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Research paper

Studying the Effectiveness of Shaped Charge Jets Created by Graphene-containing Shaped Charge Liners

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Abstract. The paper presents selected results of studies conducted within the framework of the following research project: "Use of graphene and new multilayer explosive technologies in materials for shaped charge liners" (The National Centre for Research and Development in Poland: project No: DOB-BI08/03/01/2016). This study was performed by a consortium made up of the following entities: Institute of Precision Mechanics, Military University of Technology and the Mototechnika company (Poland). The main objective of the performed experiments was to test the effectiveness of shaped charge liners produced with the use of powder metallurgy methods, from mixtures containing copper powder and graphene-coated copper powder. The content of the latter equaled 0%, 1%, 5% and 10%, respectively. Shaped charge jets created with the use of liners made from the powder mixtures tested were recorded with the help of X-ray technology. Firing tests were conducted against steel barriers and the depth of penetration was determined. The obtained results showed that the addition of graphene powder to pure copper powder practically does not increase the depth of penetration of the shaped charge jet compared to scenarios in which sintered liners without this additive were used.
Keywords: powder metallurgy, shaped charge liners, graphene

1. INTRODUCTION

Shaped charge systems (SCS) are widely used in weapons. They are relied upon in warheads of rockets and torpedoes, artillery shells, grenades and mines. The effectiveness of a SCS is determined by the depth of penetration of the shaped charge jet (SCJ) generated by the shaped charge liner (SCL), into a partition made of armored steel. It is expressed in multiples of the diameter of the explosive charge [1]. The first SCS, used in anti-tank munitions, were designed to meet the penetration requirements prevailing at the time, but their potential capabilities were significantly greater. It was not until ways to observe and record the generated shaped charge jets were developed - primarily relying on X-rays to register the highly dynamic phenomena [2] - that the basic requirements for the design and manufacture of SCS were established.

The effectiveness of SCS depends on many factors, with the most prominent of them including [3]:

- the material, shape and method of manufacturing the SCL (with the precision of manufacturing the SCL exerting a very significant impact here),
- the type of explosive used,
- the design of the SCS.

The impact of the mechanical properties of the liner's material on the formation of the SCJ is of complex nature and is rooted in the mechanics of the phenomenon. The adequate strength and ductility of the liner material under dynamic loads depends on a number of factors affecting the aforementioned characteristics.

The most important of these are [2]:

- the type and chemical composition of the material,
- properties and structure of the material,
- shaped charge liner technology.

The conditions described above are closely interrelated and originate in the varieties and course of the main deformation mechanisms occurring in the polycrystalline material.

The deformation processes occurring in polycrystalline materials are, first and foremost, the result of dislocation movement and twinning. The proper effectiveness of SCS is achieved by using shaped charge liners (SCLs) made of materials that ensure the formation of a shaped charge jet characterized by a significant length of its continuous portion, high face velocity, large density and a long fragmentation onset lead time.

High-purity copper (impurity content below 0.05%) is a material that is commonly used for SCLs. Oxygen, sulfur and phosphorus are the most harmful pollutants in this particular case. Forming hard and brittle chemical compounds when combined with copper, these elements significantly reduce its mechanical properties [4]. The use of copper is advantageous because of its good plastic properties, making it possible to obtain a long, properly shaped SCJ. However, the use of SCLs made of metallurgically obtained materials is often associated with anisotropy of the linermaterial (this applies, in particular, to materials produced with the use of metal forming methods). Therefore, research has been continuing, for many years now, on the application of SCLs manufactured with the use of powder metallurgy methods [5-7]. Such an approach allowed to obtain a high purity material with a fine-grained microstructure [8].

In described investigation also attempted to use powder metallurgy methods to produce shaped charge liners. Graphene-coated copper powder was used as the input material. Detailed information on the materials, as well as shaped charge liner manufacturing process used may be found in previously published papers [9 and 10]. The results of preliminary studies concerned with the microstructure and mechanical properties of the material obtained proved its fine-grain structure. The addition of graphene-coated powder resulted in a decrease in ductility and an increase in strength and hardness.

The main purpose of the studies described below (X-ray tests of shaped charge jets and their ability to penetrate steel obstacles) was to document and analyze the results in order to select the best solutions available for their future use in newly developed shaped charge systems. In order to achieve this goal, suitable shaped charges needed to be fabricated and an X-ray recording of the process of formation of the shaped charge jet had to be performed and analyzed to determine the jet's parameters (linearity, thickness, face velocity, length and burst time). Finally, at the last stage, tests during which the charges were fired at steel shields had to be performed to determine the depths of the resulting craters and their dependence on the shaped charge liner variant used.

The results of the work carried out at the Institute of Chemistry, Department of New Technologies and Chemistry, and the Institute of Armament Technology, Department of Mechatronics and Aeronautics, Military University of Technology (Warsaw, Poland), testing the feasibility of adding graphene to the material from which sintered shaped charge liners are manufactured, are presented below.

In the study, graphene-coated copper powder was used. The method for obtaining that powder was developed at the Institute of Precision Mechanics in Warsaw (Poland). The process of manufacturing this material is protected under Patent No. PAT.225890 "Method of producing carbon structures with graphene-containing copper powders using thermo-chemical processing" issued on 1.12.2016.

2. PREPARATION OF SHAPED CHARGE SYSTEMS

The fabrication of SCS containing the researched SCLs required that the tools necessary to make the structural elements of the laboratory setup be designed and manufactured. An explosive system was chosen guaranteeing optimal (from the point of view of the efficiency of driving the SCL) parameters and profile of the detonation wave loading the linerwas selected. The effectiveness of shaped charges was determined based on the shape and velocity of jet generated by a linermade of pure copper (parameters of the jet were determined based on X-ray images and modeling). The system was used to examine the properties of the shaped charge jets generated by the SCLs used in the experiments.

Figure 1 shows the dimensions of the tested SCLs and some sample liners. The following shaped charge liner varieties were fabricated:

1. SCL made with the use of the powder metallurgy method, from copper without any graphene added,
2. SCL made by pressing a powder mixture of pure copper (Cu) and graphenated copper powder (CuG), with the following composition:
   a) 99% Cu electrolytic powder + 1% CuG graphenated copper powder,
   b) 95% Cu electrolytic powder + 5% CuG graphenated copper powder,
   c) 90% Cu electrolytic powder + 10% CuG graphenated copper powder.

A shaped charge has been designed with its dimensions corresponding to those of the charges used in RGP 40 mm anti-tank and fragmentation rifle grenades (made by ZM “Tarnów” S.A. in Poland). The charge was made of PBXW-11 explosive, containing: 96% octogen, 3% DOA plasticizer (dioctyl adipate) and 1% HyTemp plasticizer (ethyl acrylate and butyl acrylate copolymer). This material is used, inter alia, in grenade launcher munitions [11]. The charges were made using the press method.

A die and a punch were designed and fabricated to press the charge for the shaped charge liner.

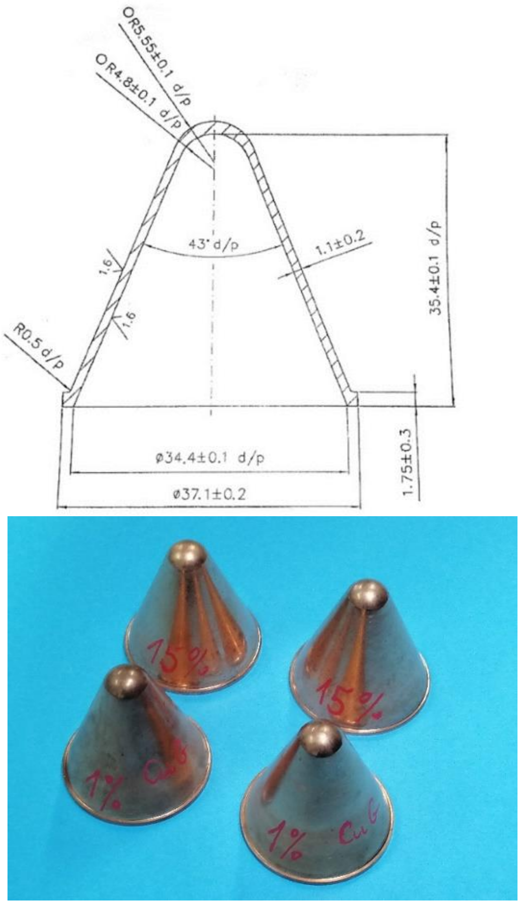


Fig. 1. Dimensions and photo of shaped charge liners made with the use of the sintering method

The shaped charge used for X-ray tests of the SCS (Figure 2) consisted of a shaped charge liner (1), a basic explosive charge (PBXW-11) (2), an auxiliary explosive charge (PBXW-11) (3), an 3D printed aperture (detonation lens) made of the Z-Ultrat filament (4), a transition charge (RDXph) (5), a steel sleeve (6), a centering disc (7), an "Erg" 9 fuse (8), and a 3D printed casing made of the Z-Ultrat filament (9).

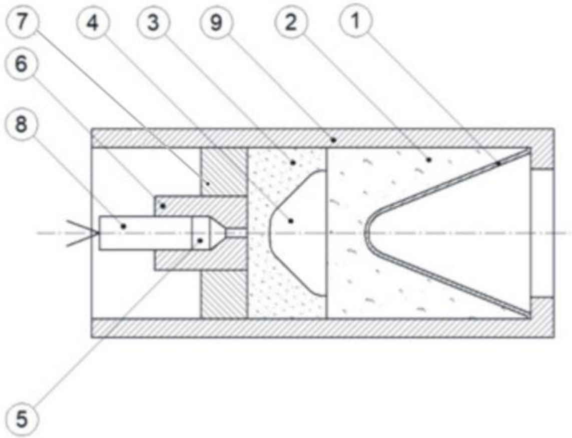


Fig. 2. Diagram of a system used for generating shaped charge jets

Figure 3 shows the elements of a shaped charge system used for X-ray recording of the SCJ.

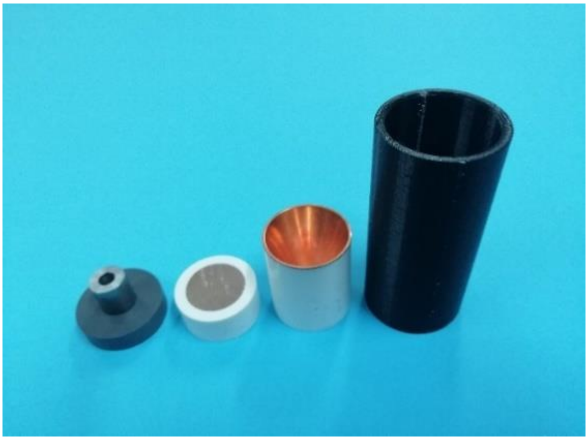


Fig. 3. Components of the shaped charge system used for recording the jet

3. TESTING METHODOLOGY

3.1. Methodology for testing the formation of shaped charge jets

X-ray recordings of the shaped charge jets were made at the Dynamic Research Laboratory, Department of Explosives, Warsaw Military University of Technology, using the SCANDIFLASH 450 pulsed X-ray recorder.

The recorder was made up of an X-ray tube (emitter), a high-voltage pulse forming system (pulser), a control module with a delay generator, an ion pump power supply, dielectric gas pressure control systems, a vacuum pump, X-ray film cassettes, and an X-ray film developing machine. The basic characteristics of the device are presented in Table 1.

Table 1. Basic characteristics of the SCANDIFLASH 450 set

Voltage range	150-450 kV
Discharge current intensity	10 kA
Pulse duration	20 ns
Dose at 1 m distance	20 mR
Steel penetration depth	18 mm

The layout of the SCJ registration stand is presented in Figure 4. Shaped charge 1 is placed at a distance of approximately 2.7 m from emitter 2 and 0.5 m from cassette 3. A short-circuit sensor is placed inside the charge, which is short-circuited when the detonation is initiated. An electrical impulse triggers a delay circuit, which in turn trigger the pulser after a certain period of time. The high-voltage pulse generated by the pulser creates X-rays in the emitter. The radiation beam passes through a wooden shielding window and is projected on the shaped charge jet. Absorption of radiation by the jet material results in attenuation of the radiation reaching the X-ray film cassette. Consequently, the shape of the shaped charge jet is recorded on film. Once the film is developed, this shape is analyzed to determine the jet's characteristics.

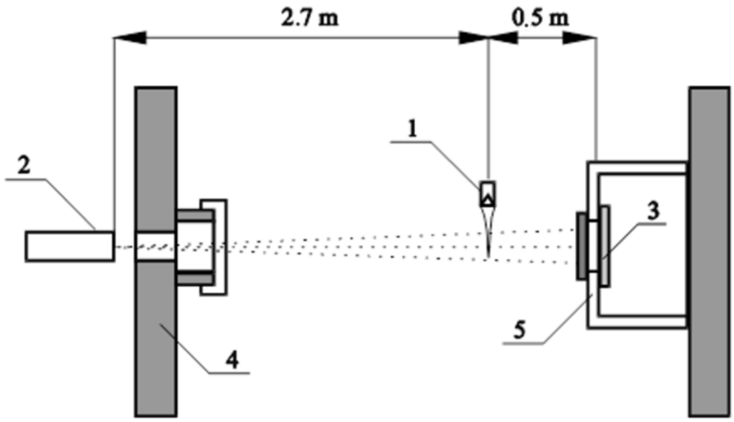


Fig. 4. Layout of for X-ray recording of shaped charge jets: 1 – shaped charge, 2 – emitter, 3 – photographic film, 4 – emitter cover, 5 – film cover

The analysis of the X-ray images took into account the magnification associated with the divergence of the radiation beam. The degree of this magnification was determined based on the image of a marker placed at a distance of 100 mm from the base of the liner. A 100 mm long metal rod was used as the marker. The linearity and symmetry of the shaped charge jet were assessed based on the X-ray images obtained. Jet lengths were determined at different times from the initiation of the detonation inside the charge. Those lengths served as a basis for determining the velocity of the jet face.

3.2.Penetration depth measurements

The system shown in Figure 5 was used to determine the penetration depth of the shaped charge jet.

Fig. 5. Images of the components and the complex system used for testing the steel penetration depth of the shaped charge jet

During the first stage of the testing procedure, a thick steel rod made of S235 JR steel with a diameter of 60 mm was used as the shield. A spacer, i.e. a tube made of Z-Ultrat filament, with an outer diameter of 45 mm and a length of 50 mm, was positioned on the rod. In this scenario, the length of the tube (spacer) corresponds to the theoretical distance between the base of the shaped charge liner and the obstacle when the explosive head in the grenade launcher ammunition is triggered. The shaped charge was placed on the upper edge of the tube. The explosive charge was stimulated to detonate using the "Erg" detonator. The tests were performed at the Dynamic Testing Laboratory of the Department of Explosives (Military University of Technology, Warsaw, Poland).

After the tests, the steel rods were cut in such a way as to reveal the hole created by the jets. The depth of the craters was measured.

4. TEST RESULTS

Prior to commencing the proper experiments, the tested liners were verified for their porosity. Table 2 shows the results of the porosity test for all variants of the sintered shaped charge liners. This test was performed using the hydrostatic method.

Table 2. Results of shaped charge liner porosity tests

Powder mixture designation	Chemical composition of powder mixture	Average porosity [%]
100% Cu	Cu	0.76
99% Cu + 1% CuG	1% CuG	1.66
95% Cu + 5% CuG	5% CuG	1.30
90% Cu + 10% CuG	10% CuG	1.82

As can be seen from the results presented, the lowest porosity (0.76%) was characteristic of linersmade of copper powder without the addition of graphene powder. The addition of graphene-coated copper powder caused a slight increase in the porosity of the liners, but in this case one can no longer see a clear relationship between chemical composition and porosity, with the latter being in the 1.30-1.82 range. In the literature, one can find information that shaped charge jets formed by linersmade of copper sinters with their porosity not exceeding 8% have characteristics similar to those made of solid copper [2]. Therefore, they can be used as elements of shaped charge systems.

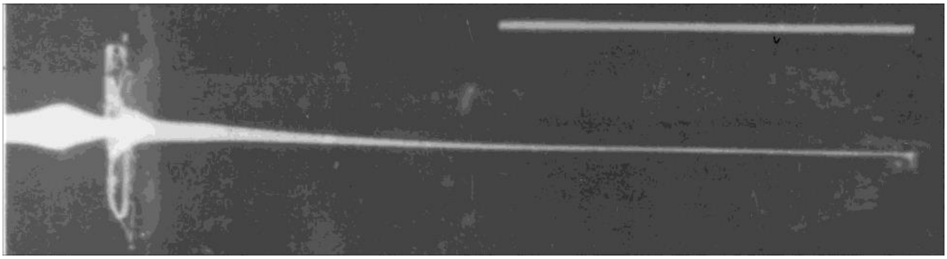
4.1. Shaped charge jet registration results

Preliminary evaluation and comparison of different variants of shaped charge liners was carried out on the basis of observations of shaped charge jets generated by explosive charges.

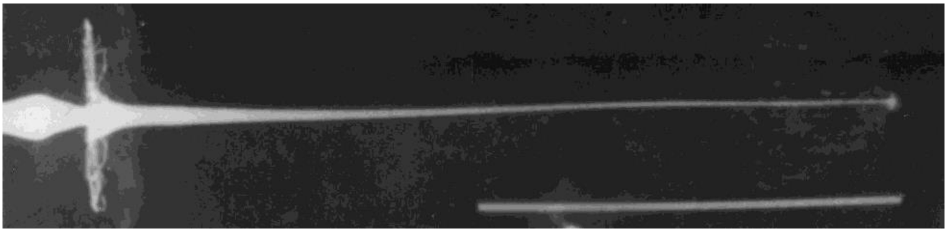
The following are samples of SCS X-ray images obtained by firing shaped charges using different types of SCL. All images were taken 35 μs after initiating the detonation of the shaped charge.

The X-ray images obtained showed that some of the recorded SCJs exhibit, in the middle and rear portions, some thicker sections and deviations from their axis of symmetry. These may be the result of a material defect, asymmetry of the load created by the detonation wave, or inaccuracies in the manufacture of the liner. The last cause, in turn, may be rooted in the fact that the punch used when extruding the powders may have been led off-axis relative to the die.

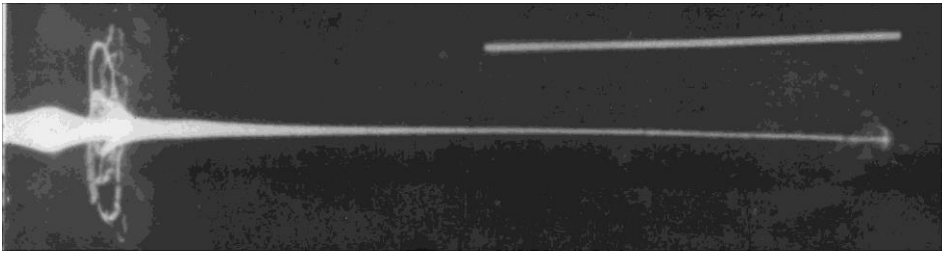
Figure 6 shows the recorded shaped charge jet images created by linersof different chemical compositions. Emitter trigger time - 35 μs.



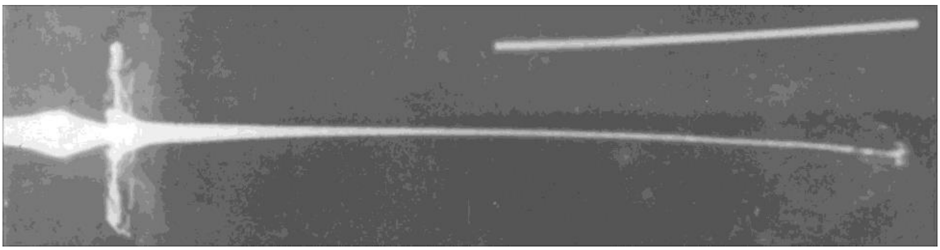
(a) – SCL material 100% Cu



(b) – SCL material 99% Cu + 1% CuG



(c) – SCL material 95% Cu + 5% CuG



(d) – SCL material 90% Cu + 10% CuG

Fig. 6. Images of shaped charge jets generated by linersmade of sintered copper powder (a), sintered copper powder and graphenated copper powder: 1% (b), 5% (c), 10% (d)

From the analysis of the images shown in Figure 6, it is apparent that jet gaps appear at the face of the jet for sintered linerswith a powder content of 5% CuG and with a powder content of 10% CuG. Using the images of the shaped charge jets, the position of the shaped charge jet face relative to the base of the charge was determined. Jet face velocity was determined from images taken at different times. The results are shown in Table 3.

Analysis of the results presented in Table 3 shows that the maximum lengths of the jets before fragmentation (for graphene powder liners) are slightly smaller than those determined for sintered copper powder liners. The lowest SCJ lengths were observed for linersmade of the following mixture: 90% Cu + 10% CuG powder.

The introduction of even the smallest amount of graphene accelerates jet fragmentation. In contrast, an increase in the content of CuG powder in the mixture has virtually no effect on the SCJ face velocity.

Table 3. Location of the face of the shaped charge jets generated by the tested linersand their velocities

Type of metal liner	Jet face position [mm]	Jet face velocity [m/s]
sintered 100% Cu powder	199.8	8,310
sintered powder 99% Cu + 1% CuG	198.8	8,260
sintered powder 95% Cu + 5% CuG	197.2	8,300
sintered powder 90% Cu + 10% CuG	196.6	8,300

4.2. Analysis of the effects of penetration of shaped charge jets into steel partitions

Further experiments involved penetration testing using shaped charges with sintered linersmade of various powder mixtures (Figure 5).

Figures 7-10 show the results of penetration testing using shaped charges with the tested MCs.

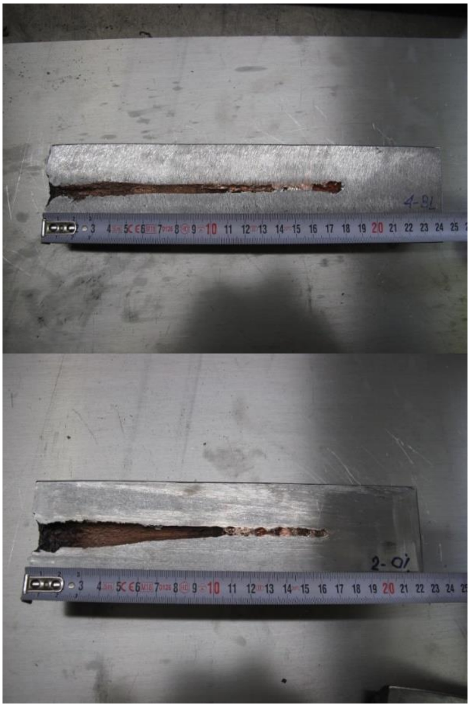


Fig. 7. Image of the crater after firing with a 100% Cu sintered liner

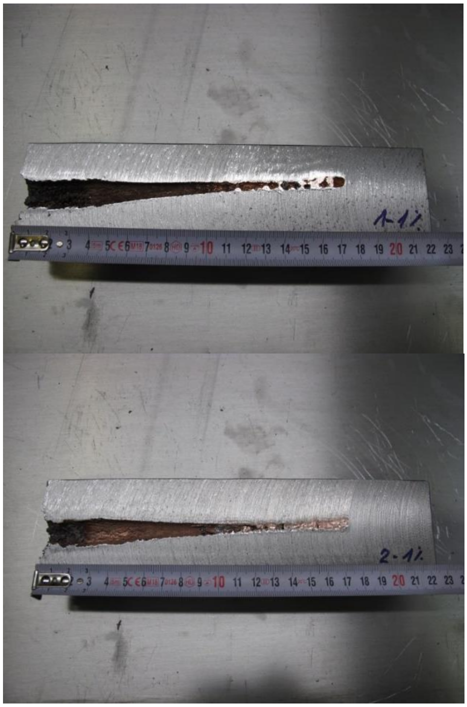


Fig. 8. Image of the crater after firing with a 99% Cu+1% CuG sintered liner

Results concerned with the jet's steel penetration depth are presented in Table 4.

Table 4. Measurement results - depth of partition penetration by the shaped charge jet

Chemical composition/type of linermaterial	Penetration [mm]	Average penetration [mm]
sintered 100% Cu powder	163	171
sintered 100% Cu powder	179	
sintered powder 99% Cu + 1% CuG	171	172
sintered powder 99% Cu + 1% CuG	173	
sintered powder 95% Cu + 5% CuG	177	175
sintered powder 95% Cu + 5% CuG	172	
sintered powder 950% Cu + 10% CuG	177	175
sintered powder 950% Cu + 10% CuG	173	

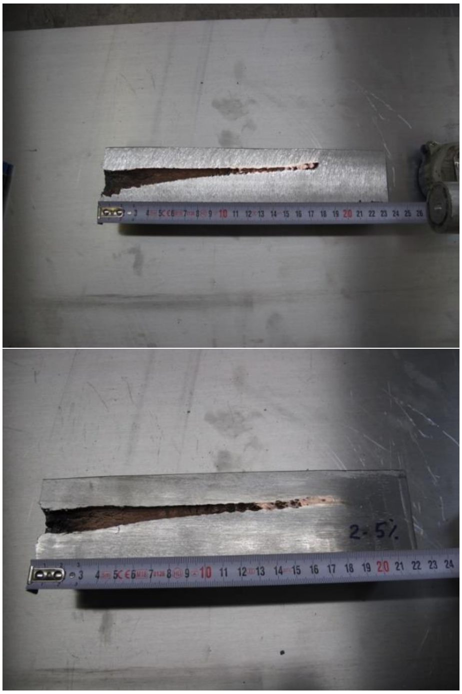


Fig. 9. Image of the crater after firing with a 95% Cu+5%CuG sintered liner

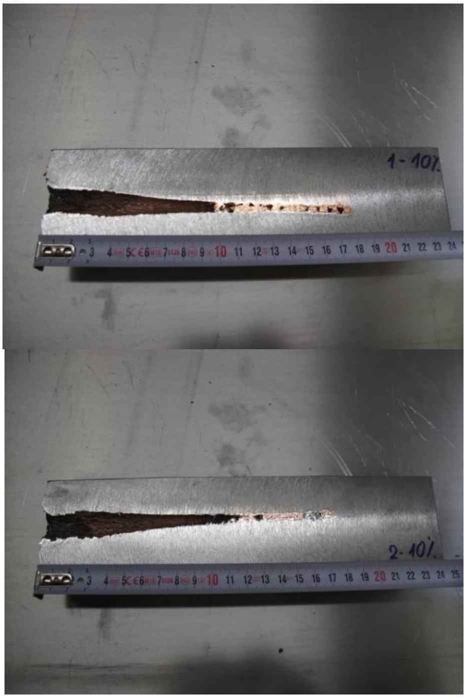


Fig. 10. Image of the crater after firing with a 90% Cu+10% CuG sintered liner

The results obtained indicate that the addition of graphenated powder, in the amount of 1 to 10%, to pure copper powder can cause only **a slight increase in the penetration depth** of the shaped charge jet compared to the case when sintered linerswithout this additive were used.

The penetration capability of a SCS depends on jet face velocity (which is very similar in this case) and the density of the shaped charge liner material (density/porosity values are very much similar).

5. SUMMARY AND CONCLUSIONS

In preparation for the study, shaped charge systems were fabricated with linermade of mixtures of copper powder and graphene-coated copper powder. Press dies were designed and fabricated for making explosive charges whose shapes were adapted to the geometry of grenade launcher munitions. The explosive charges were pressed and the shaped charge jets were recorded. The pulsed X-ray technique was used. Based on the images obtained, the quality of the jet was assessed. Jet lengths and jet head velocities were determined as well. The depth of penetration of steel rods by the shaped charge jets generated with the use of the tested linerswas also investigated.

Analysis of the obtained results allowed the following conclusions to be drawn:

- increasing the content of graphenated copper powder in the sintered linerincreases the length of the fragmented part of the jet,
- for high graphenated powder content values, the type of fragmentation changes from plastic fragmentation to brittle fragmentation,
- sintered shaped charge liners with different graphenated copper powder contents generate jets with similar face velocities,
- the introduction of even the smallest amount of graphene accelerates jet fragmentation,
- the results of the main tests, on the other hand, indicate that the addition of 1% to 10% graphenated powder to copper powder results in a slight increase in crater depth compared to a sintered linermade of pure copper powder,

Taking into account the characteristics of shaped charge jets obtained based on the X-ray images, and the results of steel rod penetration depth tests, one may conclude that the addition of graphene-coated copper powder to copper powder used for manufacturing grenade charges **is not justified**.

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Badanie efektywności strumieni kumulacyjnych uzyskanych przy wykorzystaniu wkładek kumulacyjnych zawierających grafen

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Streszczenie. W artykule zostały przedstawione wybrane wyniki badań przeprowadzonych w ramach realizacji projektu badawczego: „Zastosowanie grafenu i nowych technologii wielowarstwowych materiałów wybuchowych w materiałach na wkładki kumulacyjne" (nr projektu NCBiR: DOB-BI08/03/01/2016). Praca ta była przeprowadzona w konsorcjum, w skład którego wchodziły: Instytut Mechaniki Precyzyjnej, Wojskowa Akademia Techniczna oraz przedsiębiorstwo Mototechnika. Głównym celem wykonanych eksperymentów było zbadanie skuteczności wkładek kumulacyjnych, wytworzonych metodami metalurgii proszków, z mieszanek zawierających proszek miedzi oraz proszek miedzi pokryty grafenem. Zawartość tego ostatniego wynosiła odpowiednio:0%, 1%, 5% i 10%. Dokonano rentgenograficznej rejestracji strumieni kumulacyjnych przy zastosowaniu ładunków zawierających wkładki wytworzone z testowanych mieszanek proszkowych. Przeprowadzono próby strzelania do przegród stalowych i określono głębokość penetracji. Otrzymane wyniki badań wykazały, że dodatek proszku grafenowanego do proszku czystej miedzi praktycznie nie zwiększa głębokości wnikania strumienia kumulacyjnego w stosunku do przypadku, gdy zastosowano wkładki spiekane bez tego dodatku.
Słowa kluczowe: metalurgia proszków, wkładki kumulacyjne, grafen