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Analysis and comparison of the continuous detonation velocity measurement method with the standard method
Analiza i porównanie metody ciągłego pomiaru prędkości detonacji z metodą znormalizowaną

Piotr Mertuszka[1,*)], **Mateusz Pytlik**[2)]

[1)] *KGHM CUPRUM Ltd., Research and Development Centre, 2-8 Sikorskiego Street, 53-659 Wrocław, Poland*
[2)] *Central Mining Institute, Plac Gwarków 1, 40-166 Katowice, Poland*
**E-mail:* pmertuszka@cuprum.wroc.pl

Summary: *Detonation velocity is one of the basic parameters characterising explosives. Its value is influenced by many factors related to the conditions under which they are used. The value of the detonation velocity measured in the blasthole may differ from the value measured utilising the standard method under laboratory conditions. Thus, comparative velocity of detonation (VOD) tests were carried out, which included the start-stop method (in accordance with the EN 13631-14:2003 standard) and the continuous method (utilising the MicroTrap VOD/Data Recorder). An analysis of the influence of ambient temperature on the resistance changes of the measurement probes in the continuous VOD method was also carried out. Based on the conducted comparative tests for 5 types of packaged emulsion explosives used in the mining industry, it was determined that the MicroTrap recorder enables the obtaining of results complementary with the ones obtained using the standard method.*

Streszczenie: *Prędkość detonacji jest jednym z parametrów charakteryzujących materiały wybuchowe. Na jej wartość wpływa wiele czynników związanych z warunkami, w jakich są stosowane. Wartość prędkości detonacji zmierzonej w otworze strzałowym może różnić się od wartości zmierzonej metodami znormalizowanymi w warunkach laboratoryjnych. W związku z powyższym przeprowadzono badania porównawcze metod pomiaru prędkości detonacji, w tym metody odcinkowej (zgodnej z normą EN 13631-14:2003) oraz ciągłej (przy pomocy urządzenia MicroTrap VOD/Data Recorder). Przeprowadzono także analizę wpływu temperatury otoczenia na zmianę oporności sond pomiarowych w ciągłym systemie pomiaru prędkości detonacji. Na podstawie przeprowadzonych badań porównawczych dla 5 typów nabojowanych materiałów wybuchowych emulsyjnych stosowanych w górnictwie stwierdzono, że przyrząd MicroTrap pozwala na uzyskanie wyników komplementarnych z wynikami badań prowadzonymi metodą znormalizowaną.*

Keywords: *explosive, velocity of detonation, measuring method*
Słowa kluczowe: *materiał wybuchowy, prędkość detonacji, metoda pomiarowa*

1. Introduction

The velocity of detonation (VOD) is one of the parameters characterising explosives. It describes the velocity at which the shock wave front travels through an explosive charge [1]. Determination of the VOD is one

of the basic tests when assessing the explosive's compliance with the 2014/28/EU directive. From a mining point of view, the VOD is a parameter that directly affects the effectiveness of blasting works. The selection of a suitable explosive for given mining and geological conditions should always take into account both the acoustic density of the explosive and the acoustic density of excavated rock mass supplemented with the measurement of the VOD directly in the blasthole [2]. Detonation velocity values given by manufacturers of explosives are determined under laboratory conditions. Unfortunately, these conditions do not correlate with the behaviour of explosives under mining conditions, because they do not include a number of external factors that affect their behaviour under *in situ* conditions. The VOD can be influenced by many factors associated with the applied mining method, which are not taken into account in the standard tests [3]. The most important factors include the composition of the explosive, the type of sensitizer used, ambient temperature and the temperature of the explosive charge, type, mass and location of the initiator, time elapsed from loading to firing of the bulk emulsion explosives, diameter of the charge and blasthole, length of the explosive column and method of mixing components – particularly important in the case of bulk emulsion explosives [4-13].

Standard tests are always carried out under similar laboratory conditions, described in detail in the EN 13631-14:2005 standard [14]. However, they do not include the above-mentioned factors relating to mining technology. VOD measurements using a continuous method can be carried out directly in the blastholes. They do not disturb the technological process continuity of the mine. This type of measurement allows the determination of how the VOD values measured *in situ* compare with the values determined in the standard test. At the same time, it allows to verify whether a given explosive does not change its performance parameters, along with the change of conditions in which it is used [15].

The paper presents results of the comparative VOD measurements utilizing the standardised and continuous (unaccredited) methods, and aims to determine the extent to which the results of tests carried out using both methods in parallel, coincide. The subjects of research were selected packaged emulsion explosives. A multi-channel Explomet recorder was utilised in the accredited method, while a MicroTrap VOD/Data Recorder was used for the continuous measurement. The study also presents the results of the research on the impact of temperature on the changes in the resistance of measuring probes used in the continuous method.

2. Measuring methods

2.1. Start-stop method

The start-stop method with the use of the Explomet electronic counter (Figure 1) consisted of measuring the time interval between two sensors located within the explosive sample in a known distance. The counter in this method is triggered at the moment of breakage of the first probe by the front of the shock wave travelling through the explosive sample (start signal), and ends when the second probe is broken (stop signal). The time in this method is given with a resolution of 0.1 μs. Based on the previously determined distance between the two probes, the average VOD for a given segment is calculated. Result is shown on the display immediately upon completion of the measurement.

Figure 1. Multi-channel Explomet

The accuracy of the measurement of the VOD in the Explomet system is influenced, among others, by the distance between sensors and the precision of its determination, type of sensors (wires/optical fibres), time measurement accuracy and the way the probes are installed in the explosive sample. The measurement uncertainty in the start-stop method for the Explomet device is ±30 m/s and is related to the accuracy of the time measurement and the placement of sensors.

2.2. Continuous method

The MicroTrap VOD/Data Recorder (Figure 2) is a portable device used to measure the VOD of explosive samples and explosives directly in the blastholes [16, 17]. One channel enables recording at a maximum sampling rate of 2 MHz. For typical explosives used in the mining industry, the device records approximately 300-600 data points, on average, per each 100 cm of an explosive column.

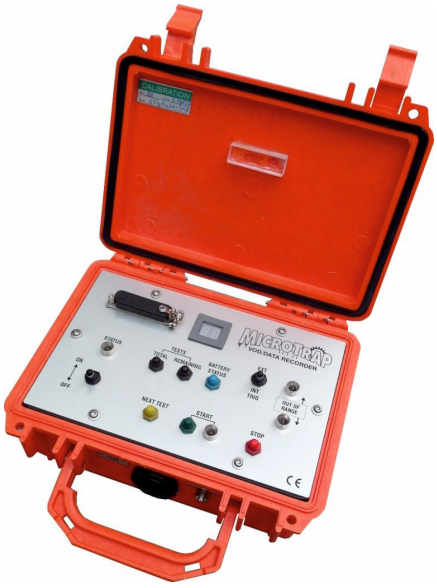
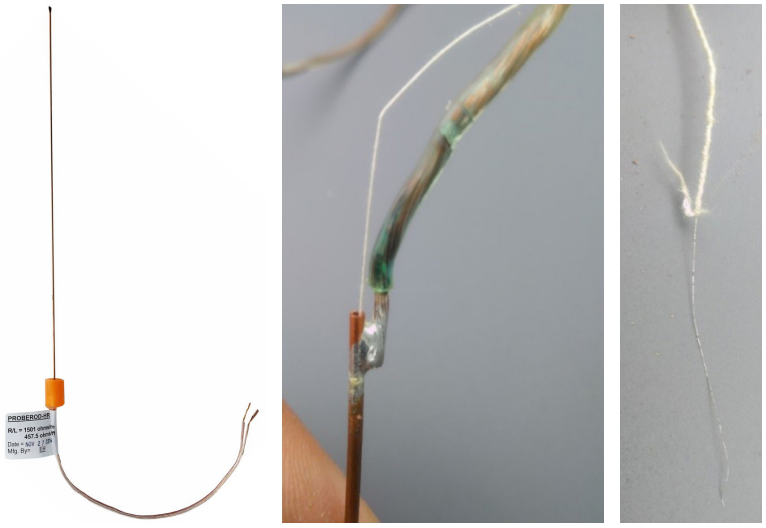


Figure 2. MicroTrap VOD/Data Recorder

The commonly known wire resistance technique is used to measure the VOD using the MicroTrap recorder. A qualified probe of known linear resistance is inserted axially in the sample of explosive (parallel to the direction of detonation). As the detonation front progresses, the explosive consumes the probe, and the circuit resistance decreases in proportion to the reduction in its length (the recorder saves the changes in the probe voltage as a function of time). During the operation, the recorder generates a low voltage not exceeding 5 V DC and low current (below 50 mA), which ensures that the MicroTrap will not initiate detonation of explosives.
Two types of the VOD probes are suitable for the application with the MicroTrap, depending on the type of measurements, including coaxial cable or coaxial tube with the classical configuration of a standard RG-type coaxial cable, where the inner wire is the main conductor and the braided shield acts as the return lead. The *ProbeCable* is used for testing VODs of explosives in blastholes, while *ProbeRod* is designed to measure the VOD of short samples of explosives outside the blastholes. They are available in various lengths: from 30 to 100 cm (Figure 3). The manufacturer states that the measurement uncertainty in the continuous method is ±2% and is related to the variability of unit resistance of the probes. Dedicated software automatically displays the recorded data in the form of a graph of distance versus time, and calculates the VOD at any position on the graph.



(a) (b) (c)

Figure 3. The VOD *ProbeRod*: general view (a), coaxial tube with a return lead (b), wire inside the tube (c)

3. Tested explosives

Five packaged emulsion explosives were tested, including:
– #1 and #2 with a diameter of 32 mm,
– #3 with a diameter of 25 mm,
– #4 with a diameter of 40 mm, and
– #5 – special methane explosive with a diameter of 32 mm.
All explosives were initiated by an electric instantaneous detonator with a PETN secondary charge of 0.65 g. The measurements were carried out in accordance with the requirements of [14], *i.e.* three samples for each analysed explosive, for which the average value was determined.

4. Experimental part

4.1. The influence of temperature on the resistance of the probes

The results of the VOD tests by the MicroTrap device may be influenced by the conditions under which they are conducted. Since the continuous VOD tests are carried out on the basis of the probe resistance measurement, it was assumed that the results may be affected by its temperature. Consequently, the effect of temperature on the resistance value of the probes was analysed.

Due to the possibility of change in the resistance of the probe placed in the explosive sample with different temperatures, a series of tests was carried out on 10 probes in the temperature range from –30 °C to +80 °C (as specified in [14]). The probes were placed in a climatic chamber and the desired temperature was set. After 30 min of conditioning the probe in the chamber, its resistance was measured. The temperature was then increased by 10 °C. The results are presented in Figure 4.

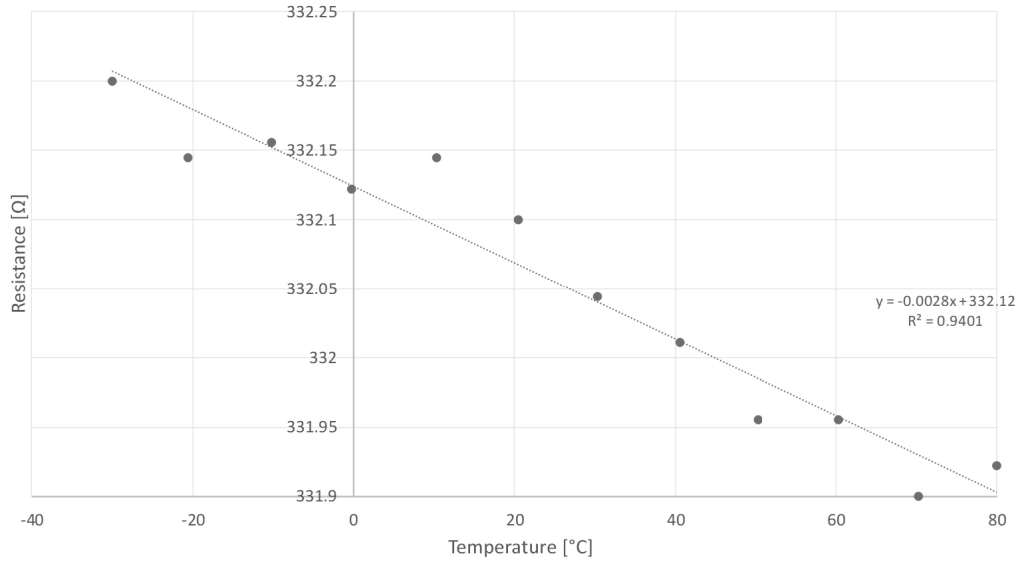


Figure 4. The dependence of resistance as a function of temperature for a VOD *ProbeRod* in a continuous method

The maximum difference in the resistance in a given temperature range was approximately 0.3 Ω, which is a maximum of 0.1% of the total probe resistance value. Hence, the effect of temperature on the change in resistance of the measurement probes can be considered insignificant.

4.2. Comparison of the measurement methods

To compare the results of the VOD measurements using the start-stop method and the continuous method, studies were carried out, in which the same explosives were fitted with continuous and start-stop measurement probes under the same conditions. The measuring system is shown in Figure 5.

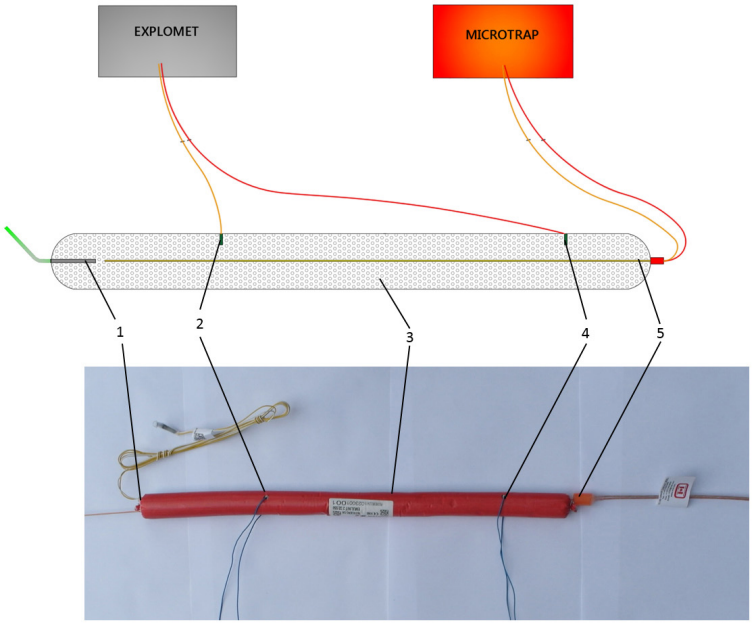


Figure 5. Comparative testing procedure: charge diagram (top) and view of the armed sample (bottom): 1 – detonator, 2 and 4 – measuring points, 3 – explosive sample, 5 – the VOD *ProbeRod*

Figure 6 presents an example of the VOD graph obtained with the MicroTrap device (sampling frequency of 1 MHz). The VOD plot shows some irregularities, which means that the determination of the velocity by the linear regression analysis may lead to a false result. However, this problem can be eliminated by determining the VOD from the slope of the curve at any position on the graph based on two selected points.

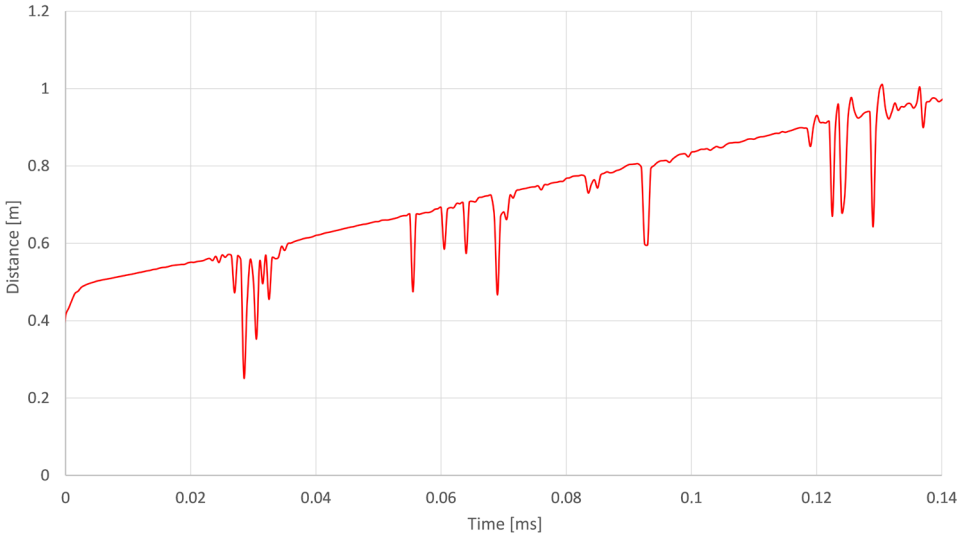


Figure 6. Detonation velocity graph determined by the continuous method

In order to compare the VOD tests using the standard (accredited) method with the continuous method, the same sampling line with a length of 30 cm was analysed, on which the probes for the start-stop measurement were placed. When analysing the graph from the continuous method using linear regression, it is necessary to remove all disturbances that may give a false result. Hence, the instantaneous VOD was used for the analysis. All VOD results above 20,000 m/s or –10,000 m/s were treated as "noise" and were rejected. The VOD graph after filtering is presented in Figure 7.

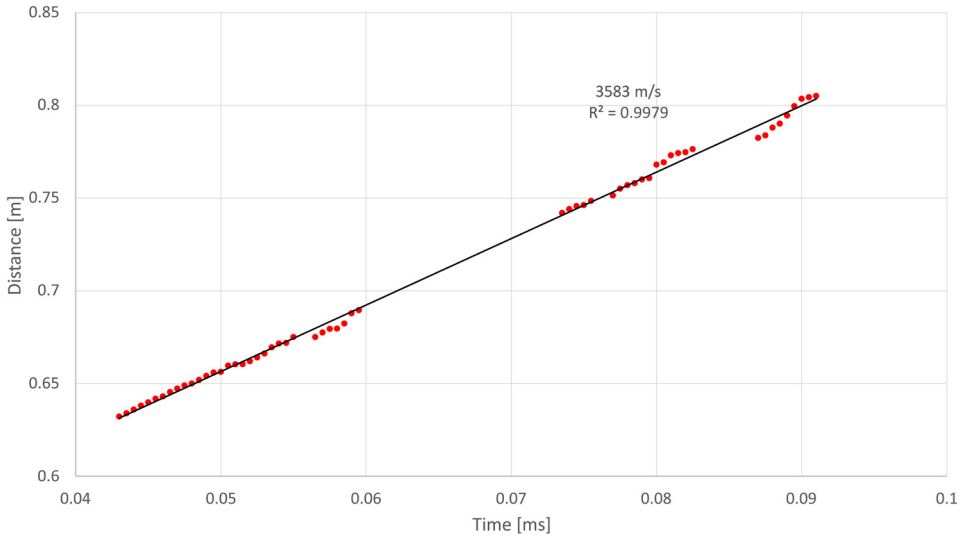


Figure 7. The VOD plot after filtration for the analysed sampling line

The graph after filtration gives a simple and accurate method for determination of the detonation velocity, using linear regression. However, as previously mentioned, this procedure can be accelerated by choosing another method for determining the VOD in the software, *i.e.* the method of any two selected points in the graph. The results of the VOD tests obtained for each sample of explosives are shown in Table 1.

Table 1. Results of the VOD measurements using the start-stop and continuous methods

Type of		VOD [m/s]			
measurement	**explosive**	**sample #1**	**sample #2**	**sample #3**	D_{av}
start-stop	#1	4380	4440	4190	4337 ±72
continuous		4580	4520	4500	4533 ±23
start-stop	#2	3810	3680	3600	3697 ±61
continuous		3580	3530	3960	3690 ±124
start-stop	#3	4040	4570	4380	4330 ±153
continuous		4280	4240	4390	4303 ±43
start-stop	#4	5510	5570	5200	5427 ±107
continuous		5280	5350	5350	5327 ±20
start-stop	#5	4700	4630	4260	4530 ±127
continuous		4730	4590	4710	4677 ±40

Note: all results are presented to the nearest ±10 m/s

A statistical procedure dedicated to small data sets was used to analyse the test results. Firstly, the mean value of the detonation velocity (D_{av}) was calculated for each type of explosive and each type of measuring system:

$$D_{av} = \frac{D_1+D_2+D_3}{N} \quad (1)$$

where D_1, D_2, D_3 – values of the detonation velocity for sample 1, 2 and 3, respectively, N – number of samples. Subsequently, the range of the obtained results (R) was determined, which indicates the difference between the maximum and minimum VOD values:

$$R = D_{\max} - D_{\min} \quad (2)$$

where D_{max}, D_{min} – maximum and minimum VOD values, respectively.
In the next step, the uncertainty of a single measurement of the detonation velocity (ΔD) was determined from the following equation:

$$\Delta D = \frac{R}{2} = \frac{D_{\max}-D_{\min}}{2} \quad (3)$$

The uncertainty in the mean value of VOD (ΔD_{av}) was then calculated according to the following equation:

$$\Delta D_{\mathrm{av}} = \frac{\Delta D}{\sqrt{N}} = \frac{R}{2\sqrt{N}} \quad (4)$$

Based on performed measurements, one may conclude that the spread of the results around the mean value is definitely smaller for measurements using the continuous method. This conclusion does not coincide with the explosive #2 only. The greatest uncertainty of the mean VOD value obtained using the multi-channel Explomet was recorded for explosives #3 and #5. These values were 153 m/s and 127 m/s, respectively. For comparison, results obtained using the MicroTrap recorder were 43 m/s for explosive #3 and 40 m/s for explosive #5. It is worth mentioning that the measurement uncertainty in the start-stop system is ±30 m/s. In contrast, the uncertainty in the MicroTrap system is ±2%, which for the obtained VODs in the range of 3530-5350 m/s means an error in the range of 71-107 m/s. It means, that it can be 3 times higher than for the Explomet recorder. Nevertheless, the VODs obtained using the continuous method are characterized by a much smaller spread. This difference may result from the fact that for continuous measurements, the detonation velocity can be calculated on the basis of the slope of the curve plotted based on any two points selected on the graph. This allows to minimize the impact of any disturbances on the result or momentary drops in the VOD within the analysed sampling line. In the case of measurements using the Explomet recorder (one average VOD value for the entire sampling line), it is not possible to eliminate this type of interference and minimise the measurement error.

5. Conclusions

The obtained results indicate that for four out of five analysed explosives, the spread around the mean value is much smaller for measurements carried out by the continuous method. These values did not exceed 1%, which is a value within measurement error. The biggest difference was recorded for explosive #2, for which the uncertainty of the mean value was over 3%. For comparison, the spread of results around the mean value using the start-stop method was approximately 3-5 times larger.
As a result of the analysis, it was found that the greater susceptibility to disturbance in the continuous method can be eliminated by using the analysis of instantaneous detonation velocities by rejecting the disturbances and calculating the average VOD based on linear regression. Another way is to determine the velocity of detonation based on the slope of the graph by the method of two points corresponding to the position of the measuring sensors in the start-stop method. In the case of changes in the detonation velocity within

the sampling line, the start-stop method, in which the sensors are placed at a specified distance, may indicate erroneous results, because it does not provide a complete view of the detonation course in a given sampling line. The analysis also confirmed that the effect of temperature on the resistance of measuring probes can be considered insignificant.

The applied methodology of continuous measurements allows the requirements of the EN 13631-14 standard to be met in the scope of the sampling line, which should not be less than 10 cm and should be away from the initiator by the distance specified in the standard. Therefore, the continuous method of the VOD measurement using the MicroTrap recorder, due to its high accuracy, can be treated as an alternative method for determining the detonation velocity in accordance with EN 13631-14 standard.

It should also be noted that the continuous method remains the only method for measuring the detonation velocity of explosives in blastholes. In the case of any irregularities, this type of measurement should be treated as an alert to withdraw the explosives from a given batch and to verify their thermodynamic parameters under laboratory conditions. Of course, this type of procedure will be limited to packaged explosives, because the performance parameters of bulk explosives change with the changing conditions in which they are used.

In summary, the accuracy of the results of detonation velocity measurements using the continuous method is definitely higher than for start-stop measurements.

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