$v_\theta = \chi\sin\theta + \frac{1}{\mathrm{Re}}\frac{\partial\chi}{\partial\theta} + \frac{1}{a}\frac{\partial\varphi}{\partial\theta} = 0. \tag{10}$$

Boundary conditions at infinity are satisfied automatically.

After substituting (7) and (8) in (9) and (10), and solving the set of equations for constants A_n and B_n, we obtain the following expressions:

$$A_0 = -\frac{3}{2}\frac{v\left[1 - \left(\frac{\mathrm{Re}}{2}\right)^2\right]}{\mathrm{Re}\left[1 - \frac{3}{8}\mathrm{Re}\right]}a \approx -\frac{3}{2}\frac{v}{\mathrm{Re}}\left[1 + \frac{3}{8}\mathrm{Re}\right]a, \tag{11}$$

$$A_1 = \frac{1}{2}\frac{v}{1 - \frac{3}{8}\mathrm{Re}}a \approx \frac{1}{2}va, \quad B_0 = \frac{3}{2}\frac{v}{1 - \frac{3}{8}\mathrm{Re}},$$

$$B_1 = -\frac{3}{4}\frac{v\,\mathrm{Re}}{1 - \frac{3}{8}\mathrm{Re}}, \quad \frac{A_2}{a} + \frac{1}{\mathrm{Re}}B_2 = \frac{1}{8}\frac{v\,\mathrm{Re}}{1 - \frac{3}{8}\mathrm{Re}}.$$

Constants A_2 and B_2 are only determined in their linear combination, although as will be seen subsequently, this situation does not affect expressions for the force of resistance with the degree of accuracy adopted.

As shown in [8], the principal vector for the force of resistance with flow of a ductile incompressible liquid around a body with a spherical head may be (taking account of the sign of velocity at infinity) presented in the form

$$R = \iint_S \left[-p_\infty \cos\theta - \rho v \frac{1}{a} \frac{\partial \varphi}{\partial R_c} \right] dS. \quad (12)$$

Here $p_\infty = 1/2\ \rho v^2$ is retardation pressure at infinity; S is the wetted surface of a streamlined body.

In the case of uninterrupted flow around a sphere, taking account of the idea of potential ϕ in the form of (7) and orthogonality conditions for the Legendre polynomials

$$\int_0^\pi P_n(\cos\theta) P_m(\cos\theta) \sin\theta d\theta = 0 \quad (m \neq n)$$

and for the force of resistance from (12) we have the equation

$$R = 2\pi a^2 \int_0^\pi \left[-\frac{1}{2}\rho v^2 \cos\theta + \frac{\rho v}{a} \sum_n (n+1) A_n P_n(\cos\theta) \right] \sin\theta d\theta$$
$$= 4\pi a^2 \rho v \frac{A_0}{a} = -6\pi\mu a v \left[1 + \frac{3}{8}\mathrm{Re} \right] = -\pi a^2 \left[6\frac{\mu v}{a} + \frac{9}{4}\rho v^2 \right], \quad (13)$$

which is an Ozeen equation.

When flow only proceeds over the front surface (up to the middle cross section) the force of resistance with the degree of approximation adopted

$$R_3(v) = 2\pi a^2 \int_0^{\pi/2} \left[-\frac{1}{2}\rho v^2 \cos\theta + \frac{\rho v}{a} \sum_n (n+1) A_n P_n(\cos\theta) \right] \sin\theta d\theta$$
$$= \pi a^2 \left[-\frac{1}{2}\rho v^2 + 2\frac{\rho v}{a}(A_0 + A_i) \right] = -\pi a^2 \left[3\frac{\mu v}{a} + \frac{5}{8}\rho v^2 \right]. \quad (14)$$

We now dwell on the limits of applicability of the suggested relationship for the dynamic comopnent of penetration resistance. As is well known [9], tests carried out by Gol'dshtein made it possible to establish a satisfactory (~15%) conformity of calculated and experimental data with flow around a sphere up to Re = 4. With greater Re deviation of calculated data from experimental results increases continuously. These deviations are explained by the fact that with quite high Re there is collapse of vortices from the rear surface of the sphere leading to phenomena of the autovibration type [9], and the flow picture does not correspond to that adopted in the Ozeen solution.

With penetration of a solid into a barrier whose material is considered as a viscous liquid, flow around the rear surface does not occur in accordance with the second assumption, and consequently vortices do not form at the rear surface. Therefore, it is possible with a considerable degree of certainty to confirm that use of this approach is permissible for much greater Re than with uninterrupted flow around a sphere.

Taking account of this last observation, from (2), (4), (6), and (14) for the total force of penetration resistance for a body with a spherical head it is possible to write

$$R = -\pi a^2 \left[H_M + 3\frac{\mu v}{a} + \frac{5}{8}\rho v^2 + \frac{1}{3} a\rho \frac{dv}{dt} \right]. \quad (15)$$

In deriving relationship (15) use was made of an assumption about complete engagement of the barrier material with surface of the penetrating body. In fact, it is possible that during penetration there will be partial sliding of the barrier material over the body surface. For this case it is possible to suggest the following modification of expression (15):

$$R = -\pi\alpha^2 \left[H_M + \beta\left(3\frac{\mu v}{a} + \frac{1}{8}\rho v^2 \right) + \frac{1}{2}\rho v^2 + \frac{1}{3} a\rho \frac{dv}{dt} \right],$$

where β is a coefficient taking account of engagement (β = 1 is complete engagement, β = 0 is absence of it) determined by experimentation.

By comparing (15) and (1) it can be seen that main difference of the suggested relationship from the Vitman–Stepanov equation is the fact that with low penetration velocities the resistance is proportional to the first power of velocity and the square of it (the effect of a term connected with weight is small in the majority of cases). With high penetration velocities, when the term proportional to the square of the velocity is important, both relationships approach each other.

As an example of using the suggested relationship we consider calculation of the depth of penetration at the stage of deep penetration. Let a solid with a spherical head of radius a and mass m after penetration to depth $x_0 > a$ at instant $t_0 = 0$ move in the barrier material with velocity v_0.

Assuming for simplicity that $\beta = 1$, and ignoring in accordance with the first assumption the nonstationary component of acceleration, in a coordinate system connected with the barrier we have

$$d/dt = \partial/\partial t + v\partial/\partial x \approx v\partial/\partial x,$$

$$\left(m + \frac{1}{3}\pi a^3\rho\right) v\frac{dv}{dx} = -\pi a^2\left[H_M + 3\frac{\mu v}{a} + \frac{5}{8}\rho v^2\right].$$

By introducing dimensionless variables $\mathrm{Re} = va/\nu = va\rho/\mu$, $\xi = x/a$ and dimensionless parameter $d_0 = H_M a^2\rho/\mu^2$, in order to calculate the depth of penetration we obtain the equation

$$d\xi = -\frac{k_m + 1}{3}\frac{\mathrm{Re}\, d(\mathrm{Re})}{d_0 + 3\,\mathrm{Re} + \frac{5}{8}\mathrm{Re}^2}. \tag{16}$$

Here $k_m = m/[(1/3)\pi\rho a^3]$ is mass coefficient of the penetrating body.

By integrating (16) for Re from $\mathrm{Re}_0 = v_0 a\rho/\mu$ to 0 and for ξ from $\xi_0 = x_0/a$ to ξ, and using tabulated ratios for the retardation path in the case of $d_0 < 18/5$, we find that

$$\Delta\xi = \xi - \xi_0 = \frac{4}{15}[k_m + 1]\left\{\ln\frac{d_0 + 3\,\mathrm{Re}_0 + \frac{5}{8}(\mathrm{Re}_0)^2}{d_0} - \frac{1}{\sqrt{1 - \frac{5}{18}d_0}}\ln\frac{\left(\frac{5}{18}\mathrm{Re}_0 + 1 - \sqrt{1 - \frac{5}{18}d_0}\right)\left(1 + \sqrt{1 - \frac{5}{18}d_0}\right)}{\left(\frac{5}{18}\mathrm{Re}_0 + 1 + \sqrt{1 - \frac{5}{18}d_0}\right)\left(1 - \sqrt{1 - \frac{5}{18}d_0}\right)}\right\}.$$

With $d_0 > 18/5$ the expression for the retardation path is determined in a similar way.

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