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Research paper

Influence of a non-Explosive Filling Included in the Conical Liner Cavity of a Shaped Charge on its Penetrative Capability

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Abstract: Based on literature, it can be concluded that the results obtained for partially or fully filled inert (non-explosive) material of the free space inside the cone created by the liner inside a shaped charge (SC), have not been deeply examined.
Preliminary results in this work were obtained for SCs taken from the warhead of an anti-tank rocket-propelled grenade, PG-7WM (also known as PG-7VM). The warhead was modified by perpendicular intersection and by inserting an inert, *i.e.* made from non-explosive, cone. Each of the inert fillers was prepared from one of the three materials: copper (type M1E), steel S355, aluminium (type 2024) or a polymer (polyoxymethylene, POM-C). The densities of these materials were

8.9, 7.86, 2.7 and 1.41 g/cm^3, respectively. Each inert cone was tightly placed inside the inner area of the cumulative liner cone of the warhead. For each filler, there were three types of cones. The differentiating feature between the fillers under test was the difference in their height, *i.e.* 1/3, 2/3 and the full height of the SC cone. In all tests the effect of the impact of the cumulative jet (SCJ) was observed in an arrangement comprised of three adjacent armoured steel plates (ARMSTAL 30PM), with a total target thickness of 25 mm.

It was shown that the application of the inert cones caused significant changes in the dimensions and shapes of the holes through the plates of ARMSTAL 30PM armour steel. The relationship between the densities of tested fillers and the height of the cones made with these fillers versus the effects observed in the armour plate were also taken under account.

The filling, obtained from non-explosive material, allows a cut off of the relevant section of the front of the SCJ. It was noted that the tested modifications of the anti-tank rocket-propelled grenade, PG-7WM could find some applications in engineering and sapper work, especially in destroying unexploded munitions.

Keywords: hollow charge, liner, anti-tank rocket-propelled grenade, PG-7WM, HEAT warhead, ARMSTAL 30PM, copper M1E, steel S355, aluminium 2024, polyoxymethylene

Symbols and Abbreviations:

H	Height of the hollow cone of the cumulative liner in a shaped charge (SC) [mm]
h	Height of the filler cone placed in the inside of the hollow SC liner cone [mm]
POM-C	Polyoxymethylene copolymer, $(CH_2O)_n$
S355	Unalloyed structural steel (in accordance with EN 10025)
SC	Shaped charge
SCJ	SC (cumulative) jet
V_c	Velocity of the jet tip [km/s]
$Ø_{IN}$	Diameter of the hole measured on the side attacked by the SCJ [mm]
$Ø_{OUT}$	Diameter of the hole measured on the distal side attacked by the SCJ [mm]
$Ø_{DOME}$	Diameter of the dome created by the SCJ [mm]

Supplementary Information (SI):

SI contains Figures S1-S13 with photographs of the holes observed in armored plates by the SCs without and with different fillers (cones of S355, copper, aluminium or POM-C) inside the cone formed by the SC's liner.

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1 Introduction

There are a large number of theoretical and experimental test results on the effectiveness of shaped charges (SCs). Despite the great importance of the technique of SCs, in both military and engineering applications, there is little analysis of results of the effectiveness of a SC with a filling, fully or partially, tightly fixed the inside area of the liner's cone. This idea was found to be interesting from the point of view of recycling in the civil industry of those SC munitions withdrawn from army use. It should be noted that because of the different demands of SCs and test methods, *e.g.* [1-8], the possibility of transferring withdrawn SCs to civil industry has to meet additional requirements. On the other hand, one should also mention the wide possibilities of quick selection of construction solutions in this type of warhead through the use of additive technology. The use of appropriate materials for insert elements such as *e.g.* tungsten alloy [9], polyamide PA2200, polylactide, polystyrene [10-16], having appropriate strength properties in combination with 3D printing, creates new possibilities for the investigation of a SC's penetration capability.

Carleone *et al.* [17] tested a SC formed with Composition B and with a filling in the form of cones made of Wood's alloy (Bi/Pb/Sn/Cd, density 9.7 g/cm^3). The charges had a copper liner of the following parameters:

– angle: 42°,
– liner base diameter: 81.3 mm,
– height: 91.19 mm.

Except for the reference variant (no filler in the inside of the inner cone) five arrangements of the height of the filler were tested: 12.7, 25.4, 38.1, 50.8 and 63.5 mm. These heights correspond to 13.9%, 27.9%, 41.8%, 55.7% and 69.7% of the SC's cone height, respectively. On the basis of the performed calculations in [17] it was found that thanks to the filler, the cumulative jet (SCJ) tip has 16% less kinetic energy when the filler is 30% of the inside of the liner's cone. This results in a very similar depth of the penetration of a target, however, the volume of the crater was smaller. These calculations had not been experimentally verified in [17], *i.e.* no tests on the effect of the SCJ on a target were executed.

More recently, Żochowski and Warchoł [18] tested SCs with the filler reaching 33%, 66% and 100% of the inner area of the liner's cone. The arrangement used in [18] was that applied in the present work.

The aim of this paper was to compare results for selected fillers to estimate how the dimensions and the density of the filling's cone can affect the result of the impact by SCJ (a punctured hole (a crater) or a dome). Special attention was paid to the changes in the diameters of the craters created by the SCJs in

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the ARMSTAL 30PM plates:
– inlet (from the front side, *i.e.* attacked by the SCJ, $Ø_{IN}$), and
– outlet (from the rear side, $Ø_{OUT}$).

2 Experimental Part

2.1 Test stand

Modified high-explosive anti-tank (HEAT) warheads, taken from rocket propelled grenades, PG-7WM, were tested. The choice of this warhead was dictated by the availability of the results of previous work on the testing of PG-7WM grenades with ARMSTAL 30PM armour plate. Properties of ARMSTAL30PM steel are described *e.g.* in [19-21]. The plates were obtained from Steel Mill „Huta Stalowa Wola S.A." (Poland) [22]. Applied modification consisted of the cutting out of part of the ballistic cap and on the disassembly of the initiation system. A schematic of the test arrangement is shown in Figure 1.

The tested warhead was composed of:
– electric fuse **(1)**,
– shell (duraluminium) **(2)**,
– other parts of the SC **(3)**: for more precise description refer to [18],
– pressed explosive A-IX-1 **(4)**: 94-96% 1,3,5-trinitro-1,3,5-triazinane (hexogen, RDX) and 4-6% wax [19], with a mass of 440 g and a density of 1.63 g/cm^3,
– SC liner **(5)**: the hollow cone was made of 1.5 mm thick copper sheet, the height (*H*) and the base of the liner cone were 44.1 and 62.8 mm, respectively, and the cone angle was 60°,
– inert filler **(6)**: a filled cone alongside the inner surface of the SC liner at a given height (*h*).

The test warhead was placed on three ARMSTAL 30PM armour plates **(7)**. The plates were in the form of a square with side of 100 mm. The thickness of the plate closest to the warhead was 5.0 mm. The thickness of each of the two remaining plates was 10.0 mm. The last of the plates **(7)** was lying down on a plastic spacer pipe (not shown in Figure 1). The height of the spacer pipe was 100 mm. The pipe was placed on a witness plate **(8)**. The witness plate was used in the form of a square (side of 10.0 mm and thickness of 3.0 ± 0.1 mm) also made of the ARMSTAL 30PM steel.

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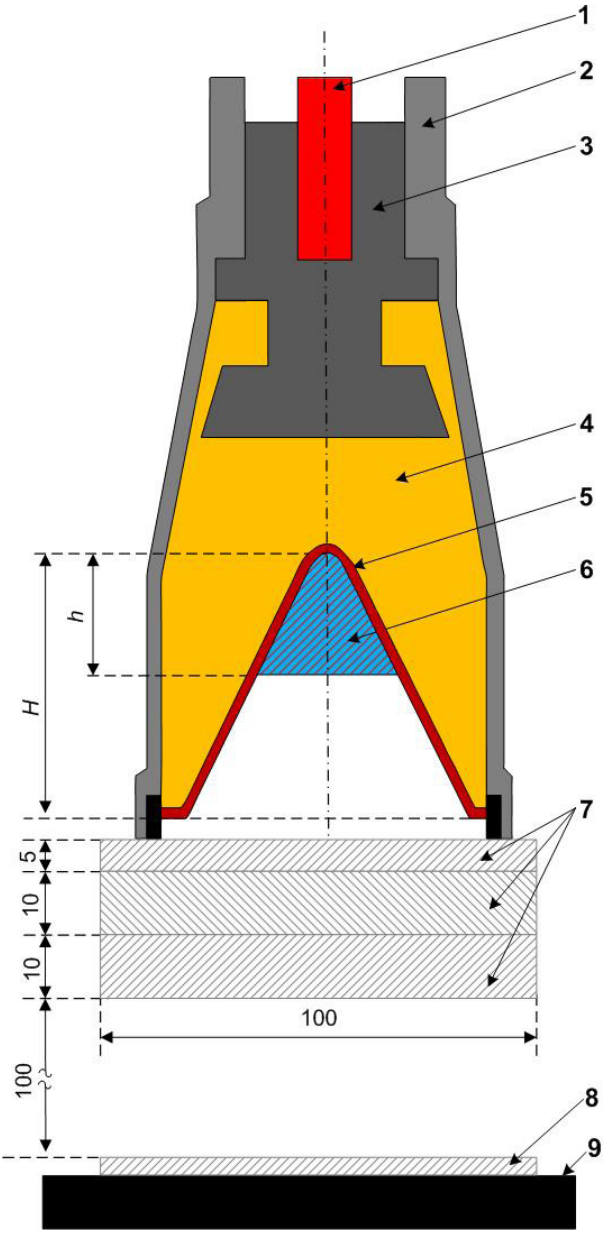

Figure 1. Schematic of the cross-section of the test arrangement (not to scale): 1 – electric fuse, 2 – warhead shell, 3 – other parts of the charge, 4 – explosive, 5 – conical liner, 6 – filling, 7 – three ARMSTAL 30PM armour plates, 8 – witness plate, 9 – base

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2.2 Fillers for the inner side of the cumulative liner cones

Non-explosive materials used for preparing the cones tightly filling the hollow space inside the SC cone liner were made of copper (Cu) type M1E , aluminium (Al) type 2024, steel type S355 (S355), and polyoxymethylene copolymer (POM-C). Data for these materials are shown in Table 1.

Table 1. Some mechanical properties of the inert filling materials

Material	Density [g/cm^3]	Yield strength [MPa]
Al, type 2024	2.7	345
Cu, type M1E	8.9	420
Steel, type S355	7.86	≥275
POM-C	1.41	67

Each of the tested inert materials was made into three cone shapes. They had different h values, *i.e.*:

– test series marked „a”: $h = 14.7$ mm, *i.e.* $h = (1/3)H$,
– test series marked „b”: $h = 29.4$ mm, *i.e.* $h = (2/3)H$, and
– test series marked „c”: $h = 44.1$ mm, *i.e.* $h = H$.

Test-ready, inert cones are shown in Figure 2. Views from the side of the inert cone of the tested charges are shown in Figure 3.

Figure 2. Inert cones made of (from the left): POM-C, Cu, S355 and Al

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Figure 3. View from the side of the inert cone of the modified PG-7WM grenades

2.2 Test methods

The tests were carried out on a test range of the Military Institute of Armament Technology (Zielonka, Poland). Two external diameters of the holes punctured in the armour plates were measured:

– inlet diameter ($Ø_{IN}$), *i.e.* measured on the plate's surface from the side attacked by the SCJ,
– outlet diameter ($Ø_{OUT}$), *i.e.* measured on the rear plate's surface.

When only a dome was observed on the armour plate, the diameter of the dome ($Ø_{DOME}$) was measured. Each diameter was measured three times and the average value taken. Due to the irregular shape of the holes and domes, the measurement error for all values of $Ø_{IN}$, $Ø_{OUT}$ and $Ø_{DOME}$ was determined to be ±2 mm.

The methodology for determining the distribution of velocities (*e.g.* tip velocity (V_c)) of parts of the SCJs as a function of an initial coordinate, were taken from numerical calculations presented by Bagrowski *et al.* in [23]. The calculations in [23] were evaluated for a cumulative warhead with a metallic filler, analogous to that used in the presented research.

3 Results

Photographs of the tested and witness armour plates are presented in Supplementary Information (SI). Average values of the diameters of the holes

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Table 4. Diameters of holes and domes in the armour plates

Inert cone	h =	Diameter [mm] in test No											
		1 (plate 1)			2 (plate 2)			3 (plate 3)			Witness plate		
		$Ø_{IN}$	$Ø_{OUT}$	$Ø_{DOME}$	$Ø_{IN}$	$Ø_{OUT}$	$Ø_{DOME}$	$Ø_{IN}$	$Ø_{OUT}$	$Ø_{DOME}$	$Ø_{IN}$	$Ø_{OUT}$	$Ø_{DOME}$
None	–	23	22	–	19	25	–	23	40	–	23	30	–
Steel	$H/3$	24	25	–	25	30	–	30	35	–	21×34		–
	$2H/3$	28	29	–	24	25	–	22	24	–	20	21	–
	H	–		11/49	–		7	–		6	–		4
Cu	$H/3$	28	30	–	35	36	–	32	34	–	16	17	–
	$2H/3$	25	26	–	30	29	–	29	31	–	–	–	–
	H	10/51		–	8		–	5		–	–		
Al	$H/3$	31	32	–	22	27	–	24	27	–	17	20	–
	$2H/3$	40	41	–	25	28	–	24	25	–	–	–	–
	H	11/57		–	7		–	6		–	4		–
POM-C	$H/3$	45	40	–	30	33	–	36	37	–	17	19	–
	$2H/3$	75	70	–	33	42	–	27	44	–	–	–	–
	H	18/67		–	15		–	13		–	7		–

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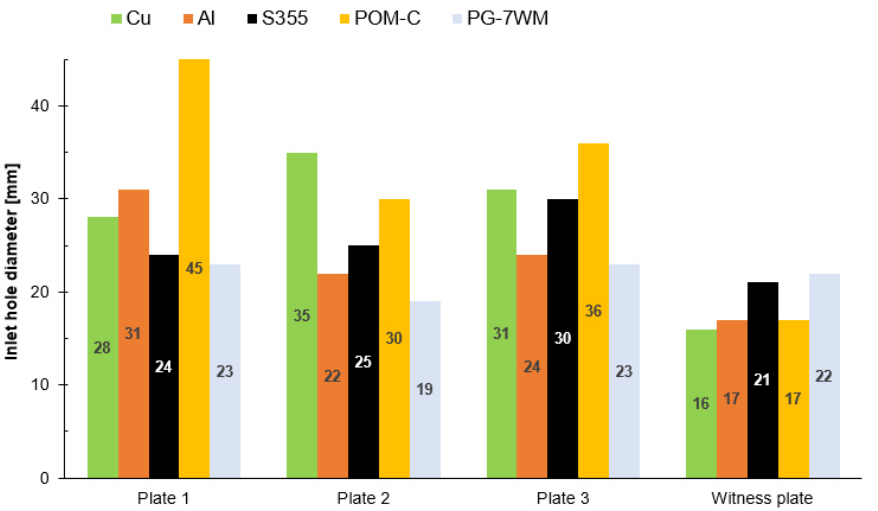
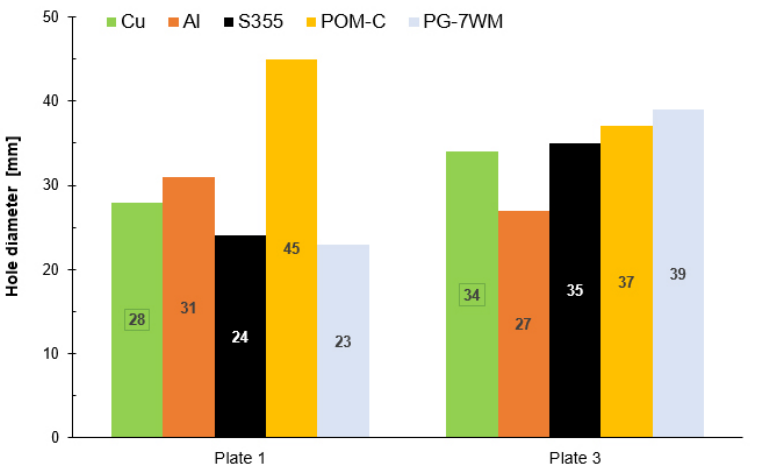
and domes obtained in the armour plates are given in Table 4. The results of the field tests are shown in Table 4 and – separately, for each height of the filler cone – in Figures 4 and 5.



(a)



(b)

Figure 4. Changes for $h = (1/3)H$: in $Ø_{IN}$ for all tests (a) and comparison of $Ø_{IN}$ in the plate 1 ($Ø_{IN}(1)$) and in $Ø_{OUT}$ in the plate 3 ($Ø_{OUT}(3)$) (b)

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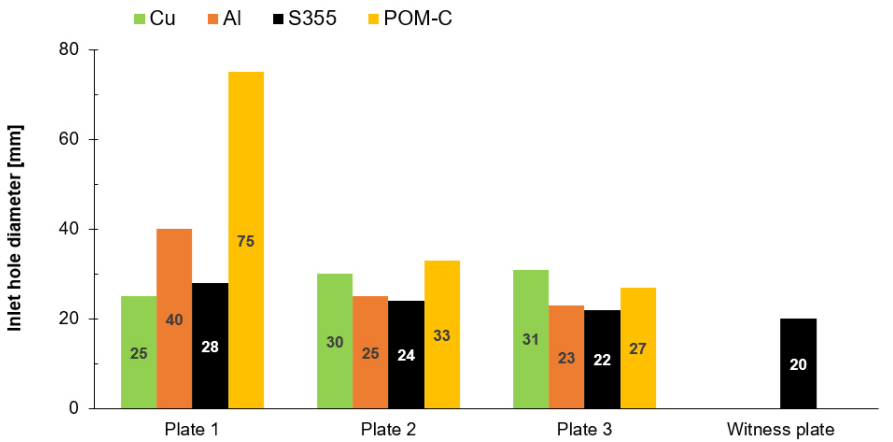

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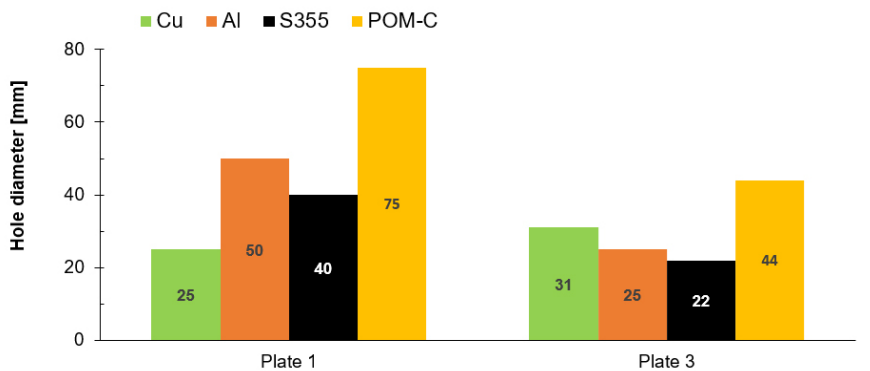

(b)

Figure 5. Changes for $h = (2/3)H$: in $Ø_{IN}$ for all tests (a) and comparison of $Ø_{IN}(1)$ and in $Ø_{OUT}(3)$ (b)

4 Discussion of Results

The $Ø_{IN}$ values for SC without the fillers (Table 4 and SI: Figure S1) and for $h = (1/3)H$ (Table 4 and SI: Figures S2, S5, S8 and S11) are shown in Figure 4(a). All plates were punctured, including the witness one. This is evidence of the high energy of the SCJ. The obtained values of $Ø_{OUT}$, in decreasing order, were:

– POM-C (37 mm),
– Cu (31 mm),

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– S355 (26 mm),
– Al (25 mm),
– PG-7WM (22 mm).

In general, one can expect the $Ø_{IN}$ value to be the limit value for plates 1 ($Ø_{IN}(1)$) and 3 ($Ø_{IN}(3)$). $Ø_{IN}$ value for plate 2 ($Ø_{IN}(2)$) ought to be somewhere in between. In other words, the expected orders of results are linear:
– $Ø_{IN}(1) > Ø_{IN}(2) > Ø_{IN}(3)$, or
– $Ø_{IN}(3) > Ø_{IN}(2) > Ø_{IN}(1)$.

Our results for $h = (1/3)H$ have shown a nonlinear order of the $Ø_{IN}$ values, *i.e.*:
– $Ø_{IN}(1) > Ø_{IN}(3) > Ø_{IN}(2)$ – for POM-C and Al fillers, as well as for PG-7WM,
– $Ø_{IN}(2) > Ø_{IN}(3) > Ø_{IN}(1)$ – for Cu filler, and
– $Ø_{IN}(a3) > Ø_{IN}(2) > Ø_{IN}(1)$ – for S355 filler.

For the witness plates punctured in tests for $h = (1/3)H$, the $Ø_{IN}$ values for POM-C, Al and Cu were approximately 17 mm, but for S355 and PG-7WM were slightly bigger (closer to 22 mm).

Comparison for the values of $Ø_{IN}(1)$ and $Ø_{OUT}$ in plate 3 ($Ø_{OUT}(3)$) for $h = (1/3)H$ is shown in Figure 5(b). For two fillers (made of POM-C and Al) $Ø_{IN}(1)$ were bigger than $Ø_{OUT}(3)$. On the other hand, when fillers were made of Cu or S355, or there was no filler (PG-7WM), $Ø_{IN}(1)$ was smaller than $Ø_{OUT}(a3)$.

The $Ø_{IN}$ values for shaped charges with $h = (2/3)H$ (see Table 4 and SI: Figures S3, S6, S9 and S12) are shown in Figure 5(a). All plates were punctured, as well as one witness plate for the S355 filler. The puncture could be questioned in the case of the Cu filler, as there were Cu residues left in the hole. However, puncture of the witness plate confirms our conclusion that a full puncture was observed also in the case of Cu filler. The obtained values of $Ø_{OUT}$, in decreasing order, were:
– POM-C (45 mm),
– Al (29 mm),
– Cu (28.6 mm), and
– S355 (24.6 mm).

Unlike the results obtained for $h = (1/3)H$, linear orders of the $Ø_{IN}$ values were observed, *i.e.*:
– $Ø_{IN}(1) > Ø_{IN}(2) > Ø_{IN}(3)$ for POM-C, Al and S355 fillers, and
– $Ø_{IN}(3) > Ø_{IN}(2) > Ø_{IN}(1)$ for Cu filler.

Comparison for the values of $Ø_{IN}(1)$ and $Ø_{OUT}(3)$ for $h = (2/3)H$ is shown in Figure 5(b). For two fillers (made of POM-C and Al) $Ø_{IN}(1)$ values were bigger than $Ø_{OUT}(3)$. On the other hand, when fillers were made of Cu or S355, or there was no filler (PG-7WM), $Ø_{IN}(1)$ was smaller than $Ø_{OUT}(3)$. In the case of plate 3 (inert cone made from Al) and plates 2 and 3 (inert cone made of POM-C),

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significant damage to the plates in the form of cracks and fractures were observed (see Table 4 and Figures S11-S13 in SI).

Changes in the dimensions of the domes for inert cones of height $h = H$ are shown in Figure 6. The biggest values were observed when an inert cone made from POM-C was applied. For cones made from Cu, S355 and Al the observed values were very similar and not as high (see Table 4 and SI: Figures S4, S7, S10 and S13). $Ø_{DOME}$ in plate 1 was the biggest for SC with the POM-C cone (67 mm). $Ø_{DOME}$ values for Al, Cu and S355 cones were 57, 51 and 49 mm, respectively.

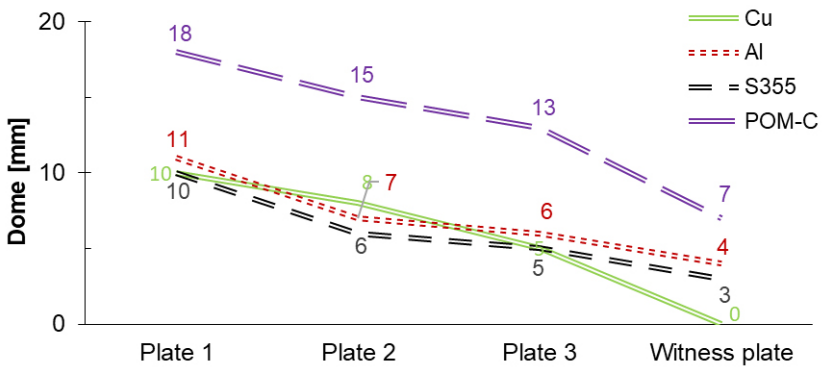

Figure 6. Changes in $Ø_{DOME}$ for $h = H$

The influence of the inert material's density on the diameter of the hole is shown in Figures 7 and 8. For $h = (1/3)H$, one can see in Figure 7 that for cones made from POM-C (density 1.4 g/cm^3) and Al (density 2.7 g/cm^3) the result is $Ø_{IN}(1) > Ø_{OUT}(3)$. The opposite situation occurs in the case of cones made of higher density materials, *i.e.* S355 (7.8 g/cm^3) and Cu (8.9 g/cm^3). In these cases, $Ø_{IN}(1) < Ø_{OUT}(3)$. For $h = (2/3)H$, Figure 8, and for cones made from POM-C and Al the resulting trends are the same ($Ø_{IN}(1) > Ø_{OUT}(3)$). However, in the case of results for $h = (2/3)H$, the spread of the results is higher than those for $h = (1/3)H$. This same trend ($Ø_{IN}(1) > Ø_{OUT}(3)$) was observed for the cones made from S355, although the results were much more concise than in the case of results for $h = (1/3)H$. For cones made from Cu, the opposite result was observed ($Ø_{IN}(1) < Ø_{OUT}(3)$), as was shown for $h = (1/3)H$, in Figure 7. The spread of the results is not so significant.

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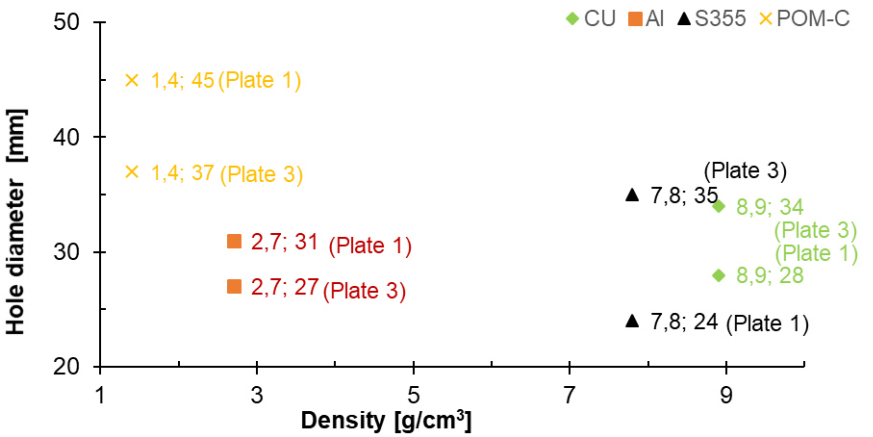

Figure 7. Density of the inert material versus $Ø_{IN}(1)$ and $Ø_{OUT}(3)$ – for $h = (1/3)H$

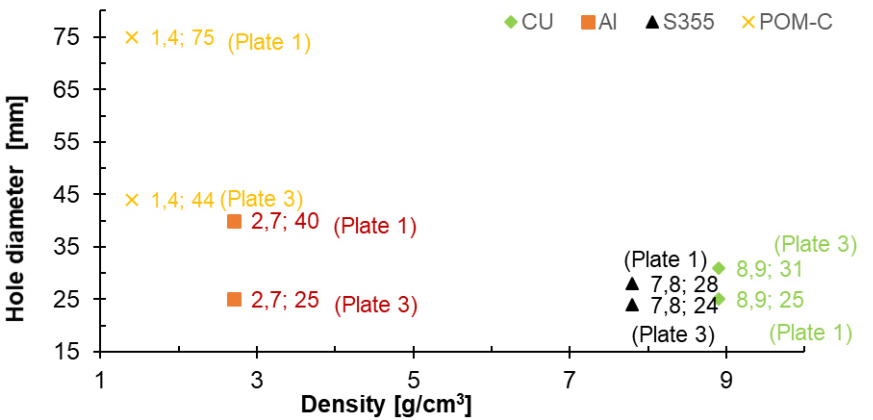

Figure 8. Density of the inert material versus $Ø_{IN}(1)$ and $Ø_{OUT}(3)$ – for $h = (2/3)H$

The distribution of velocities (*e.g.* tip velocity (V_c)) of parts of the SCJs as a function of an initial coordinate, which refers to the appropriate zones of the cumulative liner are shown in Figure 9 [23]. In this case, the obtained results are:

– without filler – $V_c = 6.818$ km/s,
– for $h = (1/3)H$ – $V_c = 5.894$ km/s, and
– for $h = (2/3)H$ – $V_c = 3.585$ km/s

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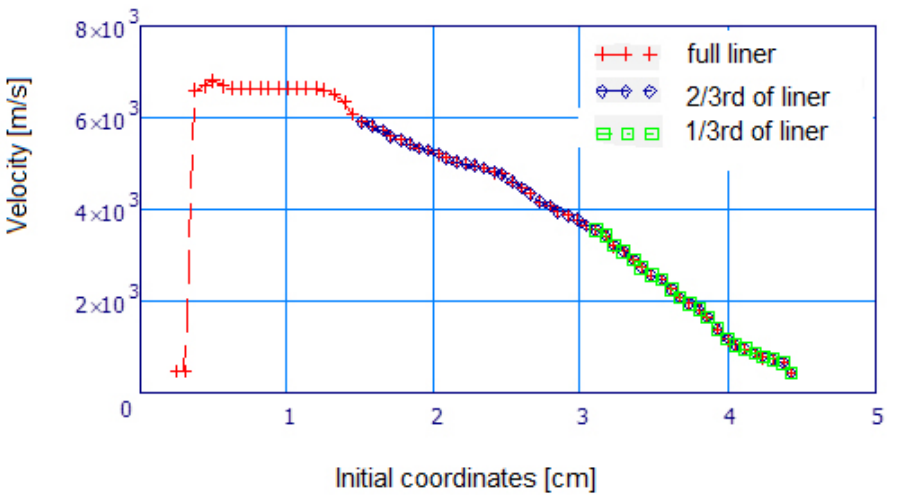

Figure 9. Distribution of velocities (*e.g.* tip velocity (V_c)) of parts of the cumulative jets as a function of an initial coordinate (on the basis of [23])

From the point of view of the effectiveness of the SCJ, a foreign body placed in the cumulative liner significantly reduces the ability of the jet to penetrate the object. As a result of filling the hollow of the SC cone with the foreign body, the active length of the cone is reduced and thus the appropriate front part of the SCJ is cut off. In this way, parameters of such SCJs, eg radial dimensions, front velocity and velocity distributions of the SCJ parts along the longitudinal axis, can be controlled. Moreover, under the influence of pressure from the detonation products, the material of the cone undergoes strong impact compression and, after unloading on the free surface of the cone base, the material flows out at high velocity along that axis.

In the cases of S355 and Cu cones, these velocities should be twice the value of the axial component of the mass velocity in the shock wave propagating in the liner, and the separated layers of these materials accelerated along the axis should have a solid aggregate form with a density close to the initial one. In the cases of cones made from Al and POM-C, melting and evaporation processes occur in the vicinity of the axis during the isentropic flow of the material from the free surface, as well as a significant reduction in density when compared to the initial value. The resulting SCJ can reach a high axial velocity, flowing into the accumulation area of the free part of the liner. In the case of cones made from S355, the observed holes are of much larger diameters, and indicate that

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parts of the liner do not converge on the axis, but are halted on the surface of the filling material stream.

5 Conclusions

- On the basis of the experimental analyses some conclusions on the relationship of the type of a non-explosive material (inert filler) and the height of the cones made of these fillers versus the shapes and dimensions of craters and domes created in tested steel plates were presented.
- Evident influence of the density of the material used in the filling on the character of the resulting SC jet, and, finally, on the interaction of this jet with the armour ARMSTAL 30PM plates were observed.
- Further considerations on the possible application of the tested arrangements could be focused on engineering or sapper work, especially on SCs for:
  - statically detonated cutting SCs,
  - mines with directional fragmentation effects,
  - destruction of unexploded (UXO) and obsolete ordnance.

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