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DETERMINATION OF THE CRITICAL JET VELOCITY DURING THE PENETRATION INTO THE HOMOGENOUS STEEL OBSTACLE

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Abstract. *The procedure of the experimental determination of the critical jet velocity during the penetration into the homogenous obstacle is given in the paper. The procedure is based on the use of the logic analyzer and special captures to record the discrete data of the curve - the penetration length depending on time. A polynomial form of that mathematically fitted functional curve gives the possibility to determine the critical jet velocity. Also, the results of the experimental determination of the critical velocity of the copper shaped charge jet during the penetration into the homogenous steel obstacle are shown. The use of these results, obtained by the given procedure, in the program code HYDRO for a numerical simulation of the shaped charge function and jet penetration, make it possible to calculate more accurately the jet penetrability in the obstacles of different mechanical properties.*

Labels and abbreviations

A - Coefficient in the equation of Tait
a_0 - Coefficient of polynomial equation
a_1 - Coefficient of polynomial equation
a_3 - Coefficient of polynomial equation
a_4 - Coefficient of polynomial equation
Cu - Copper
l - Length of jet penetration
n - Exponent in the equation of Tait
p_x - Pressure on the contact surface
p_{cr} - Critical (stagnation) pressure
r - Coefficient of correlation
r_m - Tensile strength of material
t - Time
t_{cr} - Critical (total) penetration time
$u = v_j$ - Jet velocity
v_0 - Specific volume of material
v_x - Specific volume of material under high pressures
v_{jcr} - Critical (stagnant) jet velocity
α - Compressibility coefficient of material
α_m - Compressibility coefficient of the jet
α_p - Compressibility coefficient of the obstacle
ρ_0 - Initial density of material
ρ_x - Density of material under high pressures
ρ_{mx} - Density of jet material under high pressures
ρ_{m0} - Initial jet density
ρ_{px} - Density of the obstacle material under high pressures
ρ_{p0} - Initial obstacle density
HB - Brinell Hardness

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u_x	- Penetration velocity without the influence of obstacle mechanical properties	*HRC*	- Rockwell Hardness
		HP-4	- Label of the obstacle steel plates quality
u_{x0}	- Penetration velocity with the influence of obstacle mechanical properties	*GAO*	- Generator for electrical activation

During the impact, i.e. during the jet penetration into the obstacle, the shock wave is generated in the obstacle material and jet material. For the determination of the penetration velocity and pressure onto the contact surface (collision surface) of the jet and the obstacle during the penetration process, a well-known equation of the shock wave theory for an ideal case [1,2,3] is used:

$$u_x = u - \sqrt{p_x\left(\frac{1}{\rho_{m0}} - \frac{1}{\rho_{mx}}\right)} = \sqrt{p_x\left(\frac{1}{\rho_{p0}} - \frac{1}{\rho_{px}}\right)} \tag{1}$$

In order to satisfy the calculation accuracy it is shown that the material compressibility for the pressure values over 1.0E^{+9}Pa may not be ignored. Supposing $v_x=v_0(1-\alpha)$ and in consideration of the compressibility of the jet material and the obstacle material, after some transformation of equation (1), the equations for the determination of the penetration velocity and the contact pressure are given in the form:

$$u_x = \frac{u}{1+\sqrt{\dfrac{\alpha_m}{\alpha_p}\dfrac{\rho_{p0}}{\rho_{m0}}}} \tag{2}$$

$$p_x = \frac{\rho_{m0}u^2}{\left(\sqrt{\alpha_m} + \sqrt{\alpha_p \dfrac{\rho_{m0}}{\rho_{p0}}}\right)^2} \tag{3}$$

The equation of state for material that with sufficient accuracy defines the relation between the pressure and the material density is known as equation of Tait (law of Tait):

$$p_x = A\left[\left(\frac{\rho_x}{\rho_0}\right)^n - 1\right] \tag{4}$$

The coefficient of compressibility α defined by the ratio $\alpha=\rho_x/\rho_0$ and equation (4) lead to the expression:

$$\alpha = 1 - \frac{1}{\left(1+\dfrac{p_x}{A}\right)^{\frac{1}{n}}} \tag{5}$$

The final equations for the determination of the penetration velocity and the contact pressure that consider the material compressibility [1] are given by the substitution of expression (5) in equations (2) and (3).

Under real conditions during the obstacle penetration, the real penetration velocity is lower due to the mechanical resistance of the obstacle material r_{mp}, so-called *internal pressure in the obstacle material* in the impact theory and labeled as a p_{cr}. Finally, the equation for the determination of the real penetration velocity u_{x0} is:

$$u_{x0} = u\sqrt{\frac{1}{\left(1+\sqrt{\frac{\alpha_m}{\alpha_p}\frac{\rho_{p0}}{\rho_{m0}}}\right)^2} - \frac{p_{cr}}{\rho_{p0}}\frac{\alpha_p}{u^2}} \tag{6}$$

The end of the jet penetration, i.e. the zero penetration velocity (u_{x0} =0) appears at the instant when the contact pressure decreases to the value of the internal pressure in material ($p_x = p_{cr}$). It occurs at the critical, i.e. stagnation value of the jet velocity $u = u_{cr} = v_{jcr}$.

The real jet velocity near the value of which the obstacle penetration rapidly begins to stop, i.e. the critical or stagnation jet velocity $u = u_{cr} = v_{jcr}$, is obtained on the basis of equation (2) for $u_x = u_{\text{exp}}$:

$$u_{cr} = v_{jcr} = u_{\text{exp}}\left(1+\sqrt{\frac{\alpha_m}{\alpha_p}\frac{\rho_{p0}}{\rho_{m0}}}\right) \tag{7}$$

The value of the penetration velocity $u_x = u_{\text{exp}}$ is determined experimentally at the stagnation point nearly prior to the instantaneous stopping of the penetration. It is necessary to emphasize the rapid transition process of the penetration stagnation, when $u_x = u_{\text{exp}}$ decreases at range value $u_x = 0$, corresponds simultaneously to the very small (negligible) relative change of the jet velocity.

On the basis of the known values of the stagnation jet velocity u_{cr} for given materials of the jet and the obstacle, the critical value of the contact pressure p_x ($p_x = p_{cr}$) that is equal to the mechanical resistance of the material under dynamic conditions, is calculated by the following equation:

$$p_{cr} = \frac{\rho_{m0} u_{cr}^2}{\left(\sqrt{1-\frac{1}{\left(1+\frac{p_{cr}}{A_m}\right)^{\frac{1}{n}}}} + \sqrt{\frac{\rho_{m0}}{\rho_{p0}}\left(1-\frac{1}{\left(1+\frac{p_{cr}}{A_p}\right)^{\frac{1}{n}}}\right)}\right)^2} \tag{8}$$

EXPERIMENT

The experimental determination of the jet penetration velocity and the contact pressure during the penetration and its critical values at the end of the penetration process is very complicated and hard because of the nature of the phenomenon accompanied by abnormally high values of the pressure (million bars of range) and velocities (10 thousands m/s of range).

Fig. 1. The experimental determination of the jet penetration velocity (sequential analysis)

The jet penetration velocities, like the stagnation velocity of the jet penetration, have been determined most frequently by the method of the continual impulse radiography or the electro-magnetic method (in special cases only) and by the method of sequential analysis [2,4,5]. On the basis of the values of the jet velocity penetration obtained experimentally and equations (7) and (8) it is possible to calculate the value of the jet velocity and the contact pressure at the stagnation moment of the penetration.

The experimental determination of the jet penetration velocity (Figure 1.) is based on the measuring of the time (sequences), needed by the shaped charge jet to pass a priory defined distance (depth of the layers of the steel obstacle) [2,5,6,7].

For measuring (recording) the characteristic temporary intervals of the jet penetration into the obstacle, the method of sequential analysis of the timing phases of process by the logic multi-channel analyzer is used. The scheme of the experimental measuring installations, necessary for the method of sequential analysis, is shown in Figure. 2.

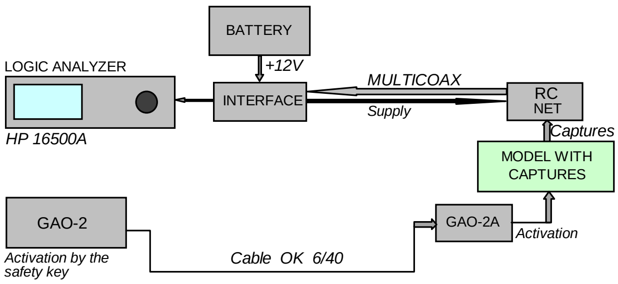

Fig. 2. The method of the sequential analysis of the process (set-up scheme)

For experimental measuring, the 40-channel logic analyzer HP-16500A type and the digital oscilloscope NICOLET-4094B type are used as control instruments. Besides these mentioned complex and very precise electronic measuring instruments, the special electronic equipment is used. The equipment developed by the MTI and intended for the same research consists of: device for an activation by the safety key (GAO-2), high-voltage transformer with possibilities for the instantaneous electric discharge (GAO-2A) and applied for the shaped charge activation, interface with a filter for the noise suppression in electrical signals, etc. Naturally, there is an auxiliary measuring equipment: source of the electricity (battery +12V), multi-coaxial cables, foliar captures of electric signals, etc.

The use of the mentioned method in the experimental measuring of the jet penetration of 60 mm shaped charge into armor steel obstacle of *HP*-4 quality (r_m= min. 9300E^{+5} Pa, *HB*=min. 280) made it possible to record a series of experimental data – the penetration length depending on time (Figure 3). Each point in the integral diagram of the total penetration time has been calculated on the basis of the average value of the jet penetration time during the layers penetration of 20 mm thickness, determined on the specimen of 6 single experiments. The stagnation of the jet penetration was registered after t_{cr}=112.5μs of the total penetration time. Simultaneously, the length l=260 mm of the total penetration was realized.

A polynomial form of the functional relation of the penetration length depending on time (Figure 4), made by the mathematically fitting of the experimental data and shown in Figure 3, is:

$$l(t) = a_3 t^3 + a_2 t^2 + a_1 t + a_0 \tag{9}$$

In equation (9) the values of the coefficients are a_0 = +2.1517, a_1 = +3.7242, a_2 = –0.020, a_3 = +4.8E–5, and the coefficient of correlation is r^2 = 0,9999.

The first derivation of equation (9) gives the function of the jet penetration velocity depending on time in the form of the quadratic polynomial equation, graphically shown in Figure 4 as well:

$$u_{x0} = \frac{dl(t)}{dt} = 3a_3 t^2 + 2a_2 t + a_1 \tag{10}$$

The value of the critical, i.e. the stagnation jet penetration velocity u_{x0} = 1046.7m/s has been calculated by the substitution $t = t_{cr}$= 112.5μs of the total (critical) time of the penetration in equation (10).

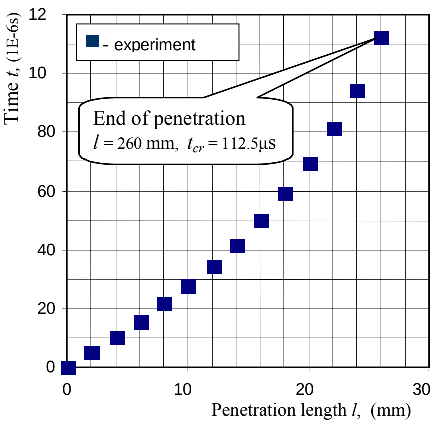

Fig. 3. The penetration length depending on time (experimental data)

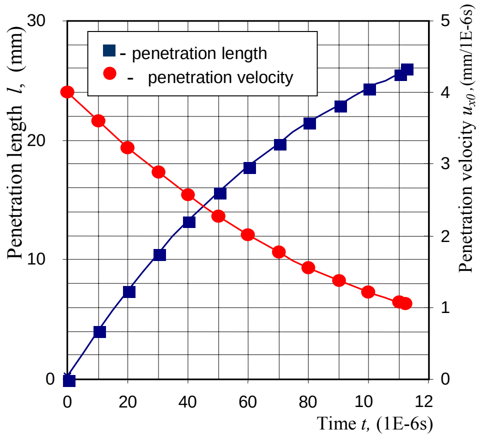

Fig. 4. The jet penetration length and velocity depending on time

This value of the critical jet penetration velocity with equations (7) and (8), respectively makes it possible to determine critical, i.e. the stagnation jet velocity v_{jcr} = 2225m/s and the critical value of the contact pressure p_{cr} = 527483E^{+5}Pa. Nonlinear equation (8) has been resolved by the numerical iterative method.

The relevant experimental data and some literature data realized practically in the similar experimental conditions are given in Table 1. On the basis of these data the quality of the given results can be accurately estimated as well as the validity of the proposed method for the determination of the critical jet velocity.

Table 1. Data review concerning the experimental determination of the critical jet velocity

	Type [-]	Density ρ [kg/m^3]	Coeff. A [MPa]	Coeff. n [-]	Resistance r_m [MPa]	Hardness HB [-]	Critical velocity v_{jcr} [m/s]	Comment
Jet Obstacle	Cu Steel	8930 7850	0.235 0.450	4.0 4.0	min. 230 min. 930	80-90 280-340	2225	Experiment
Jet Obstacle	Steel Steel	7800 7850	0.450 0.450	4.0 4.0	min. 400 min. 930	100-110 HRC=55	2200	Literature: [1]
Jet Obstacle	Cu Steel	8960 7850	0.235 0.450	4.0 4.0	min. 230 min. 930	HRC=30 min. 300	2200-2300	Literature: [8,9]
Jet Obstacle	Cu Steel	8930 7850	0.235 0.450	4.0 4.0	min. 230 min. 950	min. 80 min. 300	> 2000	Literature: [10]

The comparative analysis of the results from Table 1 shows that the critical values, i.e. the stagnation values of the jet velocities depend on the type and the mechanical properties of the jet material and the obstacle material. Also, it shows that the suggested method has possibility to record with sufficient accuracy all variations of the stagnation velocity range, for example, in the case of varying only mechanical properties of the steel obstacle (variation of the mechanical resistance and hardness) while all other experimental conditions stay unchanged.

Finally, it is necessary to emphasize that the error of the experiment measurement of the jet penetration velocity is less than 0.1%, and at the same time the numerical accuracy of the calculation of the stagnation jet velocity and the contact pressure is realized with an error less than 1.0E^{-4}. From the point of view of modern engineering practical work in the filed of construction of shaped charge projectiles and evaluation of terminal ballistics effects it is absolutely suitable.

CONCLUSION

The shaped charge is one special explosive device that has been used in the military and civil industry for different purposes, for example: penetrating, cutting, forming, welding, etc. The process of the shaped charge jet penetration into the homogenous obstacle, generally, like other phenomena of the penetration, belongs to the class of nonlinear mechanics problems, and it can be described very successfully by equations of the fluid mechanics in the field of the shock wave theory. It is possible because of the enormously high values of the velocities, pressures and temperatures that follow this process when the penetrator and obstacle materials behavior is similar to the fluid behavior.

It is shown that the displayed procedure of the theoretical and experimental determination of the critical jet velocity during the penetration into the homogenous obstacle based on the use of the logic analyzer and special captures makes it possible to evaluate accurately this parameter. The comparative analysis of reference data has confirmed the validity of this method in the experimental determination of the critical velocity of the copper shaped charge jet during the penetration into the homogenous steel obstacle. Also, the use of these results in the program code HYDRO for one numerical simulation of the shaped charge function and jet penetration, makes it possible to calculate more accurately the contact pressure and the jet penetrability in the obstacles with different mechanical properties.

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ODREĐIVANJE KRITIČNE BRZINE MLAZA PRI PRODIRANJU KROZ HOMOGENU ČELIČNU PREPREKU

Ugrčić Marinko

Kumulativno punjenje predstavlja specijalni eksplozivni sklop koja se koristi u vojnoj i civilnoj industriji za različite namene, naprimer: probijanje, sečenje, oblikovanje, spajanje, itd. Proces prodiranja kumulativnog mlaza kroz homogenu prepreku, generalno, kao i ostali fenomeni probijanja, pripada klasi problema nelinearne mehanike, a može se veoma kvalitetno opisati jednačinama mehanike fluida. To je moguće zbog enormno visokih vrednosti brzina, pritisaka i temperature koji prate ovaj proces, pri čemu je ponašanje materijala penetratora i prepreke jednako ponašanju fluida.

Numeričko rešavanje i testiranje programa procesa prodiranja, pored savremenog hardvera i softvera, zahtevaju poznavanje određenih grupa podataka kao što su koeficijenti jednačina stanja, mehaničke i dinamičke karakteristike materijala penetratora i prepreke i kinematskih parametara

procesa. U cilju testiranja programa, jedan od veoma važnih parametra je kritična brzina penetratora, tj. brzina koja karakteriše kraj procesa prodiranja. Takođe, da bi se ocenila probojnost kumulativnog mlaza potrebno je odrediti što je moguće tačnije kritičnu brzinu mlaza.

U radu je izložena metoda eksperimentalnog određivanja kritične brzine mlaza pri prodiranju kroz homogenu prepreku. Metoda je zasnovana na primeni logičkog analizatora i specijalnih davača koji se koriste za registrovanje diskretnih podataka krive - dužina probijanja u zavisnosti od vremena. Konačno, ovako dobijena matematički fitovana kriva polinomijalnog oblika omogućuje određivanje kritične brzine mlaza.

U radu su, takođe, prikazani rezultati eksperimentalnog određivanja kritične brzine mlaza formiranog dejstvom kumulativnog punjenja sa bakarnom oblogom pri prodiranju kroz homogenu čeličnu prepreku. Korišćenje ovih rezultata, dobijenih izloženom metodom, u programu HYDRO za numeričku simulaciju funkcije kumulativnog punjenja i penetracije mlaza, omogućava tačnije određivanje probojnosti kumulativnog mlaza na preprekama različitih mehaničkih karakteristika.