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Testing the effectiveness of multi-layer target penetration by linear shaped charges

Badanie skuteczności przebijania celu wielowarstwowego przez liniowe ładunki kumulacyjne

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ABSTRACT: Although the cumulative detonation phenomenon is well-known and used in shooting techniques all over the world, the oil industry continues to search for an oil and gas well completion method of the highest possible effectiveness. Utilisation of explosives in shaped charges intended for perforation jobs provides effective hydraulic connection of the borehole with the reservoir, but local adverse effects of detonation remain in place in the form of crushed and damaged zones around the perforation channels. The work proposes new insight into methods of perforating boreholes. Although still within the domain of explosives, it presents a method of perforation based on the use of linear shaped charges, whose action is boosted by the energy of the combustion of the propellant. The work presents the course and results of four shooting experiments with a conceptual perforating and fracturing tool with the working name of 'fracperforator', the main task of which is the penetration of a multi-layered target comprised of diversified materials, whose downhole structure represents a borehole. The presented tests were directed for studying the effectiveness of steel/water/concrete system perforation. In the course of the study, fears were dispelled that concerned of all armed charges initiating and the occurrence of phenomenon producing damage to the tool before the operation was completed. However, the hypothesis of thorough modernisation of the linear shaped charges was confirmed, as in the current form they release too much energy outside the axis of cumulative jet action. The subject energy losses firstly reduce the charge action strength, and secondly cause damage to the body pipe as the load carrying part, by extensive bulging and tearing. The analysis of the created cumulative slots enables one to state that they are uniform and no significant changes of their width are observed. The depths or range of the slots have not been determined at this stage of work because of complete damage of the concrete part of the models simulating the lengths of borehole. The completed tests, performed in the form of four shooting experiments, confirm the ability of linear shaped charges to effectively penetrate multi-layered targets.

Key words: borehole perforation, linear shaped charges, propellants, gas fracturing.

STRESZCZENIE: Choć zjawisko kumulacji detonacyjnej jest dobrze znane i wykorzystywane w technice strzelniczej na całym świecie, to branża naftowa wciąż poszukuje jak najefektywniejszego sposobu perforacji odwiertów naftowych i gazowych. Wykorzystanie materiałów wybuchowych w ładunkach kumulacyjnych przeznaczonych do prac perforacyjnych zapewnia skuteczne połączenie hydrauliczne odwiertu ze złożem, ale wciąż pozostają lokalne negatywne skutki detonacji w postaci stref zmiażdżonych i zniszczonych wokół kanałów perforacyjnych. W niniejszym referacie zaproponowano nowe spojrzenie na sposób perforacji odwiertów. Pozostając w domenie materiałów wybuchowych, przedstawiono metodę perforacji opartej na wykorzystaniu liniowych ładunków kumulacyjnych, których działanie potęguje energia spalania propelantów. W referacie przedstawiono przebieg i rezultaty czterech testów strzałowych koncepcyjnego urządzenia perforująco-szczelinującego o roboczej nazwie Szczelinogenerator, którego głównym zadaniem jest przebicie wielowarstwowego zróżnicowanego materiałowo celu, jakim jest wgłębna konstrukcja odwiertu. Przedstawione badania poświęcone są skuteczności perforowania układu stal–woda–beton. W ich toku rozwiano obawy dotyczące braku jednoczesności zainicjowania wszystkich uzbrojonych ładunków i wystąpienia działań niszczących urządzenie jeszcze przed jego pełnym zadziałaniem. Potwierdziła się jednak hipoteza o konieczności gruntownej modernizacji ładunków liniowych, które w obecnej formie uwalniają zbyt dużą ilość energii poza oś działania strumienia kumulacyjnego. Przedmiotowe straty energii, po pierwsze, osłabiają działanie ładunku, po drugie, powodują zniszczenia rury korpusowej jako urządzenia nośnego poprzez wydatne rozdęcie i rozerwanie. Analiza przekrojów powstałych szczelin kumulacyjnych pozwala stwierdzić, że są one jednorodne i nie obserwuje się w nich znaczących zmian szerokości. Głębokości czy zasięgu szczelin na tym etapie pracy nie określono z powodu zniszczenia części betonowej modeli imitujących odcinki otworu wiertniczego. Przeprowadzone badania, zrealizowane w postaci czterech testów strzałowych, potwierdzają zdolność ładunków kumulacyjnych liniowych do skutecznego penetrowania celów o budowie wielowarstwowej.

Słowa kluczowe: perforacja odwiertów, ładunki liniowe, paliwa prochowe, szczelinowanie gazowe.

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Introduction and literature review

Analysis of subject literature clearly indicates lasting interest of research centres in the research domain related to the physics of detonation. The scientific publications from the recent decade concerning utilisation of explosives both for civil and military purposes, originate mainly from China. In the work (Saran et al., 2013) *Experimental Investigations on Aluminium Shaped Charge Liners*, the authors studied the possibility of steel target penetration and sandstone block by shaped charges made of aluminium. The researchers composed together conical liners having 100° apex angle and varying thickness. The cumulative jet was characterised in the tests by means of X-ray radiography. It has been found that penetration depth increases with decreasing thickness of the liner tip. In the work (Xi et al., 2012) *Effect of interaction mechanism between jet and target on penetration performance of shaped charge liner*, the team of researchers describe their experiences connected with steel target penetration ability by shaped charges with liners made of pure tungsten, tungsten-nickel-iron alloy and tungsten-copper alloy. The research proved that all shaped charges created continuous cumulative jets with similar velocities of their tips. Because of its lowest density, the liner made of tungsten-copper alloy has the best steel target perforating parameters. Similar research has been done by Beijing-based researchers in the work (Zhao et al., 2016) *Effect of Zn and Ni added in W–Cu alloy on penetration performance and penetration mechanism of shaped charge liner*. The researchers tested the possibility of penetrating steel targets by shaped charges equipped with liners made of tungsten-copper-zinc, tungsten-copper-nickel and tungsten-copper alloys. The results of the research showed that zinc and nickel additives added to the tungsten-copper alloy significantly decrease target penetration ability. In the article (Zygmunt et al., 2014) *The concept of sintered metallic liners for Explosively Formed Projectile (EFP)*, scientists describe research on cumulative jets created from liners made of metallic powder, which compared to cumulative jets created by liners made of solid metal have high penetrating ability and stable flight ability while maintaining continuity. In the EFP type shaped charges, the liners have the shape of sphere section or of a cone with an apex angle over 120°. In the article (Borkowski at al., 2018) *Application of sintered liners for explosively formed projectile charges*, the authors describe experimental tests on fabrication and target penetration ability by explosively formed projectiles with liners made by means of powder metallurgy methodology. The research has proved that the charges produced with use of powder metallurgy can be fully functional substitutes for traditional liners made of solid metal, produced in more complex technological process. In the work (Shuai et al., 2017) *Penetration research of dual-mode penetrator formed by shaped charge with wave sharper*, the authors describe research done for shaped charge that has two cumulative liners (the conical and the EFP, on two opposite sides. Four types of cumulative charge, composed of two liners of different types, have been modelled in the LS Dyna software package. Subsequently fire-ground tests were performed, in which the EFP liner penetrates armour, and the conical liner penetrates a concrete target. The researchers focused on obtaining the highest cumulative jet velocities, in order to achieve optimal perforation parameters. In the article (Ho et al., 2018) *Additive Manufacturing of Liners for Shaped Charges* the researchers describe production of cumulative liner having internal honeycomb structure, fabricated by means of Selective Laser Melting (SLM). The material of the liner was high quality stainless steel SS 304L. The C-4 explosive was used. The research has shown that the liner of honeycomb cross-section achieved velocity of jet at 4200 m/s level, while steel plate penetrating ability was at 6.35 mm. In the work (Koślik et al., 2014) *The split shot device – simulation testing and efficiency testing of new tool for restoring circulation in borehole*, the researchers described design of the new device to remedy failure conditions related to loss of circulation in a borehole. The split shot device is composed of single, linear shaped charge, enclosed in hermetic housing together with a firing unit. The article (Cheng et al., 2018) *Design of a Novel Linear Shaped Charge and Factors Influencing its Perforation Performance* describes design of a novel linear shaped charge composed of a liner having a dual divergence angle (a small one of 40°at the apex and a bigger one in the further part (60º)). The penetration ability of the charge was compared against traditional linear charge (the liner having 60° apex angle). The article (Huanguo et al., 2018) *Penetration behaviour of reactive liner shaped charge jet impacting thick steel plates* describes ability of shaped charge with a reactive liner for penetrating steel plate. The reactive liner was produced from aluminium (Al) powder and Teflon (PTFE). The study has shown that because of the fragmentation of steel plates, a shaped charge with a reactive liner creates a bigger inlet hole diameter but a shorter perforation channel as compared to traditional liners in the work (Wenqi et al., 2016) *Comparison of penetration performance and penetration mechanism of W-Cu (wolfram-copper) shaped charge liner against three kinds of target: Pure copper, carbon steel, and Ti-6Al-4V alloy*, the researchers study an interaction between cumulative jet in a shaped charge with a liner made of tungsten and copper alloy, and various targets: one made of pure copper, one made of carbon steel and one made of Ti-6Al-4V alloy. The researchers determined that interaction between the jet and target significantly influences depth of penetration. The article (Wang et al., 2017) *Penetration of shaped charge into layered and spaced-apart concrete targets* presents results of research concerning impact of liner divergence angle and liner material on penetration of sandwiched and spaced apart concrete targets. The article (Han et al. 2010) *Effect of Shaped Charge Case Materials on Perforating Gun* describes interaction of cumulative charges with steel and zinc casings made for pressure and temperature created within the housing of the perforator. The charges enclosed in zinc casing create a higher pressure pulse and generate a higher temperature following detonation. The detonation of shaped charges with a zinc casing generated much more heat as compared to the steel charges. The heat was generated in result of exothermic reaction. This is why the shaped charges in zinc casing create more damage in the perforator body. In the work (Frodym and Koślik, 2016) authors present results of numerical modelling of a detonation process for three shaped charges in various operation modes (a hybrid, a hybrid with a diaphragm, and a hypercumulation) performed in order to verify whether the energy delivered by a cumulative stream can surely ignite a propellant within the working arrangement of a complex perforating-fracturing device. Estimation of the energy obtained by numerical method was compared with energies obtained earlier in fire ground experiments with real perforating-fracturing device models, giving confirmation of the possibility of propellant ignition with a cumulative jet derived from all three versions of the considered shaped charges.

Fire-ground testing of multi-layer targets penetration

The fire-ground scale tests were performed in the conceptual perforating-fracturing tool. The firing initiation and conveying path was based on the group of shooting means having close energetic characteristics. The elements of ballistic line elements were: 1) the immediate electrical detonator; 2) detonating booster based on high-explosive of hexogen (RDX) type, 3) short section of detonating cord in lead jacket; 4) the linear shaped charge; 5) propellant. Estimation of target penetration ability was done on the grounds of shooting experiments on a physically fabricated model of the conceptual tool, the fracperforator. The series of tests comprised of four shooting experiments, executed on the experimental fire-ground. Their common feature was the geometry of the tested arrangement and the routing method of the shooting line. The differences consisted in seating the shooting model (in concrete or in the ground; calibre of linear shaped charge used Ø = 32 mm/Ø = 40 mm; presence or absence of propellant.

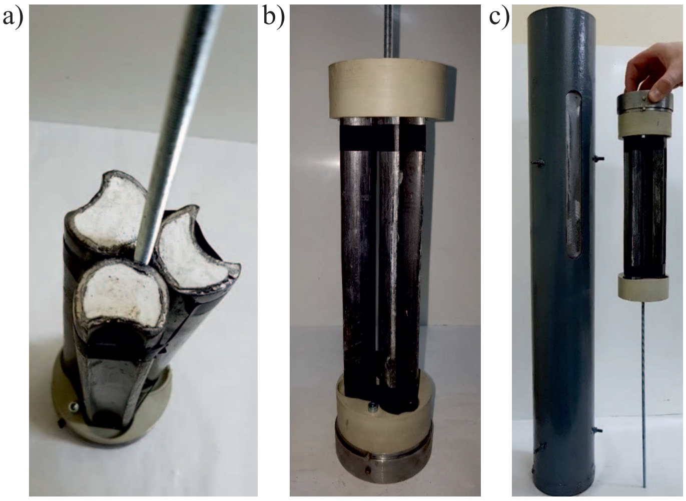

Fig. 1. A – view of three linear shaped charges, seated in lower centraliser seat; B – view of complete perforating arrangement, equipped with centralisers, carrying rod and steel cover of the head; C – view of fracperforator model, prepared for fire-ground testing of multi-layer target perforation

Rys. 1. A – widok trzech ładunków kumulacyjnych liniowych posadowionych w gnieździe centralizatora dolnego; B – widok pełnego układu perforującego wyposażonego w centralizatory, żerdź nośną i stalową osłonę głowicy; C – widok modelu szczelinogeneratora przygotowanego do badań poligonowych przebijania celu wielowarstwowego

The shooting test No. 1 – the linear shaped charges Ø = 32 mm diameter, in the aerial conditions

By the aerial condition it is meant here the free seating of the shooting model on the open fire-ground. Only the lower part of fracperforator was seated in the ground in order to maintain the vertical orientation of the tool.

The results of shooting test No. 1

The shooting test resulted in effective transmission of initiation between individual components of the tool and performing work in the form of notches both in the body part and in casing part. Transmission of detonation energy into each subsequent element of ballistic line and the primary charges was observed. All the three linear shaped charges used were effectively initiated, and the effect of their action can be seen on the steel elements of the body and casing pipe. Visual inspection of the penetrated pipes – the internal one of the tool body and external one of the casing – confirm effective transmission of initiation and ability of exemplary linear shaped charges Ø = 32 mm to cut the steel targets in form of coaxial steel pipes consisting of Ø = 7”/s = 10 mm and Ø = 5”/s = 5 mm.

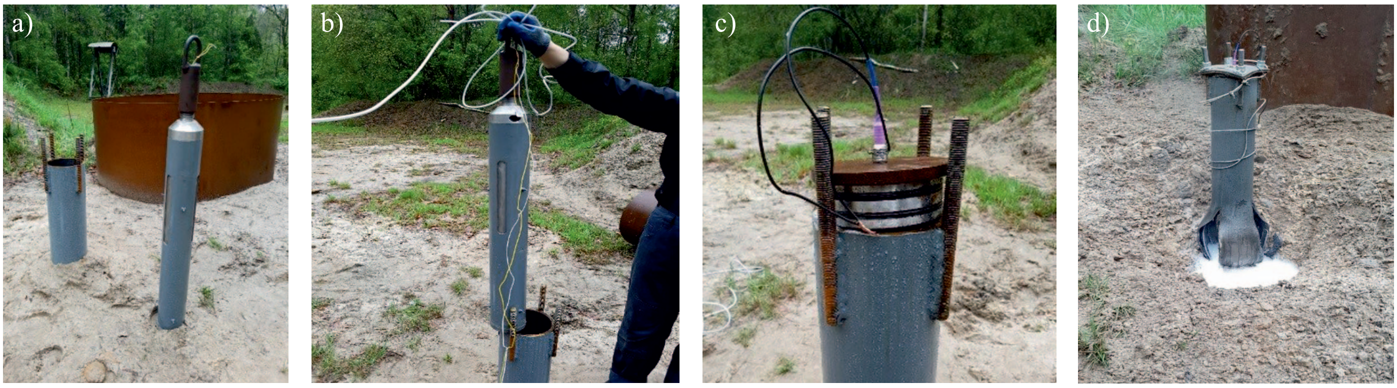

Fig. 2. View of tested device model on the fire-ground; a) Ø = 7” casing pipe, b) conceptual fracperforator being run down the shooting model by means of the cap and wireline, c) movable plug with current pass-through d) the view after the linear shaped charges were fired

Rys. 2. Widok modelu badanego urządzenia na poligonie doświadczalnym; a) rura okładzinowa Ø = 7”, b) koncepcyjny szczelinogenerator zapuszczany do modelu strzałowego za pomocą kołpaka i liny stalowej, c) korek stalowy z przepustem linii strzałowej, d) widok po odpaleniu ładunków liniowych

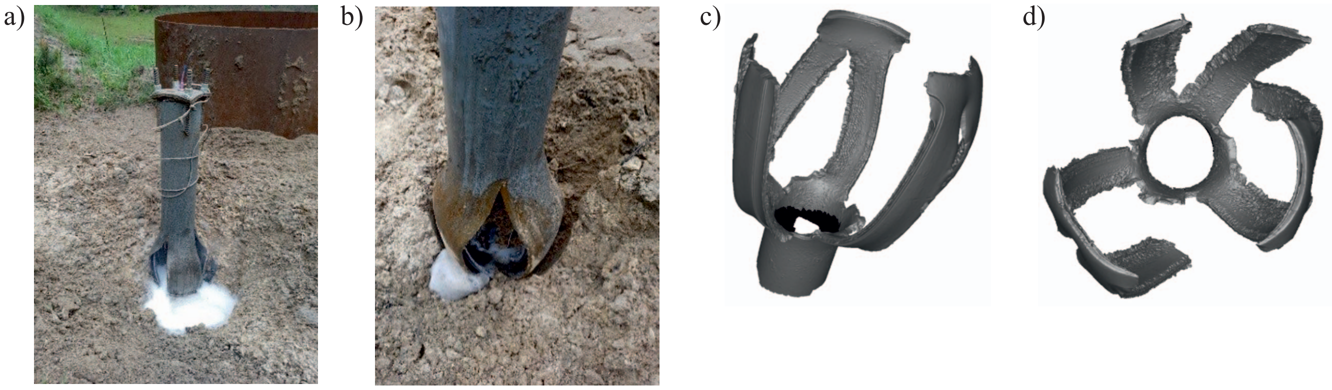

Fig. 3. A view of shooting model following the test completion; a) front view, b) side view, c) d) the views of 3D scans of tested tool body pipes, removed from inside of the shooting model

Rys. 3. Widok modelu strzałowego po ukończeniu testu; a) widok frontowy, b) widok boczny, c), d) widoki – skany 3D rur korpusowych testowanego urządzenia wyjętych z wnętrza modelu strzałowego

After the completion of the test, the whole experimental set-up was handed over to the mechanical workshop in order to dismantle and extract the jammed components. In order to make a better inventory of the created fractures and deformations, a series of three-dimensional scans was performed.

The shooting test No. 2 – the linear shaped charges Ø = 40 mm diameter, in aerial conditions

Similarly as in case in the first experiment, the conceptual model of the fracturing and perforating tool was placed in the Ø = 7” casing pipe, having s = 10 mm wall thickness. The lower part of the casing pipe was blinded by welding a steel plug into it, while in the upper part a movable plug was placed, which constituted a head with a current pass-through (Fig. 2c). Also in this case the whole assembly was situated vertically, slightly sunk into the ground.

The results of shooting test No. 2

The shooting test consisted in verification of the ability to cut a multi-layer system and indication of possible areas requiring improvement. The arrangement of the three linear shaped charges of Ø = 40 mm diameter was effectively initiated by intermediate shooting line elements comprised of an electrical detonator, a booster, and short sections of detonating cord. The image of punched holes, subjected to visual inspection, enables one to exclude the existence of a negative influence of detonation products on individual elements of the ballistic line. The selection of shooting means / components of the ballistic line is assumed to be correct and provides conveying in synchronous manner the firing pulse onto all links of the tool.

Visual inspection confirms ability of transferring ignition between individual links of the fracperforator and indicates simultaneous immediate firing of all linear shaped charges. The effect of this test dispelled the fear of the research team

a) b) c) d)

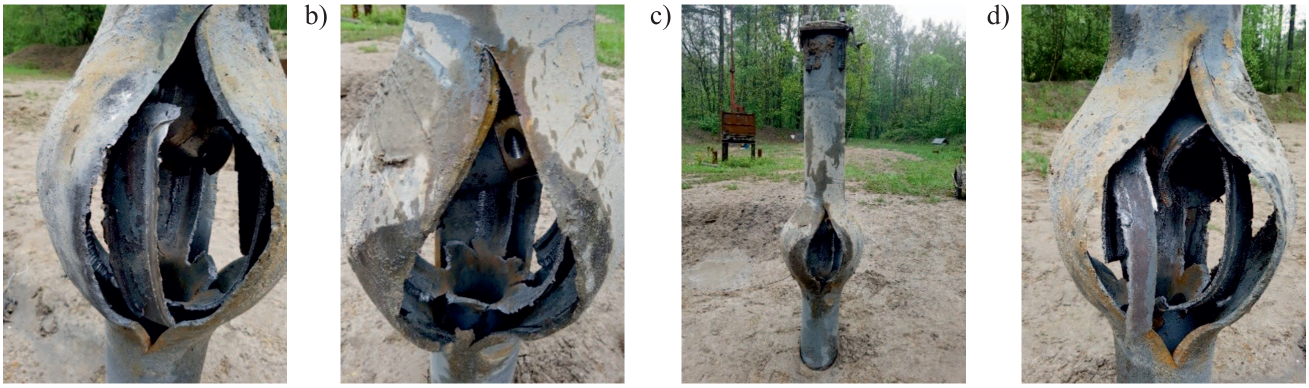

Fig. 4. View of various perspectives of perforated body and casing pipe in shooting test No. 2, performed with use of the linear shaped charges of Ø = 40 mm diameter and L = 250 mm length

Rys. 4. Widok w różnych ujęciach przestrzelonej rury korpusowej i okładzinowej w teście strzałowym nr 2 realizowanym z użyciem ładunków kumulacyjnych liniowych o średnicy Ø = 40 mm i długości L = 250 mm

a) b)

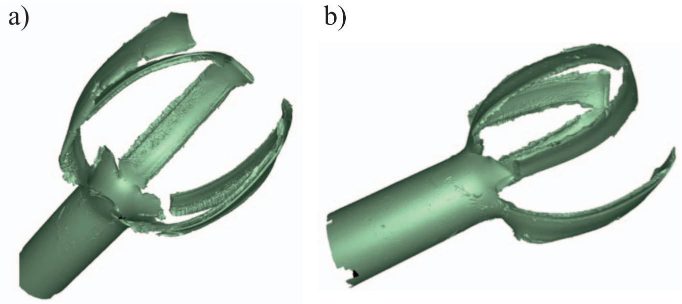

Fig. 5. The result of three-dimensional scanning of body pipe of the tool removed from inside of shooting model

Rys. 5. Efekt skanowania trójwymiarowego rury korpusowej urządzenia wyjętej z wnętrza modelu strzałowego.

concerning potential occurrence of damaging the tool (prior to its complete intended action is done) through non-uniform detonation of shaped charges, due to, e.g., insufficiently quick, non-uniform distribution of the explosive firing pulse.

The shooting test No. 3 – the linear shaped charges Ø = 32 mm diameter on the shooting tool simulating a section of borehole

The significant expansion of the shooting model observed during the two preceding experiments persuaded the research team to change the methodology. In order to make the testing condition closer to real-world conditions, two concrete steel stands were prepared, simulating a fragment of borehole section. In this way additional elements have been introduced to the arrangement under tests, such as water, filling the annulus and cement jacket having Ø = 1200 mm diameter (Fig. 6c), with the task of acting as a countermeasure to the forces disrupting the model.

The shooting test stand consisted of two pipes coaxially seated in a concrete ring. The external pipe (casing one) Ø = 7” contained the tool body pipe Ø = 5”. The annulus between the two pipes was filled with water by means of an inlet on the

a) b) c) d)

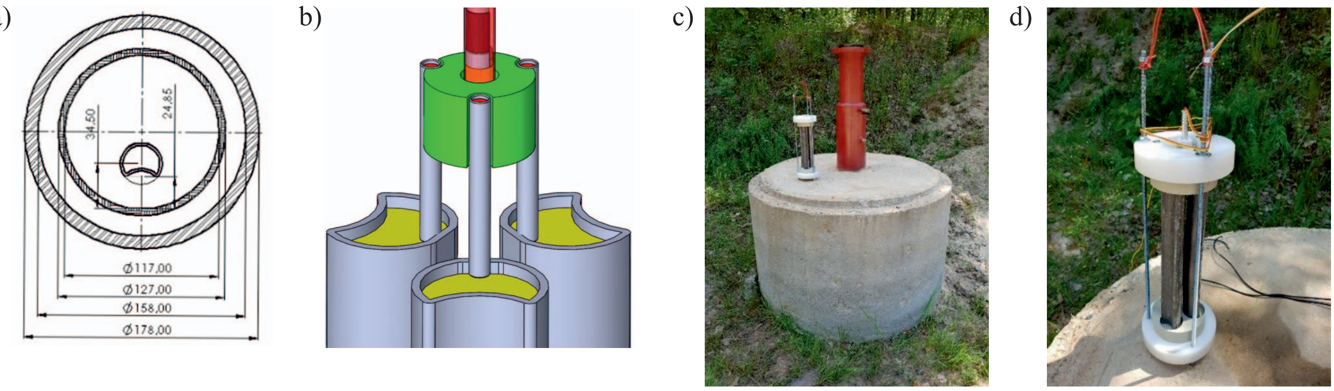

Fig. 6. View of test arrangement for realisation of multi-layer perforation with linear shaped charges, a) cross sectional view of shooting stand with marked position of single charge; b) design of ballistic line path; c) the concrete and steel stand; d) the key elements of the testing arrangement – three linear shaped charges united with a system of centralisers; firing unit; temporary carrying system

Rys. 6. Widok układu badawczego do realizacji testu perforacji wielowarstwowej liniowymi ładunkami kumulacyjnymi; a) przekrój poprzeczny stanowiska strzałowego z zaznaczoną pozycją jednego ładunku; b) projekt ścieżki linii balistycznej; c) stanowisko betonowo-stalowe; d) kluczowe elementy układu testowego – trzy ładunki kumulacyjne liniowe zespolone układem centralizatorów; zespół zapalczy; prowizoryczny zestaw stabilizujący side surface of the external pipe. After the model of the tool was seated on the bottom of the test stand, its upper part was blinded with a steel plug equipped with a current pass-through.

The results of shooting test No. 3

The effect of firing the fracperforator in a test under conditions simulating those in the real world is the positive transmission of initiation onto all components of the arrangement and the creation of regular perforation fractures within all three planes. It has been proved once again that the ballistic line of the fracturing-perforating tool fulfils its task and demonstrates its repeatability.

In test No. 3 once again all three charges were simultaneously initiated, which is proved by the creation of cumulative slits in both internal and external pipes. Furthermore, the cumulative jet penetrated the surrounding concrete target, leading ultimately to its failure. The important finding gained from this experiment is the fact that additional gaps (tears) have been revealed in the body pipe of the tool. The cuts created in the steel have a ‘paired’ nature – each cumulative slot is accompanied by its opposite-located tear of the pipe. When the cumulative jet goes towards the target for it to be perforated, the remaining detonation energy is focused in the opposite direction, creating undesired damage of the tool. This phenomenon is a consequence of using the ‘off the shelf’ catalogue products for tests of linear cumulative charges, which by definition were intended for different applications. Such charges were applied only for cognitive purposes, serving initial recognition of perforation effectiveness in the context of a multi-layered target. The three-dimensional imaging of the perforated elements serves a more precise inventory of shaped-charges action effects. For example, it can result in thickness distribution of slots created during shooting tests, serving the estimation of the initiation transmission effectiveness between individual components of the fracperforator. The measurement results of the created slots are shown on the Figure 8, in the form of notch profiles on a 25 cm length, measured every1 cm.

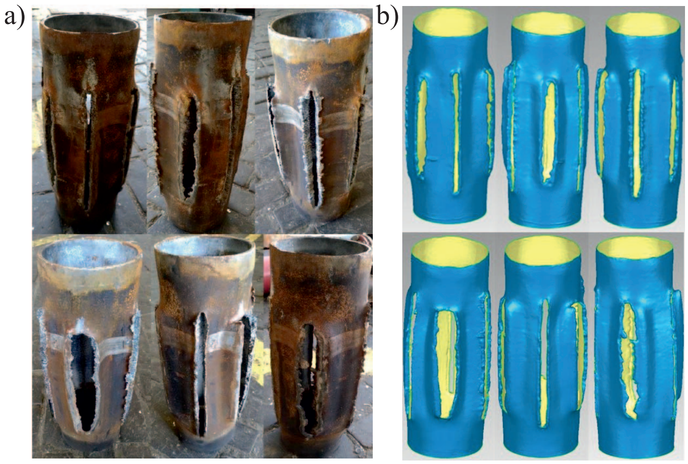

Fig. 7. View of body pipe Ø = 5”, removed from casing pipe after completion of the test (left side); results of 3D scanning of the same body pipe

Rys. 7. Widok rury korpusowej Ø = 5” wyjętej z rury okładzinowej po ukończeniu testu (z lewej); wyniki skanowania 3D tej samej rury korpusowej

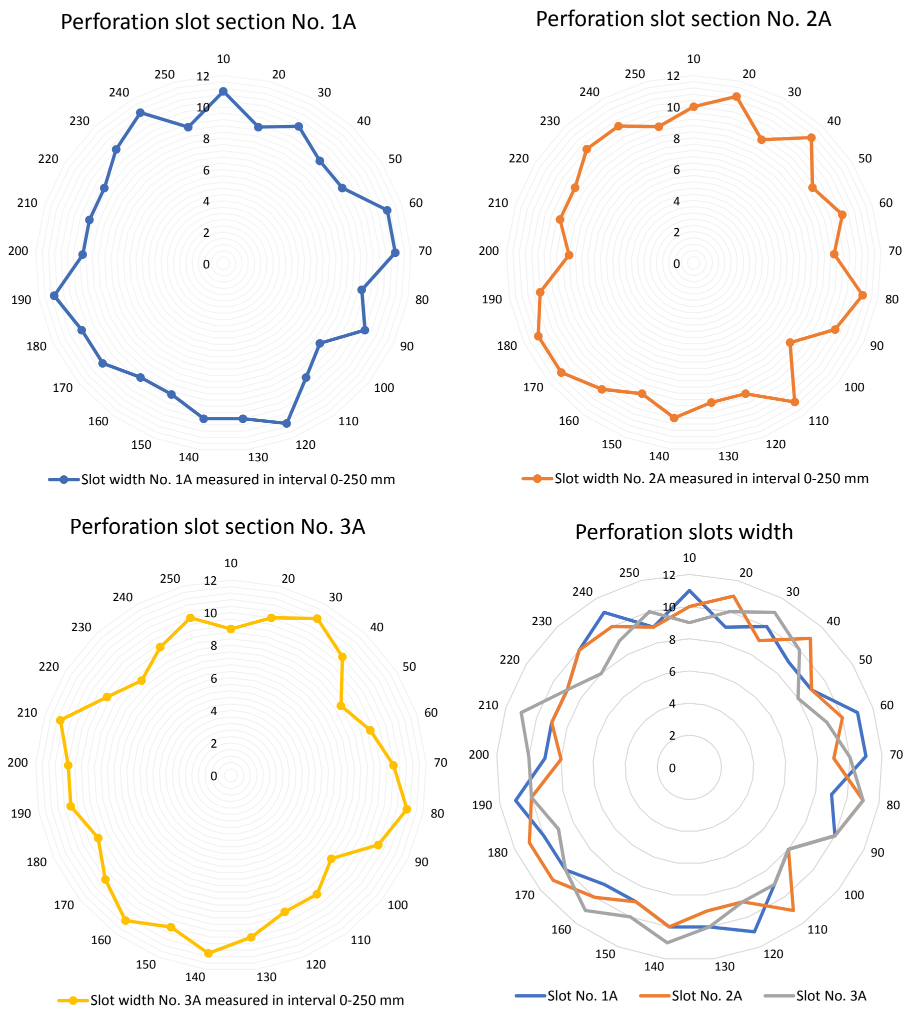

Fig. 8. Statement of widths for cumulative slots created within body pipe of the tool (Ø = 5”) in result of firing linear shaped charges of Ø = 32 mm diameter and L = 250 mm length

Rys. 8. Zestawienie szerokości powstałych szczelin kumulacyjnych w rurze korpusowej urządzenia (Ø = 5”) w wyniku odpalenia ładunków kumulacyjnych liniowych o średnicy Ø = 32 mm i długości L = 250 mm

Fig. 9. The frames of the video from the shooting test No. 3 recording. Total damage and scattering of the concrete part is visible. The steel pipes remain in good condition, enabling free assessment of cumulative cuts. However, lack of undisturbed concrete body excludes possibility of target penetration depth measurement

Rys. 9. Kadry zapisu video z rejestracji przebiegu testu strzałowego nr 3. Widoczne całkowite zniszczenie i rozrzut części betonowej. Rury stalowe pozostają w stanie dobrym, umożliwiającym swobodną ocenę nacięć kumulacyjnych. Brak calizny betonowej wyklucza jednak możliwość pomiaru głębokości przebicia celu

Considering the high probability of damaging instruments, the test was conducted without measuring equipment. An assessment of the length/depth of the perforation slots, created within the concrete jacket surrounding the model, was considered to be an additional result of the test. The selected basis weight of the shaped charges, however, excluded such analysis, considering the final results of the experiment presented on Figure 9 – showing some frames originating from the video recording depicting the course of the test.

a) b) c)

Fig. 10. View of the working part of the tested arrangement; a) test version without propellant; b) view of target, internal part of the tool withthe linear shaped charges surrounded by the NDT-3 propellant; c) moment of weighing the NDT-3 propellant intended for fracperforator model arming; the tested arrangement was armed with homogeneous propellant in the form of three bundles of tubular propellant, each having 83 g mass on average. The total mass of the propellant did not exceed 250 g

Rys. 10. Widok części roboczej badanego układu; a) wersja testowa bez propelantu; b) widok docelowej wewnętrznej formy urządzenia – ładunki kumulacyjne liniowe w otoczeniu paliwa prochowego NDT-3; c) moment ważenia wiązki rurek paliwa prochowego NDT-3 przeznaczonej do zbrojenia modelu szczelinogeneratora; badany układ uzbrojono w paliwo prochowe homogeniczne w formie trzech wiązek propelantu rurkowego o średniej masie 83 g każda. Łączna masa paliwa nie przekroczyła 250 g

Shooting test No. 4 – with use of linear shaped charges Ø = 32 mm diameter, L = 250 mm length and propellant NDT3 in tubular form

As to the test stand and methodology the course of shooting test No. 4 (the last one in the series) was identical twin-like to the preceding test. The only important change consisted in filling the shooting model with NDT-3 propellant, a solid propellant in tubular form. The propellant used has a solid form in which the oxidiser and the combustible component are bonded chemically, creating a uniform physical structure. The propellant is based on nitrocellulose (NC) with liquid nitroesters, such as nitroglycerin (NG), diethyleneglycol dinitrate (DEDGN), and triethyleneglycol dinitrate (TEDGN), which result in NC gelatinisation, which subsequently enables the obtaining of a uniform structure. Dibutyl phtalate, diethyl phtalate or triacetin phtalate are added as flexibilisers and stabilisers.

Fig. 11. View of casing pipe, perforated with linear shaped charges of Ø = 32 mm diameter, L = 250 mm length, in set-up with 250 g NDT-3 propellant

Rys. 11. Widok rury okładzinowej sperforowanej ładunkami liniowymi Ø = 32 mm, L = 250 mm w układzie z ładunkiem 250g propelantu NDT-3

The results of shooting test No. 4

The effect of firing the fracperforator in a test under conditions simulating the real world is positive transmission of initiation onto all components of the arrangement and creation of regular perforation fractures within all three planes. It has been proved once again that the designed ballistic line of the fracturing-perforating tool fulfils its task and demonstrates its repeatability.

In test No. 4 once again all three charges were simultaneously initiated, which is proved by the creation of cumulative slits in both internal and external pipes. As has also been observed in the preceding test, the cumulative jet penetrated the surrounding concrete target, leading ultimately to its failure. Once again additional slots (tears) in the body pipe of the tool were revealed. The cuts created in the steel have a 'paired' nature – each cumulative slot is accompanied by an opposite-located tear of the surface of the side of the pipe. When the cumulative jet goes towards the target for it to be perforated, the remaining detonation energy is focused in the opposite direction, creating undesired damage of the tool. The contribution of propellant is observed in the form of the increased scatter of the concrete jacket and extensive expansion of the inside pipe, located particularly within the upper part of tested model.

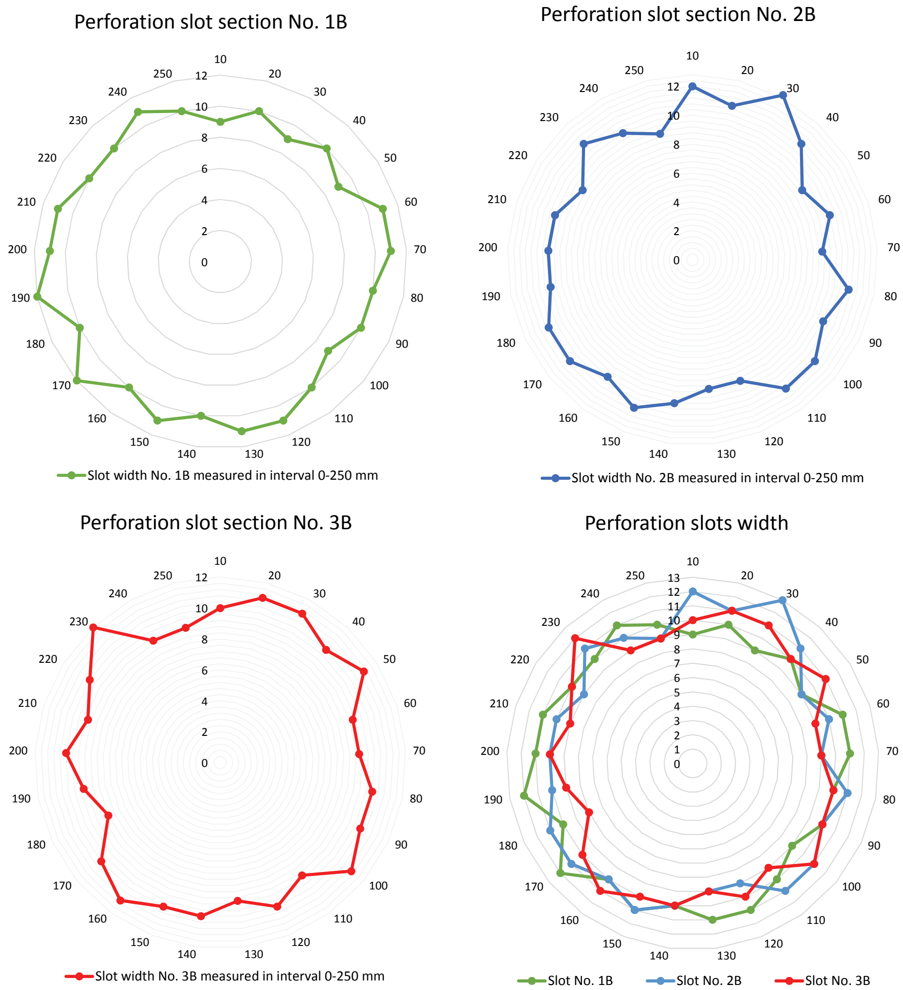

Fig. 12. Statement of widths for the cumulative slots created within the body pipe of the tool (Ø = 5"), created by firing linear shaped charges of Ø = 32 mm diameter and L = 250 mm length, jointly with NDT-3 propellant of 250 g total mass

Rys. 12. Zestawienie szerokości powstałych szczelin kumulacyjnych w rurze korpusowej urządzenia (Ø = 5") wywołanych odpaleniem ładunków kumulacyjnych liniowych o średnicy Ø = 32 mm i długości L = 250 mm wraz z ładunkiem paliwa prochowego NDT-3 o masie łącznej 250 g

The three-dimensional imaging of the perforated elements serves a more precise inventory of the shaped-charges action

Fig. 13. Video images from the shooting test No. 4 recording. Total damage and scattering of the concrete part is visible. The steel pipes remain in good condition, enabling the free assessment of cumulative cuts. However, the lack of undisturbed concrete body excludes possibility of target penetration depth measurement

Rys. 13. Obraz video z rejestracji przebiegu testu strzałowego nr 4. Widoczne całkowite zniszczenie i rozrzut części betonowej. Rury stalowe pozostają w stanie dobrym, umożliwiającym swobodną ocenę nacięć kumulacyjnych. Brak calizny betonowej wyklucza jednak możliwość pomiaru głębokości przebicia celu

effects on the designed tool. For example, it can result in the thickness distribution of slots created during the shooting tests, serving the estimation of the initiation transmission effectiveness between individual components of the fracperforator. The measurement results of the created slots are shown in Figure 12 in the form of notch profiles on a 250 mm length, measured every 10 mm.

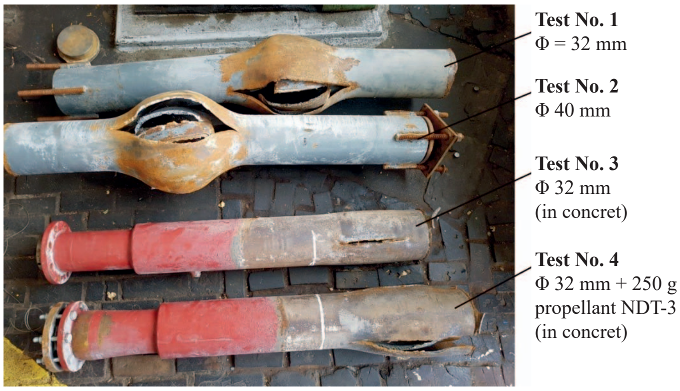

Fig. 14. Statement of shooting models, on which tests of multilayered target perforation were completed

Rys. 14. Zestawienie modeli strzałowych, na których zrealizowano testy perforacji celu wielowarstwowego

Summary and conclusions

The work proposes new insight into methods of perforating boreholes. The method of perforation based on use of linear shaped charges, the action of which is boosted by the energy of the combustion of the propellant, has been presented. The work presents the course and results of four shooting experiments of the conceptual perforating and fracturing tool with the working name ‘fracperforator’, the main task of which is the penetration of a multi layered target comprised of diversified materials, whose downhole structure represents a borehole. The presented tests were directed for purposes of studying the effectiveness of steel/water/concrete system perforation.

In the course of the study, fears were dispelled concerning lack of synchronism of all armed charges initiating and occurrence of phenomenon damaging the tool before its operation is completed. However, the hypothesis of thorough modernisation of the linear shaped charges was confirmed, as in the current form they release too much energy outside the axis of the cumulative jet action. The subject energy losses firstly reduce the charge action strength, and secondly cause extensive bulging and tearing damage of the body pipe load carrying part. The analysis of the created cumulative slots enables one to state that they are uniform, and no significant changes of their width are observed. The depths or range of the slots have not been determined at this stage of work, because of the complete damage of the concrete part of the models that simulate the lengths of borehole.

The completed tests, performed in the form of four shooting experiments, confirm the ability of linear shaped charges to effectively penetrate multi-layered targets.

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References

Borkowski J., Wilk Z., Koślik P., Szymańczyk L., Zygmunt B., 2018. Application of sintered liners for explosively formed projectile charges. *International Journal of Impact Engineering*, 118: 91–97. DOI: 10.1016/j.ijimpeng.2018.04.009.

Cheng X., Huang G., Liu C., Feng S., 2018. Design of a Novel Linear Shaped Charge and Factors Influencing its Perforation Performance. *Applied Sciences*, 8(10): 1863. DOI: 10.3390/app8101863.

Frodyma A., Koślik P., 2016. Numerical analysis of shaped charges for igniting modified propellants. *Nafta-Gaz*, 10: 841–850: DOI: 10.18668/NG.2016.10.09.

Han Ch., Du M.H., Ference B., 2010. Effect of Shaped Charge Case Materials on Perforating Gun. *International Oil and Gas Conference and Exhibition in China, Beijing, China*. DOI: 10.2118/130477-MS.

Ho J., Lough C.S., Mulligan P., Kinzel E.C., Johnson C.E. 2018. Additive Manufacturing of Liners for Shaped Charges. Solid Freeform Fabrication 2018. *Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference*.

Huanguo G., Yuanfeng Z., Qingbo Y., Chao G., Haifu W., 2019. Penetration behaviour of reactive liner shaped charge jet impacting thick steel plates. *International Journal of Impact Engineering*, 126: 76–84. DOI: 10.3390/ma12213486.

Koślik P., Wilk Z., Frodyma A., Habera Ł., 2014. The split shot – simulation study and testing effectiveness of the new tool for regaining circulation in borehole. *Nafta-Gaz*, 12: 891–898.

Saran S., Ayisit O., Yavus M.S., 2013. Experimental Investigations on Aluminium Shaped Charge Liners. *Procedia Engineering*, 58: 479–486.

Shuai C., Wei-bing L., Xiao-ming W., Wen-jin Y., 2017. Penetration research of dual mode penetrator formed by shaped charge with wave sharper. *Procedia Engineering*, 173: 57–64. DOI: 10.1016/j.proeng.2016.12.022.

Wang Ch., Xu W.L., Yuen Ch. K., 2017. Penetration of shaped charge into layered and spaced-apart concrete targets. *International Journal of Impact Engineering*, 112: 193–206. DOI: 10.1016/j.ijimpeng.2017.10.013.

Wenqi G., Jinxu L., Yao X., Shukui L., Ziying Z., Jin C., 2016. Comparison of penetration performance and penetration mechanism of W-Cu shaped charge liner against three kinds of target: Pure copper, carbon steel and Ti-6Al-4V alloy. *International Journal of Refractory Metals and Hard Materials*, 60: 147–153. DOI: 10.1016/j.ijrmhm.2016.07.015.

Xi B., Jinxu L., Shukui L., Cuicui L., Wenqi G., Tengeteng W., 2012. Effect of interaction mechanism between jet and target on penetration performance of shaped charge liner. *Materials Science and Engineering A*, 553: 142–148. DOI: 10.1177/1464420717753233.

Zhao Z., Liu J., Guo W., Li S., Wang G., 2016. Effect of Zn and Ni added in W–Cu alloy on penetration performance and penetration mechanism of shaped charge liner. *Int. Journal of Refractory Metals and Hard Materials*, 54: 90–97. DOI: 10.1016/j.ijrmhm.2015.07.022.

Zygmunt B., Wilk Z., Koślik P., 2014. On concept of sintered metallic liners for EFP charges. *Problemy Mechatroniki, Uzbrojenie, Lotnictwo, Inżynieria Bezpieczeństwa*, 5, 2(16): 63–76.

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