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THE APPLICATION OF THE CYLINDER TEST TO DETERMINE THE ENERGY CHARACTERISTICS OF INDUSTRIAL EXPLOSIVES

ZASTOSOWANIE TESTU CYLINDRYCZNEGO DO WYZNACZANIA ENERGEYCZNYCH CHARAKTERYSTYK GÓRNICZYCH MATERIAŁÓW WYBUCHOWYCH

The work attempts to apply results produced by the so-called "cylinder test" for the estimation of some energy characteristics of industrial explosives. Representative explosives as used in commercial mining containing ammonium nitrate, trinitrotoluene and aluminium powder formed the subject of the research. For each explosive, a cylinder test was conducted and its results were then used to determine the detonation energy and the acceleration capability of the products of detonation. It was also shown that the cylinder test results enable the expansion work of the gaseous detonation products to be calculated.

Key words: commercial explosives, performance of explosives, testing methods

Praca ekspansji produktów detonacji jest jednym z podstawowych parametrów materiałów wybuchowych i charakteryzuje ona efektywność zamiany uwalnianej energii chemicznej na pracę mechaniczną, czyli jest miarą zdolności materiału wybuchowego do wykonania pracy. Energia odpowiadająca teoretycznej maksymalnej pracy ekspansji, nazywana energią detonacji, powinna być zbliżona do ciepła detonacji. Z kolei zdolność miotająca produktów detonacji charakteryzuje ilość energii chemicznej zamienianej na energię kinetyczną miotanych ciał. Można ją opisać za pomocą tzw. energii Gurneya lub prędkości Gurneya. Obserwacja procesu napędzania metalowej rurki przez produkty detonacji ładunku materiału wybuchowego umieszczonego wewnątrz niej może dostarczyć informacji umożliwiających wyznaczenie tych charakterystyk. Próba taka nazywana jest testem cylindrycznym. Napędzanie metalowej otoczki może być śledzone za pomocą metod pomiaru szybkozmiennych procesów, takich jak: fotografia smugowa, interferometria laserowa czy impulsowa fotografia rentgenowska.

W pracy podjęto próbę wykorzystania wyników testu cylindrycznego do oszacowania energetycznych charakterystyk górniczych materiałów wybuchowych. Przedmiotem badań były mieszaniny saletry amonowej z trotylem lub proszkiem glinowym (tabl. 1). Proces napędzania miedzianej rurki produktami detonacji rejestrowano techniką rentgenografii impulsowej (rys. 1). Układ do testu cylindrycznego składał się z miedzianej rurki elaborowanej badanymi mieszaninami wybuchowymi o zbli-

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żonej gęstości. Zastosowane w układzie czujniki zwarciowe umożliwiały pomiar prędkości detonacji (rys. 2). Zdjęcie rentgenowskie rozpęczanej rurki (rys. 3) poddawano obróbce komputerowej i otrzymywano zależność położenia zewnętrznej ścianki rurki od współrzędnej osiowej (rys. 4). Zależność ta i zmierzona prędkość detonacji były wynikami testu cylindrycznego.

Na podstawie uzyskanych wyników określono w pierwszej kolejności zdolność miotającą produktów detonacji badanych materiałów. Parametr ten wyrażono za pomocą energii Gurneya (1), która jest sumą energii kinetycznej miotanego ciała i podążających za nim produktów detonacji. Prędkość rurki miedzianej określano na podstawie jej profilu wykorzystując własną, oryginalną metodę. Obliczoną energię Gurneya przedstawiono w funkcji względnej objętości produktów detonacji (rys. 5). Dzięki temu możliwe było badanie zmiany energii Gurneya w trakcie rozpęczania rurki. Wykazano również, że wartość energii Gurneya określona dla 9-krotnego wzrostu objętości rurki jest zbliżona do wielkości energii zamienianej na pracę ekspansji produktów detonacji w górotworze. Może być zatem wykorzystana do oszacowania efektywnej pracy wykonanej przez produkty detonacji materiału wybuchowego umieszczonego w skale.

Wyznaczone zależności prędkości rurki od jej objętości wykorzystano również do oszacowania energii detonacji badanego materiału wybuchowego. Energię detonacji (7) zdefiniowano jako pracę wykonaną przez produkty detonacji w trakcie ich izentropowego rozprężania od objętości w fali detonacyjnej (punkt Chapmana-Jougueta) do objętości nieskończonej. Do jej określenia wykorzystano związek między energią detonacji i energią kinetyczną miotanej rurki dla objętości produktów detonacji dążącej do nieskończoności (8). W celu wyznaczenia wartości energii kinetycznej, kwadrat prędkości rurki przedstawiono w funkcji odwrotności objętości produktów detonacji (rys. 6).

Analizując otrzymane wyniki dla badanych materiałów wybuchowych (tabl. 2) stwierdzono, że mieszaniny trotylu i saletry amonowej z glinem charakteryzują się wyższymi wartościami energii Gumeya niż mieszaniny bez glinu. Zastąpienie 10% trotylu proszkiem glinowym obniża co prawda o około 200 m/s prędkość detonacji (tabl. 1), ale jednocześnie podwyższa zdolność miotającą produktów detonacji oraz energię detonacji o około 10%. Zmiana stopnia rozdrobnienia proszku glinowego nie wpływa znacząco ani na parametry detonacyjne, ani na charakterystyki energetyczne badanych materiałów. Natomiast zastosowanie subtelniej rozdrobnionego trotylu do sporządzania mieszanin jest ze wszech miar wskazane, jako że podwyższa to zdecydowanie zarówno prędkość i ciśnienie detonacji, jak i zdolność miotającą oraz energię detonacji.

Wyniki testu cylindrycznego oraz rezultaty modelowania numerycznego umożliwiły wyznaczenie adiabaty Poissona (10) oraz izentropy JWL (Jones, Wilkins, Lee — (12)) dla produktów detonacji badanych mieszanin wybuchowych (tabl. 3 i 4). Dla przykładowej mieszaniny trotylu i saletry amonowej porównano izentropę Poissona z izentropą JWL, przedstawiając je w postaci wykresów zależności ciśnienia od objętości produktów detonacji (rys. 8). Stwierdzono, że odpowiadające tym izentropom krzywe rozbiegają się zdecydowanie już przy trzykrotnym wzroście objętości produktów detonacji. Oznacza to, że postać równania izentropy produktów może mieć istotne znaczenie przy oszacowywaniu pracy ekspansji.

Wyznaczone równania stanu wykorzystano do określenia zależności teoretycznej pracy ekspansji (9) od stopnia rozprężenia produktów detonacji (rys. 7 i 9). Oszacowano pracę ekspansji dla 10, 15 i 20-krotnego wzrostu objętości produktów i wykorzystano ją do oceny efektywnej zdolności do wykonania pracy odpowiednio w skałach o dużej, średniej i małej zwięzłości. Z analizy rezultatów otrzymanych dla przypadku, gdy właściwości fizyczne produktów detonacji badanych materiałów wybuchowych opisywano równaniem stanu JWL wynika, że do momentu spękania skał o dużej zwięzłości praca wykonana przez produkty detonacji wynosi od 58 do 60% całkowitej energii detonacji, zaś w przypadku skał o małej zwięzłości od 63 do 65% tej energii (rys. 9). Rezultaty te dobrze korelują z danymi literaturowymi, z których wynika, że w przybliżeniu tylko 50–70% energii detonacji wykorzystywana jest do niszczenia skał. Przy założeniu, że izentropa JWL stosunkowo dokładnie przybliża rzeczywiste właściwości produktów detonacji wykazano, że opisując rozprężające się produkty adiabatą Poissona popełnia się błąd rzędu 10% przy szacowaniu ich efektywnej pracy ekspansji w górotworze (dla v/v_0 ok. 10–20 na rys. 7 i 9). Zdecydowanie większy błąd popełnia się natomiast przy szacowaniu pracy produktów rozprężających się do dużych objętości, na przykład w wodzie lub powietrzu (aż do 30% dla $v/v_0 = 500$ — rys. 7 i 9).

Wyniki pracy wskazują, że test cylindryczny może być z powodzeniem zastosowany do ilościowej oceny energetycznych charakterystyk górniczych materiałów wybuchowych. Rezultaty rentgenograficznej rejestracji procesu napędzania rurek miedzianych umożliwiają w stosunkowo prosty sposób oszacowanie zdolności miotających i energii detonacji materiału wybuchowego. Połączone z wynikami modelowania numerycznego pozwalają natomiast wyznaczyć równanie stanu produktów detonacji i oszacować efektywną pracę ekspansji gazowych produktów detonacji.

Słowa kluczowe: górnicze materiały wybuchowe, charakterystyki detonacyjne i wybuchowe, metody badań

1. Introduction

The basic energy characteristics of explosives comprise their heat, or energy of detonation, their acceleration ability and the expansion work of the products of detonation.

The heat of detonation is the heat of decomposition of the explosive into the detonation products, the chemical equilibrium of which is assumed to occur at the Chapman-Jouguet (CJ) point. It is assumed that the heat of decomposition, q, is equal to the heat released during formation of the CJ detonation products from the explosive under standard conditions (i.e., at a temperature of 298.15 K and a pressure of 1 atm). The heat of detonation is usually measured in a bomb calorimeter for charges confined in an envelope (Ornellas 1982). This envelope is made of inert material, which cools the detonation products during their expansion. Inert gas at high pressure can perform a similar role as a solid envelope (Cudziło et al. 1998). However, the calorimetric heat of reaction usually differs from the heat of detonation, because the composition of the detonation products may change during the expansion of the products. Moreover, the transfer of heat to a water jacket in the calorimetric system causes a condensation of water from the products. For this reason computer programmes, for example TIGER (Crawford 1986), CHEETAH (Fried 1996), are often used to determine the detonation products at the CJ point and to estimate the heat of detonation.

The acceleration capacity of detonation products is expressed by the so-called "Gurney" energy or "Gurney" velocity. *The Gurney energy* is the final kinetic energy of a driven metal envelope and expanding detonation products per unit mass of the explosive. Because the confining metals rupture at different degrees of expansion, the Gurney energy must be determined for a chosen expansion of detonation products. *The Gurney velocity* is the velocity corresponding to the Gurney energy (the square root of the Gurney energy multiplied by 2).

The expansion work of detonation products is the parameter of explosives, which characterises the degree of conversion of the chemical energy into the mechanical work, i.e., the expansion work determines the capacity of explosive to do work. The maximal theoretical adiabatic expansion work is sometimes termed *the detonation energy*. It should be close to the heat of detonation. But in reality, the detonation energy and the detonation heat differ from each other because a part of the chemical energy remains in the detonation products as kinetic or potential energy. Therefore *the effective expansion*

work of detonation products is determined experimentally by different methods, for example, the Trauzl test in a lead block, the ballistic mortar test, the underwater explosion test, the cylinder test. In the latter two cases, the energy transferred to the surroundings in successive stages of the expansion process can be determined.

The results of the expansion of a metal tube caused by the detonation products of an explosive charge placed within it can provide considerable information concerning the amount of chemical energy released from the explosive and the extent of its transfer to the surroundings. Such a test is called the cylinder test (CT). The quickly changing processes associated with the expansion of the tube is monitored by precise methods of measurement such as streak photography (Kury et al. 1965; Bjarnholt 1976), laser interferometry (Lee et al. 1985), or impulse X-ray photography (Cudziło, Trzciński 1997; Cudziło et al. 1997). Some methods enabling an application of the expanding tube records for determination of the acceleration capacity, the expansion work and the detonation energy of high explosives, and the equation of state of detonation products were proposed and verified by Trębiński, Trzciński (1999) and Trzciński (2000). In the present paper it is shown that the cylinder test results can also be successfully used to obtain the quantitative energetic parameters of non-ideal heterogeneous explosives to which group most industrial explosives belong.

Mixtures of ammonium nitrate with trinitrotoluene and aluminium powder were examined. The CT results in the form of X-ray photographs of the expanding copper tubes formed an experimental basis for the estimation of the detonation energy and the proportion of it converted to mechanical energy. Furthermore, equations for the state of the detonation products were determined and used to find the dependence of their theoretical expansion work on their volume expansion ratio (their relative volume). Finally, the blasting performance (the ability to break rock) of the explosives used in hard and weak rock materials was assessed.

2. Experimental details

The explosives tested were mixtures containing ammonium nitrate (AN), trinitrotoluene (TNT) and aluminium powder (Al). To prepare them, commercial grade ingredients were used: crystalline AN with particle sizes below 0.8 mm, ground TNT-1 (particle sizes less than 0.8 mm) or flaked TNT-2 (sieve fraction 1.2×2.5 mm) and paint grade aluminium Al-1 (flakes below 0.075 mm in lateral face dimensions) or powdered aluminium Al-2 (particle sizes less than 0.3 mm). Symbols and compositions of the mixtures tested, as well as their densities and detonation velocities are given in Table 1.

To record the copper tube responding to the detonation products, a SCANDIFLASH X-ray set was used. A scheme of the experimental rig is shown in Fig. 1.

The copper tube filled with the explosive being tested was placed at a distance of 2.7 m from the X-ray source and 0.5 m from the film. The charge was fixed vertically and perpendicularly to the line connecting the X-ray source with the film. The copper tubes were 250 mm in length. Their bore and wall thickness were 25 mm and 2.5 mm,

TABLE 1

Characteristics of the explosives tested

TABLICA 1

Charakterystyki badanych materiałów wybuchowych

Symbol	Composition [%]					Density, ρ_0 [kg/m^3]	Detonation velocity, D [m/s]
	AN	TNT-1	TNT-2	Al-1	Al-2		
AN/TNT-1	80	20	—	—	—	1 010	4 110
AN/TNT-2	80	—	20	—	—	1 030	3 710
AN/TNT/Al-1	80	10	—	10	—	1 000	3 900
AN/TNT/Al-2	80	10	—	—	10	1 010	3 880
AN/Al-1	90	—	—	10	—	1 000	3 540
AN/Al-2	90	—	—	—	10	1 000	3 360

respectively. The sensor triggering the X-ray pulse was placed at a distance of 20 mm from the end of the charge. This enabled the expansion process of the detonation products to be observed for approximately 40 μs starting from the moment when detonation wave reached the charge section including sensor 4. The scheme of the charge used in cylinder tests is presented in Fig. 2.

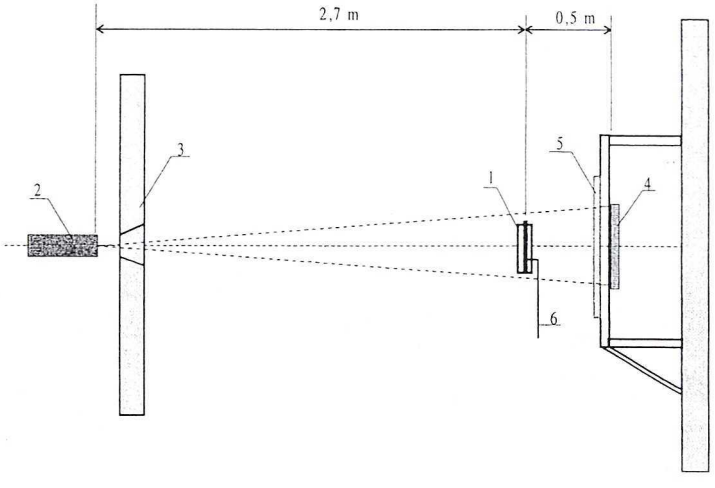

Fig. 1. Experimental set-up
1 — copper tube with explosive charge, 2 — X-ray source, 3 — source shield, 4 — X-ray film, 5 — film shield, 6 — sensor triggering X-ray set

Rys. 1. Schemat układu eksperymentalnego
1 — rurka miedziana z ładunkiem materiału wybuchowego, 2 — źródło promieniowania X (promiennik), 3 — osłona promiennika, 4 — kaseta z filmem, 5 — osłona kasety, 6 — czujnik wyzwalający promiennik

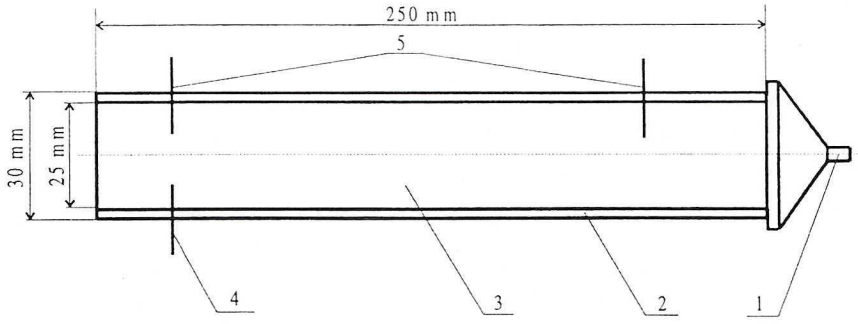

Fig. 2. Diagram of the charge used in the cylinder test
1 — fuse and plane detonation wave generator, 2 — copper tube, 3 — explosive tested, 4 — sensor triggering X-ray pulse, 5 — sensors to measure detonation velocity

Rys. 2. Schemat układu do testu cylindrycznego
1 — zapalnik i generator fali płaskiej, 2 — rurka miedziana, 3 — ładunek badanego materiału wybuchowego, 4 — czujnik wyzwalający promiennik, 5 — czujniki do pomiaru prędkości detonacji

A typical radiograph of the copper tube under the effect of detonation products is shown in Fig. 3. From the photograph, the dependence of the external surface radius of the tube on the axial co-ordinate was determined using graphical computer programs (Fig. 4). This dependence, along with the detonation velocities (Table 1), constituted the results of the CT and they formed the basis for determining the performance parameters of the explosives mentioned earlier (Sections 3 and 4).

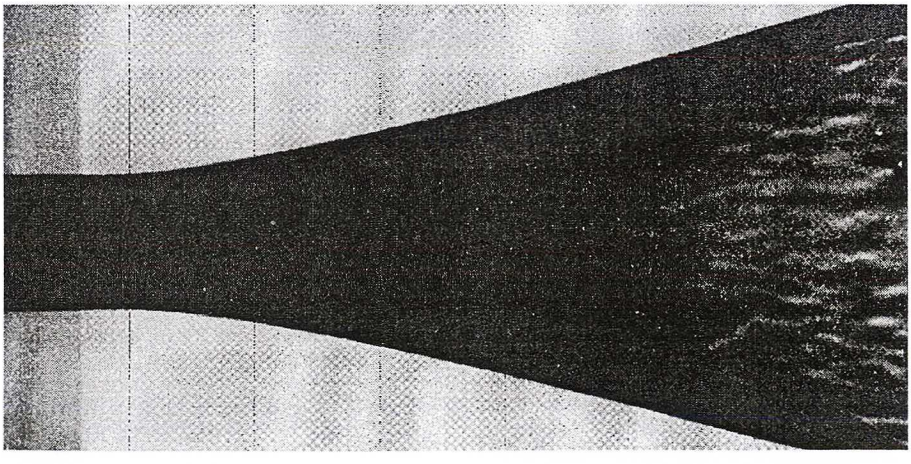

Fig. 3. Radiograph of the copper tube driven by detonation products of AN/Al-2

Rys. 3. Rentgenogram rurki miedzianej napędzanej produktami detonacji mieszaniny SA/Al-2

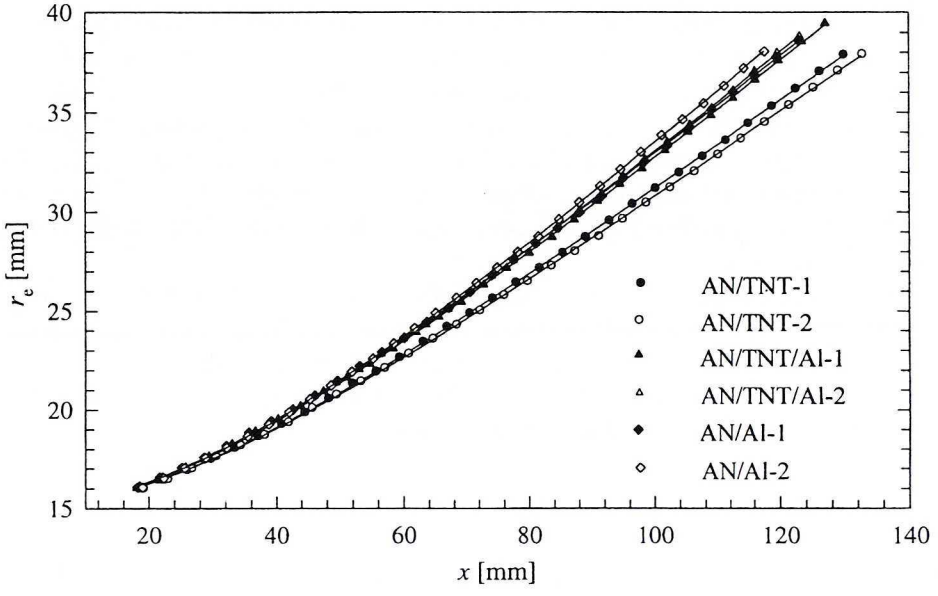

Fig. 4. Results of the cylinder test for the explosives (points) and fitting curves (solid lines)

Rys. 4. Wyniki testu cylindrycznego dla badanych mieszanin wybuchowych (symbole) i krzywe aproksymacyjne (linie ciągłe)

The range of axial co-ordinate variation analysed was limited to values for which the volume of detonation products was between nine and ten times greater than the initial volume.

3. Acceleration capability and detonation energy of the explosives

One of the parameters that characterise the process of detonation energy release and its conversion into the mechanical work is the acceleration capacity of the detonation products. Souers and Kury (1993) proposed to evaluate the parameter using velocities of the accelerated tube under CT conditions at volume expansion ratios of 2.2, 4.1 and 6.5. The acceleration ability can also be described as the Gurney energy (E_G) which is a sum of the kinetic energy of a driven liner and the detonation products following it (Walters, Zukas 1989). In the case of the cylindrical liner, E_G is expressed by equation:

$$E_G = \left(\mu + \frac{1}{2}\right)\frac{u_L^2}{2} \tag{1}$$

where μ denotes the ratio of tube mass to explosive mass and u_L is the total velocity of the tube.

In literature, the final values of the Gurney energy or Gurney velocity are usually given. These parameters correspond to the tube velocity at a tube radius for which continuity of the tube material is still preserved (Walters, Zukas 1989). Trzciński (2000) found that an assessment of the acceleration capacity of an explosive could be made using the complete dependence of the Gurney energy, described by eq. (1), on the relative volume of the expanding detonation products. From eq. (1) it follows that in order to determine the dependence one must know the velocity of the tube driven by the detonation products.

A detailed description of the procedure of the tube velocity computation, applying the dependence of the external tube surface on axial co-ordinate, as recorded in the CT, is given by Trzciński (2000). First, the position of the central cylindrical surface of the tube (r_m) is determined. Assuming a complete incompressibility of the tube material, this position can be calculated from the relation:

$$r_m = \sqrt{r_e^2 - \frac{1}{2}(r_{e0}^2 - r_{i0}^2)} \tag{2}$$

where r_{e0} and r_{i0} denote the initial radii of the internal and external surfaces of the tube, respectively, r_m and r_e are the radii of external and central surfaces of the tube for given value of co-ordinate x, respectively.

Assuming that the motion of the detonation products and the tube material may be treated as stationary one (which means that $x = D\,t$, where D — detonation velocity, t — time) we can replace the dependence of the radius r_m on the axis co-ordinate by the time function of this radius. The time-dependence of the position of the tube central surface is approximated by the following function (Trzciński 2000)

$$r_m = r_{m0} + \sum_i a_i \left\{ b_i (t - t_0) - [1 - \exp(-b_i (t - t_0))] \right\} \tag{3}$$

where r_{m0} is the initial values of r_m, a_i, b_i, t_0 are parameters.

Then the radial velocity of the tube can be calculated by differentiating function (3)

$$u_m \equiv \frac{dr_m}{dt} = \sum_i a_i b_i \left[1 - \exp(-b_i (t - t_0))\right] \tag{4}$$

and the total velocity is expressed by equations:

$$u_L = 2D \sin\left(\frac{\Theta}{2}\right) \tag{5}$$

$$\Theta = \text{arc tg}\left(\frac{u_m}{D}\right) \tag{6}$$

Applying the experimental profiles of the expanding copper tubes, which are shown in Fig. 3, and detonation velocities measured while the profiles were recorded (Table 1), values of u_L and then E_G were computed. The results of the calculation in the form of

TABLE 2

The final Gurney energy and the detonation energy

TABLICA 2

Energia Gurneya i energia detonacji

Explosive	E_G ($v/v_0 = 9$) [kJ/kg]	e_0 [kJ/kg]
AN/TNT-1	1 995	3 390
AN/TNT-2	1 535	2 640
AN/TNT/Al-1	2 200	3 700
AN/TNT/Al-2	2 210	3 730
AN/Al-1	1 795	3 070
AN/Al-2	1 805	3 060

dependence of the Gurney energy on the relative volume of the detonation products (volume expansion ratio v/v_0) are illustrated in Fig. 5. For comparison, the figure also includes the dependence for TNT with density of 1590 kg/m^3 obtained by Trzciński et al. (2000). In Table 2, the final values of E_G for the explosives tested are listed. They were

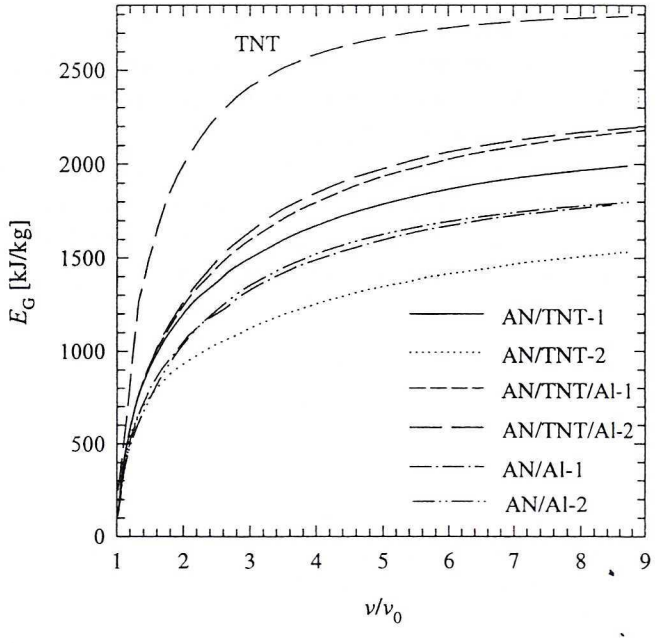

Fig. 5. Acceleration ability– the Gurney energy as a function of the relative volume of the detonation products

Rys. 5. Zdolność miotająca — zależność energii Gurneya od względnej objętości produktów detonacji

determined for $v/v_0 = 9$, i.e. just before the moment when the copper tube started to break. For TNT ($\rho_0 = 1590$ kg/m^3) and TNT/Al = 85/15 ($\rho_0 = 1670$ kg/m^3) the final values of the Gurney energy were found to be 2795 kJ/kg and 3078 kJ/kg, respectively (Trzciński et al. 2000).

From an analysis of the data, shown in Fig. 5 and Table 2, it follows that the aluminized explosives AN/TNT/Al-1 and AN/TNT/Al-2 are characterised by higher values of Gurney energy than those without aluminium. The replacement of 10% of TNT with Al-1 or Al-2 lowers detonation velocity (Table 1) by about 10% but at the same time all the energetic parameters increase by approximately 10% (Table 2, Fig. 5).

Even great size reduction of the aluminium particles only slightly influences the detonation parameters and the energetic characteristics of the explosives, whereas the use of fine TNT particles is very advantageous as it considerably increases both detonation (Table 1) and performance parameters (Fig. 5).

The CT results can also be used for estimation of the detonation energy, e_0, which is defined as the work done by the detonation products during their expansion from the volume at Chapman-Jouguet's point, v_{CJ}, to infinite volume (Jacobs 1956; Ficket, Davis 1979)

$$e_0 = -e_c + \int_{v_{CJ}}^{\infty} p_i \, dv \tag{7}$$

where p_i is the pressure on the isentrope starting from the CJ point, and $e_c = (p_{CJ} - p_0) \cdot (v_0 - v_{CJ})/2$ is the energy of compression of the explosive at the detonation front, p_0 and p_{CJ} denote the initial pressure and detonation pressure, respectively, and v_0 is the specific volume of the explosive ($v_0 = 1/\rho_0$).

The detonation energy, defined by eq. (7), only insignificantly differs from the calorimetric detonation heat. Trzciński (2000) additionally showed that a correlation exists between the detonation energy and the tube kinetic energy that corresponds to the infinitive volume of the detonation products driving the tube. The correlation is as follows:

$$\frac{e_0}{e_0^{st}} = \frac{\left(\mu + \frac{1}{2}\right)}{\left(\mu^{st} + \frac{1}{2}\right)} \left(\frac{u_L}{u_L^{st}}\right)^2 \tag{8}$$

where e_0 and e_0^{st} denote detonation energies related to mass unit of an explosive being tested and a standard explosive, respectively, and u_L, u_L^{st} are velocities of the driven the tubes determined for an infinite volume of the detonation products of the given and standard explosives respectively.

In order to estimate the detonation energy of the explosives examined, a dependence of the tube velocity to the power of two on the reciprocal volume of detonation products was constructed and extrapolated to null (Fig. 6), according to the method proposed by Trzciński (2000).

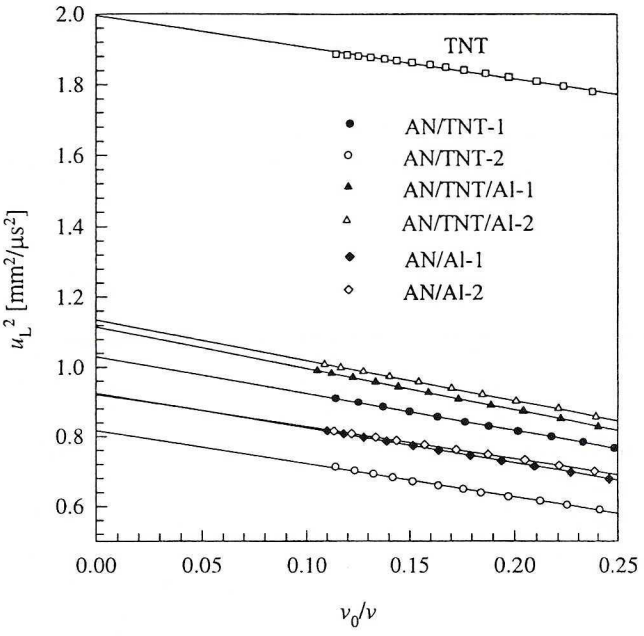

Fig. 6. Velocity square of copper tube versus reciprocal volume of detonation products

Rys. 6. Zależność kwadratu prędkości rurki miedzianej od odwrotności objętości produktów detonacji

As a standard explosive, TNT with density of 1590 kg/m^3 was chosen. Its heat of detonation (e_0^{st} = 4430 kJ/kg) was determined in a bomb calorimeter filled with compressed argon (Cudziło et al. 1998). Next, for $v/v_0 = 0$ ($v \to \infty$), values of u_L^2 were found and used to calculate the detonation energy from relation (8). Results of the calculation (e_0) are given in Table 2.

Comparing the parameters in Table 2, it should be pointed out that the final Gurney energy accounted for 58–60% of the detonation energy for all the explosives. As it is shown in Section 4 of this paper, exactly the same proportion of the energy contained in an explosive is converted into the expansion work used for breaking hard rock. This implies that the Gurney energies determined at an expansion ratio of nine to one can be directly used for estimation of the blasting performance of explosives.

4. Equations of state and the expansion work of the detonation products

In the literature, *the expansion work of detonation products*, w, is defined as the work done by the products expanding from the volume at the CJ point (v_{CJ}) to a volume v minus the energy of compression of the explosive (Ficket, Davis 1979)

$$w(v) = -e_c + \int_{v_{CJ}}^{v} p_i dv \tag{9}$$

To compute the expansion work, it is necessary to know the isentrope of expansion of the detonation products. One of the simplest forms of isentropes is the Poisson adiabate:

$$p_i = p_{CJ}\left(\frac{v_{CJ}}{v}\right)^{\gamma} \tag{10}$$

where is the adiabate exponent.

In order to determine the constants in eq. (10), one must know values of two detonation parameters at least. The first of them is usually the experimental detonation velocity, and the second is the exponent of the isentrope of the detonation products, γ. Most often it is the so-called *effective exponent of isentrope* which is not determined from the parameters at the CJ point but on the basis of the real isentrope for some interval of detonation product volume changes. According to the procedure proposed by Trębiński and Trzciński (1996), this can be obtained using the CT data. In this method the experimental profile of the copper tube is compared with that obtained from numerical modelling of the expansion process. The detonation products, driving the tube, are described by the Poisson adiabate (10). The value of γ for which the calculated profile is sufficiently close to the experimental one is chosen. The effective exponents of the detonation products for the explosives tested are given in Table 3.

After combining the Poisson adiabate with eq. (9) and integrating the equation obtained within the limits from v_{CJ} to v, we have following expression for the work done by the expansion

$$w = \frac{p_{CJ} v_{CJ}}{\gamma - 1}\left[\frac{\gamma + 1}{2\gamma} - \left(\frac{v_{CJ}}{v}\right)^{\gamma - 1}\right] \tag{11}$$

TABLE 3

Effective exponent of the Poisson adiabate

TABLICA 3

Efektywny wykładnik adiabaty Poissona

Explosive	γ
AN/TNT-1	2.32
AN/TNT-2	2.40
AN/TNT/Al-1	2.10
AN/TNT/Al-2	2.12
AN/Al-1	2.10
AN/Al-2	2.03

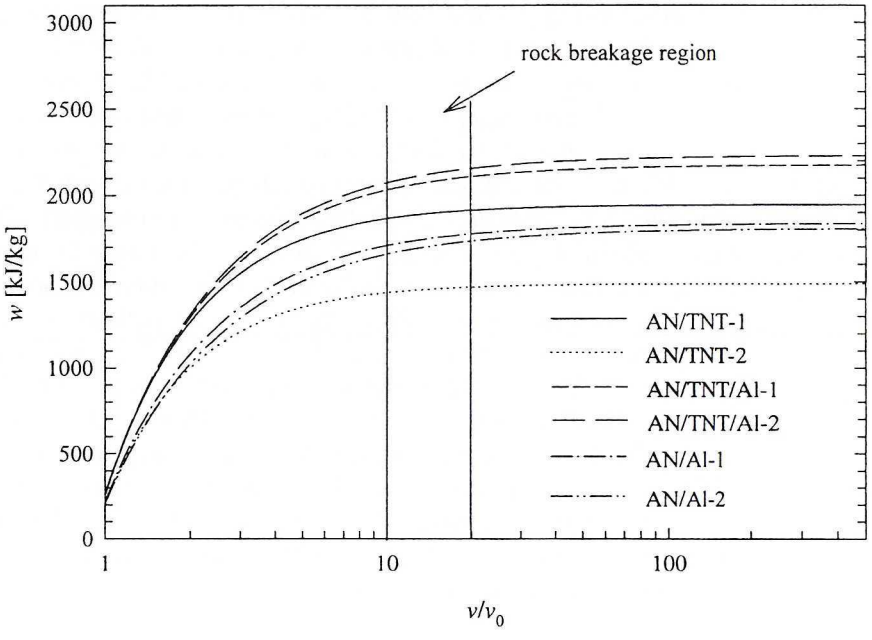

Fig. 7. Expansion work performed by the detonation products described by the Poisson adiabate

Rys. 7. Praca ekspansji wykonana przez produkty detonacji opisywane równaniem adiabaty Poissona

The expansion work, computed using relation (11), is presented in Fig. 7 as functions of the relative volume of the detonation products (expansion volume ratio).

In the diagram, the interval of changes of the detonation products volume that corresponds to the pressure region for rock breakage is also shown. As the rock starts to break, cracks open up and the detonation products propagate and escape through them, weakening the breakage performance of the explosive. Therefore it is suggested that the work done by the expansion as determined for $v/v_0 = 10, 15, 20$ can be used to compare the blasting performance in hard, medium and weak rock (Persson, Chiappetta 1994).

In reality, the exponent of the isentrope greatly changes during the expansion of the detonation products — from a value of about 3 at the CJ point to approximately 1.2 at low pressure. Therefore the physical properties of the expanding gaseous detonation products are more precisely described by the isentrope which was proposed by Jones, Wilkins and Lee in the following form (Lee et al. 1968)

$$p_i = Ae^{-R_1 V} + Be^{-R_2 V} + CV^{(-1-\omega)} \tag{12}$$

where A, B, C, R_1, R_2 and w are constants for given explosive, $V = v/v_0$. It can be proved that eq. (12) becomes the Poisson adiabate with $\gamma = \omega + 1$ at low pressure.

CT results are commonly employed in most methods of determination of the JWL constants. In one of them, proposed by Trębiński and Trzciński (1999), some connec-

tions between JWL coefficients (following from the conservation laws written for the CJ point) are used. As a result, parameters A, B, and C are expressed as functions of R_1, R_2, ω and ρ_0, D, e_0 and p_{CJ}. Density of explosive, ρ_0, as well values of detonation velocity, D, detonation energy, e_0, and pressure, p_{CJ}, at the CJ point are found experimentally or theoretically. Thus, only the constants R_1, R_2 and ω remain to be determined. They are calculated by the method in which the experimental dependence of the radial displacement of the outer tube wall on the axial co-ordinate is compared with that obtained from a numerical simulation. A set of JWL constants is chosen for which the experimental and simulated displacements are sufficiently close to each other.

Using the model described above, as well as the values of detonation velocity, detonation pressure and detonation energy of the explosives tested, the constants of the JWL equation of state were calculated. Results of the calculations are given in Table 4. All the parameters needed to perform the calculations were obtain on the basis of the cylinder test, except for the detonation pressure which was computed with the TIGER code (Crawford 1986). The computations of p_{CJ} values were done with the assumption that part of the ammonium nitrate does not react in the detonation wave. The basis for determining the inactive proportion of ammonium nitrate was the conformity of the experimental and theoretical values of the detonation velocity.

TABLE 4

The detonation pressure and the constants of JWL equations of state for the detonation products of explosives examined

TABLICA 4

Ciśnienie detonacji i stałe równania stanu JWL dla produktów detonacji badanych materiałów wybuchowych

Explosive	p_{CJ}* [GPa]	A [GPa]	B [GPa]	C [GPa]	R_1	R_2	ω
AN/TNT-1	4.1	1 430.630	6.034334	0.4659000	9.08	1.45	0.21
AN/TNT-2	3.3	2 294.431	5.967547	0.3576082	10.01	1.60	0.20
AN/TNT/Al-1	3.8	1 925.707	5.155479	0.5194825	9.88	1.33	0.21
AN/TNT/Al-2	3.7	2 798.851	4.580575	0.5243490	10.31	1.22	0.21
AN/Al-1	3.1	8 599.265	5.327028	0.4406544	12.48	1.47	0.21
AN/Al-2	2.7	10 578.44	5.234876	0.4235920	13.59	1.39	0.27

* p_{CJ} values calculated with TIGER code.

Fig. 8 displays how different JWL and Poisson isentropes for AN/TNT-1 detonation products are. From the comparison it follows that they give quite different values of pressure when the volume expansion ratio of the detonation products exceeds three and with increasing volume the differences rise considerably. It shows conclusively that

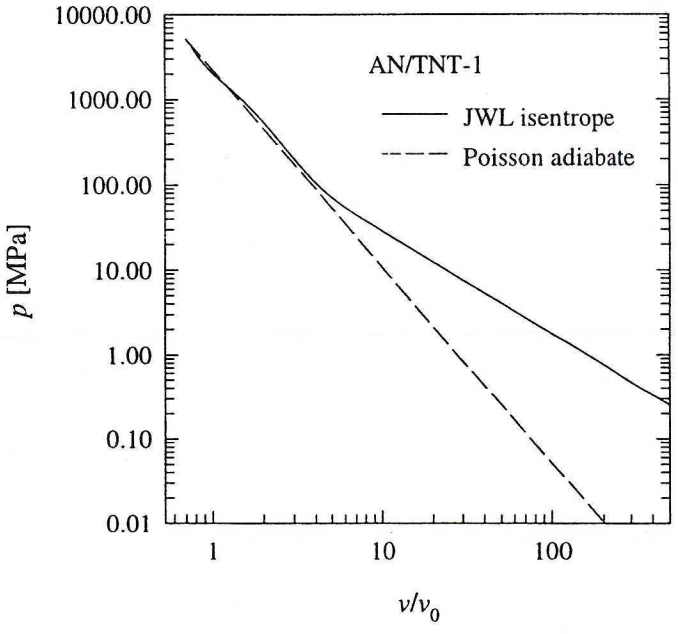

Fig. 8. The Poisson adiabate and the JWL isentrope for detonation products of AN/TNT-1

Rys. 8. Adiabata Poissona i izentropa JWL dla produktów detonacji SA/TNT-1

a proper form of the applied isentrope has a crucial implication for the results of calculations, especially when they are performed for a lower pressure region.

Combining eq. (12) with eq. (9) and, then, integrating the equation obtained, the expression for the expansion work of the detonation products described by the JWL equation of state has the following form

$$w = e_0 - e_x(v) \tag{13}$$

where

$$e_x(v) = v_0 \left[\frac{A}{R_1} e^{-R_1 v/v_0} + \frac{B}{R_2} e^{-R_2 v/v_0} + \frac{C}{\omega} \left(\frac{v}{v_0} \right)^{-\omega} \right] \tag{14}$$

The expansive work of the detonation products described by the JWL equation of state (with constants from Table 4) versus the expansion volume ratio is shown in Fig. 9.

From an analysis of the curves in Fig. 9, it follows that up to the moment when cracks begin to appear in rock materials, the expansive work accounts for 58–60% and 63–65% of the detonation energy, e_0, in hard and weak rock, respectively. This result is in a good consistence with the values given by Persson and Chiappetta (1994). They stated that only approximately 50–70% of the detonation energy corresponds to the expansive work used for breaking the rock.

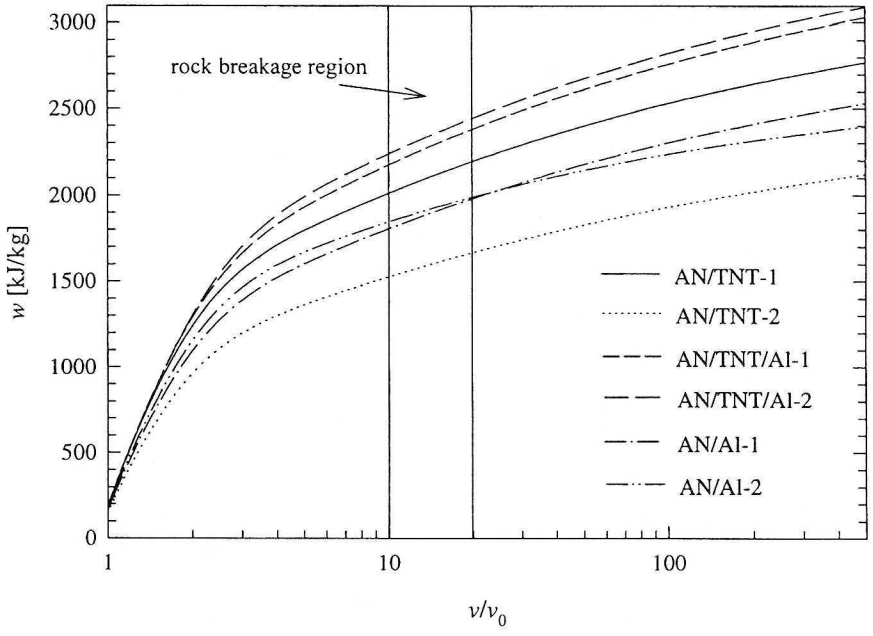

Fig. 9. Expansion work performed by the detonation products described by the JWL equations of state

Rys. 9. Praca ekspansji wykonana przez produkty detonacji opisywane równaniem stanu JWL

In closing, we would like to underline the differences in the expansive work calculated using the Poisson adiabate (Fig. 7) and the JWL isentrope (Fig. 9). As the JWL equation of state comparatively exactly describes the real physical properties of the detonation products, it can be assumed that using the Poisson adiabate to evaluate the expansive work in rock materials (when $v/v_0 \sim 10$–20) errors of the order of 10% may occur. But a distinctly higher level of error is likely to be present during an assessment of the work of detonation products expanding to a huge volume, for example in water or in air. For $v/v_0 = 500$, the discrepancy grows up to 30% (Figs. 7 and 9).

5. Conclusions

The results obtained in this study indicate that the cylinder test can be successfully applied to obtain a quantitative evaluation of the energy characteristics of industrial explosives. The X-ray records of the process of driving the copper tube make it possible to determine the Gurney energy and the detonation energy in a comparatively simple way. Moreover the CT results combined with the numerical modelling results of the driving process enable determination of the equation of state of the detonation products and, consequently, the assessment of their effective expansive work.

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