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THE EFFICIENCY OF LINEAR SHAPED CHARGES

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Original scientific paper

The efficiency of a linear shaped charge is estimated based on the penetration depth in a target material. Taking into consideration a significant number of parameters that affect the penetration depth, the optimization of the linear shaped charge parameters is a complex process. The effect of a certain parameter can be determined experimentally or predicted theoretically by using hydrodynamic computer programmes that simulate the formation of jet and penetration process of the linear shaped charges. The computer simulation can predict the jet velocity and penetration depth with certain accuracy. Therefore, field measurements are essential for the validation of computer simulation. This paper presents experimental determination of the effect of a mass of explosive, liner material and standoff distance on the penetration depth of the linear shaped charges. The relation between the penetration depth and various factors is established, as well as the relation between the various factors in the case of the maximum penetration depth.

Keywords: *explosive, linear shaped charges, penetration depth*

Učinkovitost linijskih kumulativnih rezača

Izvorni znanstveni članak

Učinkovitost linijskih kumulativnih rezača ocjenjuje se na osnovu dubine penetracije u ciljanom materijalu. S obzirom na značajan broj parametara koji utječu na dubinu reza, optimiziranje konstrukcijskih parametara linijskih kumulativnih rezača je složen proces. Utjecaj pojedinoga parametra moguće je odrediti eksperimentalno ili teorijski predvidjeti primjenom računalnih programa, koji na temelju hidrodinamičke teorije simuliraju proces nastajanja i penetriranja mlaza linijskih kumulativnih rezača. Računalnim simulacijama moguće je predvidjeti brzinu i dubinu penetracije mlaza s određenom točnosti. Stoga su terenska mjerenja neophodna za validaciju računalne simulacije. U radu je prikazan eksperimentalni način određivanja utjecaja materijala obloge i udaljenosti rezača od mete na dubinu penetracije linijskih kumulativnih rezača. Utvrđena je ovisnost dubine penetracije o pojedinom čimbeniku te je ustanovljen međusobni odnos pojedinih čimbenika za slučaj najveće dubine penetracije.

Ključne riječi: *dubina penetracije, eksploziv, linijski kumulativni rezači*

1 Introduction

The efficiency of linear shaped charges is determined based on the achieved penetration depth in a target material. Due to a significant number of factors that affect the efficiency of the linear shaped charges the optimization is very complex. In order to determine the effect of a single factor, it is necessary to conduct measurements with other factors that do not vary. Since that increases the number of measurements, the research is usually directed towards the effect of a single factor. The published papers include the data on the effect of liner material [1, 2], liner shape [3], liner thickness [3, 4, 5], asymmetry of construction parameters [5], housing material [4, 6], liner angle and standoff [7], etc. Most of the research is related to conical shaped charges, and less to linear shaped charges. The effect of a single factor can be determined experimentally or predicted theoretically by using hydrodynamic computer programmes that simulate the formation of jet and penetration process of the linear shaped charges. If computer simulation is used, it is necessary to verify the results experimentally, therefore the majority of researchers apply both methods [3 ÷ 5, 7, 8] in order to reduce the necessary number of measurements, adjustments and improvements of models.

2 Shaped charges

An explosive charge is a quantity of explosive material which, when detonated, carries out mechanical work. The energy of explosives is used for blasting in mining and civil engineering, for forming, perforating and welding of metals, cutting and demolition of various structures, etc. In relation to their shape, the explosive charges can be divided into three groups:

- concentrated explosive charges,
- linear explosive charges and
- shaped charges [9].

The shaped charges differ from other charges due to the possibility of focusing the energy released by detonation.

A cylinder of explosive with a hollow cavity at one end and a detonator at the opposite end is known as a hollow charge. If the hollow cavity is lined with a thin layer of metal, plastic, ceramic, or similar materials, the liner forms a jet when the explosive charge is detonated [2].

The increased penetration depth of shaped charges is achieved by moving the charge at a certain distance of a target material (standoff distance). The performance of the shaped charges and the effect of the liner and standoff distance are represented schematically in Fig. 1.

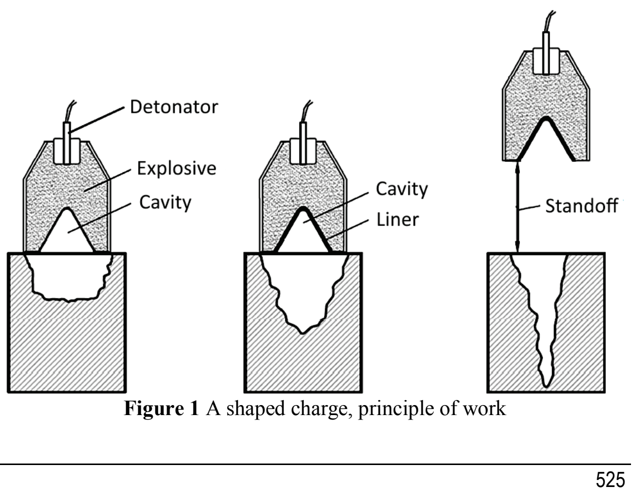

Figure 1 A shaped charge, principle of work

The shaped charges can be divided into the following categories, according to their shape, focusing detonation energy and function:
- conical shaped charges or perforators and
- linear shaped charges or cutters.

The conical shaped charges or perforators are used for the perforation of a target material. The liner is of a conical shape, and detonation energy is focused on the single point.

The linear shaped charges are used for cutting a target material. The liner is of prism shape and detonation energy is focused along the longitudinal axis. The performance of the conical shaped charge is defined by the depth of perforation in the material, while the performance of the linear shaped charge is defined by the maximum thickness of a material that can be cut.

2.1 Linear shaped charges

The shaped charges with one dimension, usually length, significantly larger than the other are called the linear shaped charges (LSC).

The detonation of an explosive charge focuses detonation energy towards a cavity while the shock wave deforms and accelerates the liner. With an appropriate selection of geometrical properties, liner material and the ratio between the mass of the liner and explosive charge the optimal efficiency of the linear shaped charges is achieved. It is presented as the maximum penetration depth performed by the linear shaped charge in the target material, and it is proportional to kinetic energy of the accelerated liner material. Cutting or the performance of the linear shaped charge consists of two mechanisms. The primary mechanism is the penetration of the jet of the linear shaped charge into the target material. When the jet reaches the target, the pressure of the jet on the material is significantly larger than the compressive strength of the material. Due to that the material is torn apart and the jet penetrates into the target and forms a cut. The target material is plastically deformed and it resists the penetration which results in decreased velocity and kinetic energy of the jet. When kinetic energy of the jet in the process of penetration is reduced to a certain value, which depends on the target material, the penetration stops. The secondary mechanism is caused by the impact of compressive shock waves and it results in the formation of a crack in the target material after the jet penetration. If the thickness of the material is sufficiently large, the impact of the shock waves is lowered, and the size of the crack created in that manner is insignificant. The sum of these mechanisms equals the total thickness of the material which can be cut by the linear shaped charge.

3 Influencing factors

Out of the series of factors influencing the penetration depth of the linear shaped charges, the following ones that affect the general performance can be singled out:
- liner material and liner shape,
- explosive,
- standoff distance,
- initiation,
- housing.

3.1 Liner

One of the most important elements of the shaped charges is a cavity liner. The liner is a source of heavy molecules accelerated by detonation energy and focused on the target material [10]. The mass of the accelerated molecules of the liner increases kinetic energy which causes the formation of the cut. It is necessary to coordinate the properties of the liner with the explosive mass per unit length in order to achieve the maximum efficiency of the linear shaped charge. The most important parameters are the liner material and shape.

Held analyses specific metals used for the liner according to the density, bulk sound speed, maximum theoretical velocity of a primary jet, and the product of primary jet velocity and material density [1]. Based on the results, and in relation to the possibility of use as the material for the shaped charges, the metals are ranked from the best to the worst. The possibility to apply various metals as liner material of shaped charges is presented in the table.

Table 1 Possibility of application of different liner materials for shaped charges [1]

	Al	Ni	Cu	Mo	Ta	U	W
Density / g/cm^3	2,7	8,8	8,9	10	16,6	18,5	19,4
Bulk sound / km/s	5,4	4,4	4,3	4,9	2,4	2,5	4
$v_{j\max}$ / km/s	12,3	10,1	9,8	11,3	5,4	5,7	9,2
$v_{j\max}\sqrt{\rho_j}$	20,2	30	29,2	35,7	22	22	40,5
Rank	7	3	4	2	6	5	1

The shape and geometrical properties of the liner determine the properties of the formed cut and the application of the shaped charge. Most widely used linear shaped charges have a liner of the shape of an inverted V in cross section.

In order to achieve the successful performance of the shaped charges it is necessary that the two halves of a cross section are symmetrical in relation to the central axis. The slightest deviation in relation to the axis of the linear shaped charge will result in the decrease of efficiency. It is not possible to construct an absolutely symmetrical shaped charge due to the limitations of a manufacturing process [5].

3.2 Explosive

Shaped charges are usually filled with the explosives of high detonation velocity and pressure [2]. It is considered that the explosives with the detonation velocity below 4500 m/s have a substantially lower effect, therefore are not suitable for the shaped charges [10]. In addition to the high detonation velocity and pressure, the explosive must be homogeneous (with no cavities, bubbles and impurities), uniformly granulated and must adhere to the liner walls. The effect of the quantity of an explosive on the depth of the cut of the linear shaped charge can be expressed on the basis of the explosive mass (C) or on the basis of the relation between the mass of metal liner (*M*) and the mass of explosive (*C*) per unit area (*M*/*C*).

3.3 Initiation

Electric and non-electric detonators, and in special cases boosters, are used to initiate the linear shaped charges. Certain manufacturers recommend a detonating cord for the initiation of the linear shaped charges. The initiation location, i.e. the position of a detonator, can be at one of the ends of the shaped charge, in the centre, or a pair of detonators can be placed at the opposite ends of the linear shaped charge. In relation to the longitudinal axis of the linear shaped charge, the position of detonators can be either parallel or vertical to the axis.

3.4 Housing

The function of housing is defined through the additional focusing of detonation products towards the liner of the linear shaped charge. In addition to that, the liner provides unaltered shape of the charge during the performance. The housing is usually made of the material of high density, low price and, due to its properties, appropriate for the manufacturing process of the linear shaped charges [4]. It is known that the shaped charge covered by a metallic plate on the upper part will be more efficient than the one without a metallic plate. This knowledge is used for the design and construction of the linear shaped liners [6].

3.5 Standoff distance

The standoff (*S*) is the distance between the shaped charge and the target. It is factors which influence properties of the cut of the linear shaped charges. By moving the shaped charge away from the target the optimal standoff distance is achieved at which the jet impacts the target. The efficiency of the charge is increased to a certain standoff distance, which is called the optimal standoff distance. If the standoff distance is larger than the optimal value, the efficiency decreases due to the weakened jet, i.e. the decreased concentration of kinetic energy towards the end of the jet. The optimal standoff distance is determined by the geometrical properties of the shaped charge construction, apex angle and width of the shape charge with the constant properties of the target material, constant explosive filling and liner properties. The linear shaped charges with the same geometrical properties and mass of explosive have different impact at the same standoff distance if the liner material is different. It is the result of the different ratio of the explosive mass and liner metal mass with the same geometrical properties caused by different liner material density.

4 Experiment description

During testing the influence of the factors which are considered to have the highest effect on the penetration depth was determined. The observed factors were:

a) mass of explosive,
b) liner material,
c) standoff distance.

4.1 Test samples

The explosive filling of the linear shaped charges contains penetrate with the addition of non-explosive plasticizer used as a binder. High detonation velocity (approximately 7200 m/s), high density (1,42 g/cm^3) and the property of moulding in order to adhere to the liner are the essential properties which determine the selection of the explosive filling for the linear shaped charges.

The copper and aluminium sheets were selected for the liner of the linear shaped charges. Copper and aluminium are most commonly used for manufacturing of commercial linear shaped charges. The thickness of the aluminium liner was 1 mm, and of the copper liner 0,5 mm. The sheets were bent by a machine at the angle of 90°. The cross section of the linear shaped charge with its construction properties is presented in Fig. 2.

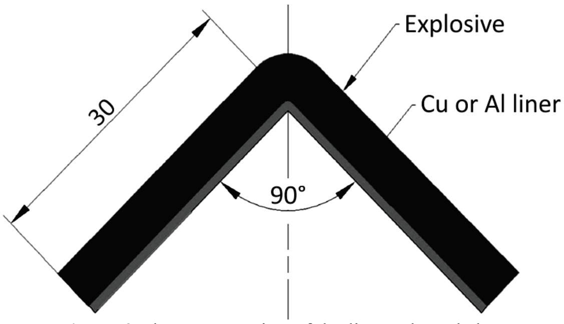

Figure 2 The cross section of the linear shaped charge

The test samples of the linear shaped charges were constructed with no housing, i.e. cover, which is the main difference in relation to the majority of commercial linear shaped charges. It is considered that the physical processes characteristic for the linear shaped charges with the housing are the same for the linear shaped charges with no housing. This or the similar model is often used in the research of the linear shaped charges [7, 11, 12].

4.2 Measurement setup

A total of 48 linear shaped charges were constructed and tested. They were divided in two groups taking into account the liner material which was used. The first group comprises the charges with aluminium liners 1 mm thick, and the second group charges with copper liners 0,5 mm thick. The mass, thickness and angle of liners were constant for all charges, and the explosive mass and standoff distance varied. The mass of the explosive for the charges with the aluminium liner equalled approximately 14 g, 19 g and 27 g, and the related *M*/*C* ratio equalled 0,9; 0,7 and 0,5. The mass of the explosive for the charges with the copper liner equalled approximately 15 g, 20 g and 27 g, and the related *M*/*C* ratio equalled 1,4; 1,0 and 0,8. The largest mass of the explosive was limited by the properties of the laboratory testing chamber.

The characteristic standoff distances of 0 mm, 10 mm, 20 mm and 30 mm were selected. In order to achieve various standoff distances the wooden slats of 10×10 mm, 20×10 mm and 30×10 mm were placed between the target and the linear shaped charge. The research was carried out with aluminium targets in which case the linear shaped charges demonstrate higher efficiency than in the case of steel targets, which results in the simpler and more precise analysis of the cut. After detonation the largest and average penetration depth was measured for each cut by a dial indicator. The measurement setup is presented in Fig. 3.

Figure 3 Measurement setup

4.3 Measurement results

Fig. 4 presents the characteristic cuts of the linear shaped charge with the aluminium liner with explosive mass of 27 g and various standoff distances (*S*), and Fig. 5 graphically depicts the largest and average penetration depth for the charge with the aluminium liner.

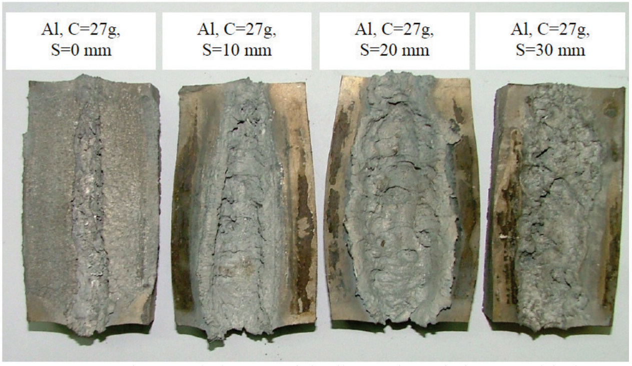

Figure 4 Characteristic cuts of the linear shaped charges with the aluminium liner

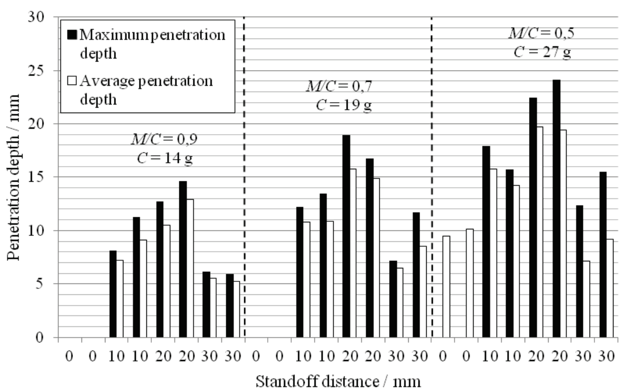

Figure 5 The largest and average penetration depth, the linear shaped charges with the aluminium liners

Tab. 2 presents construction parameters for the linear shaped charges with the aluminium liner and measured penetration depths.

Fig. 6 presents the effect of the explosive mass on the average penetration depth at various standoff distances. Fig. 7 presents the effect of *M*/*C* ratio on the average penetration depth at various standoff distances.

Table 2 Construction parameters, the largest and average penetration depth of the linear shaped charges with the aluminium liner

	M / g	*C* / g	*M*/*C*	*S* / mm	Max. pen. depth / mm	Av. pen. depth / mm
1	12,93	14,14	0,9	0	*	*
2	12,98	13,79	0,9	0	*	*
3	12,95	14,35	0,9	10	8,1	7,2
4	13,14	14,43	0,9	10	11,2	9,1
5	12,97	13,93	0,9	20	12,7	10,5
6	12,94	14,33	0,9	20	14,6	12,9
7	13,14	14,42	0,9	30	6,1	5,5
8	13,14	14,14	0,9	30	5,9	5,2
9	13,19	19,09	0,7	0	*	*
10	13,20	19,41	0,7	0	*	*
11	12,99	18,71	0,7	10	12,2	10,8
12	13,02	19,16	0,7	10	13,4	10,9
13	12,91	18,89	0,7	20	18,9	15,8
14	13,01	18,55	0,7	20	16,7	14,9
15	13,03	18,70	0,7	30	7,1	6,5
16	13,06	18,98	0,7	30	11,7	8,5
17	12,96	26,72	0,5	0	*	9,5
18	13,11	26,59	0,5	0	*	10,1
19	12,90	26,21	0,5	10	17,9	15,8
20	12,99	26,61	0,5	10	15,7	14,2
21	13,04	26,66	0,5	20	22,4	19,7
22	12,96	26,77	0,5	20	24,1	19,4
23	13,05	26,75	0,5	30	12,3	7,1
24	13,00	26,82	0,5	30	15,5	9,2

* Impossible to measure the penetration depth due to the melting and solidifying of the metal liner into the cut area.

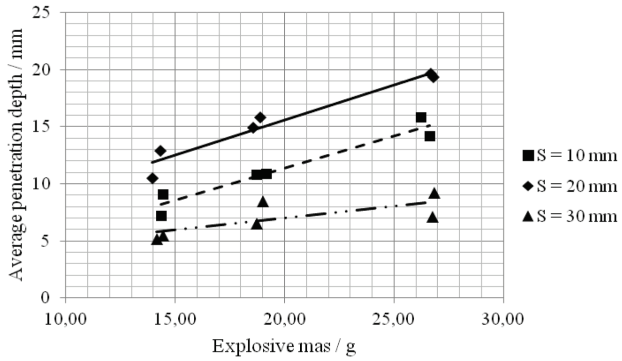

Figure 6 The effect of the explosive mass on the penetration depth at various standoff distances

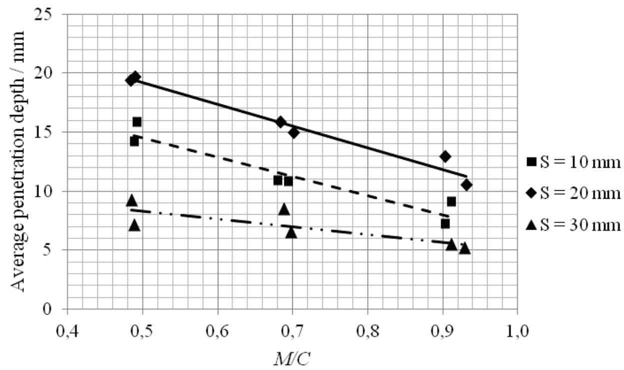

Figure 7 The effect of M/C ratio on the penetration depth at various standoff distances

Fig. 8 presents the characteristic cuts of the linear shaped charge with the copper liner with explosive mass of 26 g and various standoff distances (*S*), and Fig. 9

graphically depicts the largest and average penetration depths for the charges with the copper liner.

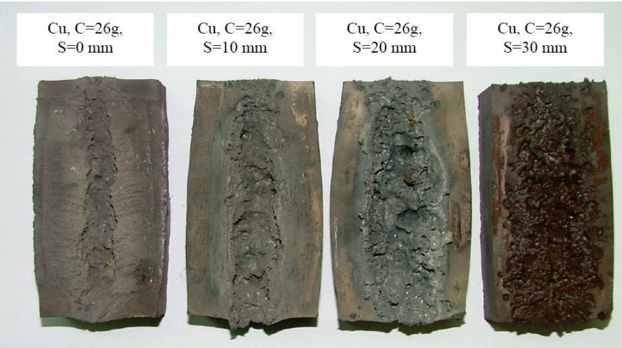

Figure 8 The characteristic cuts of the linear shaped charge with the copper liner

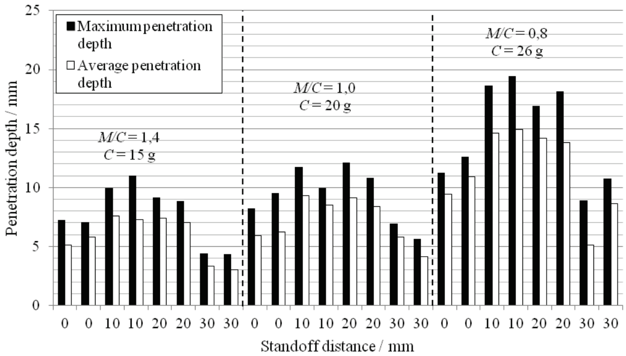

Figure 9 The largest and average depth of the cut, the linear shaped charges with the copper liners

Table 3 Construction parameters, the largest and average penetration depth of the linear shaped charges with the copper liner

	M / g	*C* / g	*M*/*C*	*S* / mm	Max. pen. depth / mm	Av. pen. depth / mm
1	20,75	15,29	1,4	0	7,2	5,1
2	20,95	14,49	1,4	0	7,0	5,8
3	20,70	14,61	1,4	10	9,9	7,6
4	20,72	15,30	1,4	10	11	7,3
5	20,95	15,19	1,4	20	9,1	7,4
6	20,83	15,12	1,4	20	8,8	7,0
7	20,91	15,16	1,4	30	4,4	3,3
8	20,72	15,31	1,4	30	4,3	3,0
9	19,99	19,96	1,0	0	8,2	5,9
10	20,43	19,56	1,0	0	9,5	6,2
11	20,19	19,90	1,0	10	11,7	9,3
12	20,36	19,49	1,0	10	9,9	8,5
13	20,40	19,59	1,0	20	12,1	9,1
14	20,08	19,85	1,0	20	10,8	8,4
15	20,44	20,06	1,0	30	6,9	5,8
16	20,37	19,60	1,0	30	5,6	4,1
17	20,29	26,49	0,8	0	11,2	9,4
18	20,10	26,36	0,8	0	12,6	10,9
19	20,29	26,76	0,8	10	18,6	14,6
20	20,00	26,60	0,8	10	19,4	14,9
21	20,35	26,11	0,8	20	16,9	14,2
22	20,36	25,85	0,8	20	18,1	13,8
23	20,03	26,66	0,8	30	8,9	5,1
24	20,05	26,46	0,8	30	10,7	8,6

Tab. 3 lists the construction parameters of the linear shaped charge with the copper liner and the measured penetration depths.

Fig. 10 presents the effect of the explosive mass on the average penetration depth at various standoff distances, and Fig. 11 presents the impact of *M*/*C* ratio on the average penetration depth at various standoff distances.

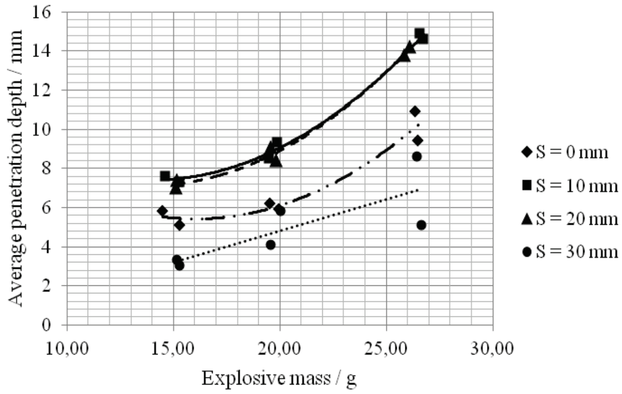

Figure 10 The effect of the explosive mass on the penetration depth at various standoff distances

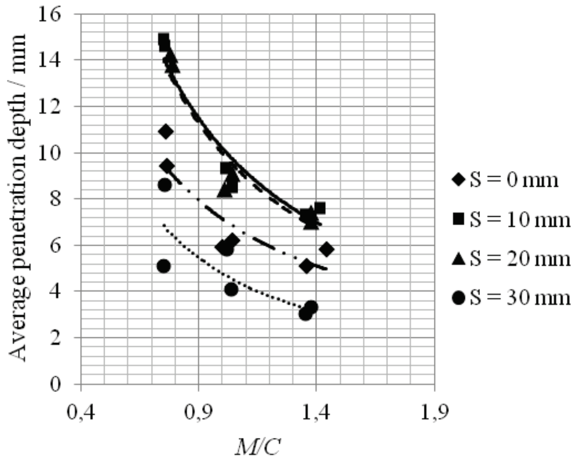

Figure 11 The effect of *M*/*C* ratio on the penetration depth at various standoff distances

Figs. 12 and 13 depict in parallel the penetration depths for different liner materials.

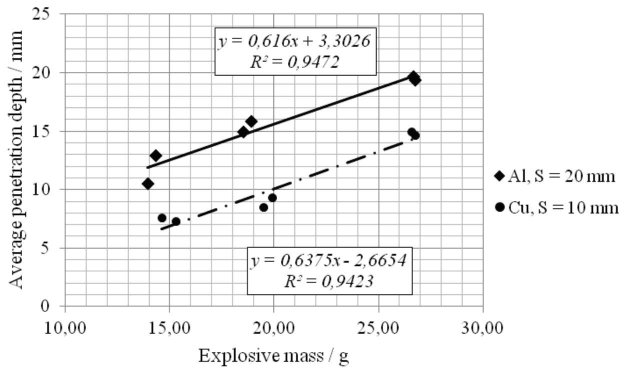

Figure 12 A parallel depiction of the effect of explosive mass on the penetration depth for different liner materials

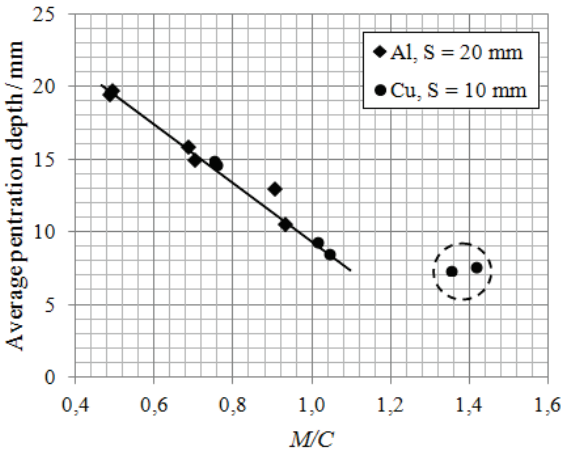

Figure 13 A parallel depiction of the impact of *M*/*C* ratio on the depth of the cut for different liner materials

5 Result analysis and conclusion

According to the measurement results for both liner materials, penetration depth grows with the increase of the explosive mass (Figs. 5 and 6). The increase of the penetration depth results in the increase of the irregularity of the cut, i.e. the difference between the largest and the average depth of the cut.

The penetration depth at the standoff distance of 0 mm is particularly irregular and impossible to measure as the liner material was melted and solidified into the cut area. The properties of the cut at the aforementioned standoff distance indicate that the time period was inadequate for the efficient formation of a jet. In addition to the alterations of the depth, as the standoff distance increases, the width of the cut also increases. The cut at the standoff distance of 30 mm, in addition to its shallowest depth, is particularly irregular which can be explained by the fragmentation of jet at higher standoff distance. The largest increase of the penetration depth in the case of the aluminium liner is when the standoff distance equals 20 mm which can be considered as the optimal standoff distance for the tested construction of the linear shaped charger. In the cases of smaller or larger differences from the optimal standoff distance, the effect of the explosive mass on the penetration depth is smaller. For the copper liner, the greatest penetration depth was achieved at the standoff distance of 10 mm, and slightly shallower depth at the standoff distance of 20 mm. In order to determine the optimal standoff distance it is necessary to carry out further measurements for the aforementioned standoff distance range.

In relation to the explosive mass and target material the linear shaped charges with the aluminium liner, at the optimal standoff distance, achieved a greater penetration depth in the aluminium target when compared to the charges with the copper liner. With the same explosive mass the average penetration depth of the charge with aluminium liner is approximately 5 mm larger than the average penetration depth of the charge with copper liner.

The relation between the explosive mass and the greatest penetration depth for both materials has the form of the linear equation (Fig. 10). The effect of the explosive mass on the average penetration depth of the charge with the aluminium liner at the standoff distance of 20 mm is expressed by the Eq. (1) and the effect of the explosive mass on the average penetration depth of the charge with the copper liner at the standoff distance of 10 mm by the Eq. (2).

$$y = 0{,}616 \cdot x + 3{,}3026, \tag{1}$$

$$y = 0{,}6375 \cdot x - 2{,}6654, \tag{2}$$

where:
y – average penetration depth (mm) and
x – explosive mass (g).

The coefficients of determination (R^2) are calculated for each curve, with the approximate values R^2 = 0,95 for the charges with the aluminium liners and R^2 = 0,94 for the charges with the copper liners.

The larger penetration depth of the charges with the aluminium liner when compared to the charges with the copper liner with the same explosive mass is caused by the lower mass, i.e. lower density of the aluminium liner when compared to the copper liner. With the same explosive mass the linear shaped charges have lower *M*/*C* ratio. Therefore, the penetration depth for different liner materials is analysed in relation to *M*/*C* ratio. If the efficiency of the linear shaped charges in relation to *M*/*C* ratio is observed, it is evident that the charges with both aluminium and copper liner achieve the penetration depth in the aluminium target. The exception is the value of 1,4 for *M*/*C* ratio for the copper liner where the measured penetration depth is larger.

The largest recorded average penetration depth in the aluminium target was achieved when detonating the linear shaped charge with the aluminium liner, explosive mass of 27 g and standoff distance of 20 mm.

It is necessary to carry out further measurements of the efficiency of the linear shaped charges with samples of larger explosive filling mass and construction parameters. In the presented research the targets were placed on the solid surface. Since the linear shaped charges are usually used for cutting metal profiles, i.e. detached construction parts, further research will be carried out with targets placed on racks. The depths of the cut achieved in that way will correspond more closely to the real circumstances of the use of the linear shaped charges.

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