Oblique impact of a 7.62x39 mm projectile on ceramic-coated aramid plates

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Abstract. Projectile ricochet is an important protection mechanism. It refers to the deflection of a surface and the avoidance of perforation. It is predominantly used on armoured vehicles, where specific designs enhance the likelihood of ricocheting incoming threats. This study applies this knowledge to investigate specific structures and designs to enhance the likelihood of projectile ricochet on combat helmets. It investigates the potential of applying thin ceramic coatings on aramid plate. In cooperation with the University of Technology Belfort-Montbéliard (UTBM), using their different spray techniques, the ceramic layer was atmospheric plasma sprayed in different thicknesses on the aramid plates. Ballistic experiments were conducted at the French-German Research institute Saint-Louis (ISL), where a 7.62 x 39-mm projectile was launched at two different angles of obliquity. The impact velocity was approximately 600 m/s, simulating a shot from a 100m distance. A high-speed camera on the target plate strike face captured the ceramic layer spalling, while a digital image correlation measurement captured the dynamic back face deformation (BFD). This paper presents and discusses the differences in the maximum BFD of the ceramic-coated plates compared to non-coated ones.

1. INTRODUCTION

Helmets are an integral part of standard soldier protection equipment. The head, which is a vital zone, requires the best possible protection. However, the helmet mass must be kept to a minimum to ensure a high level of comfort. Heavy equipment during long missions could tire a soldier and affect their ability to move and detect threats. Recent international conflicts in Iraq and Afghanistan have demonstrated the need to increase the protection of soldiers' heads and necks [1]. The proportion of injuries in these parts of the body has increased by 30–50% within the evolution of conflicts, as shown in Figure 1. The increase in head and neck injuries was not further discussed in terms of the type of threats accrued.

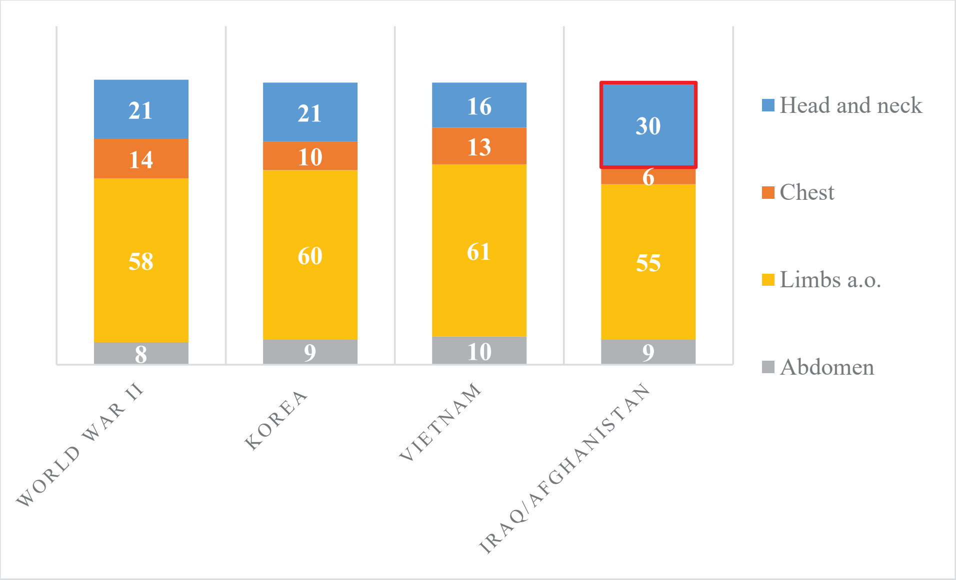

Figure 1. Percentage of various injuries of soldiers in different wars [1]

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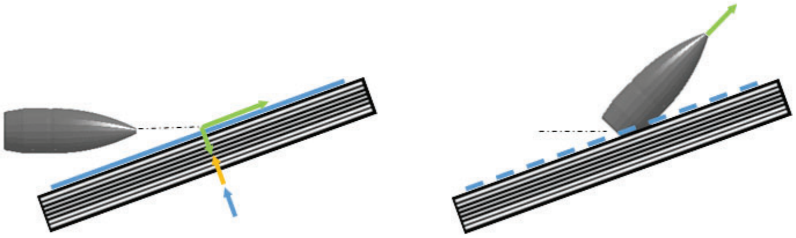
This work focuses specifically on the 7.62x39 mm projectile as there is a high probability of soldiers and armed forces facing such a threat during missions [2]. In order to design a helmet that can withstand a direct hit of such a threat, its mass would have to increase significantly, making it not feasible for daily use. One possibility to improve protection against a 7.62x39 mm without adding weight to the helmet is increasing the likelihood of projectile ricochet, e.g., through a hardened surface. In this study, ceramic spray coating was applied on aramid plates and helmets, and the protection capabilities were tested.

This work was conducted in cooperation with the University of Technology at Belfort and Montbéliard (UBTM) and the French-German Research Institute of Saint-Louis (ISL). The UBTM prepared and spray-coated the samples, while the ballistic tests were conducted at the ISL. This was a primarily experimental study to investigate the adhesion of a hard and brittle ceramic layer on a woven fibre composite plate – an aramid material. To ensure the adhesion of the ceramic coating on the composite plate, a thin layer of zinc was applied. The oblique impact and ricochet of 7.62.x39 mm was chosen as an applicable test scenario to test the performance of the ceramic coating. The hypothesis was that the harder the target surface, the lesser the penetration and the sooner the projectile would ricochet (Figure 2).

a) Initial state – no layer

b) Projectile penetrates



c) Initial state with layer (blue)

d) More resistance projectile ricochet upon layer fracture

Figure 2. Impact of the additional layer on ricochet

The influence of the ceramic coating on the projectile trajectory was measured using X-ray cinematography and back face deformation (BFD) of the aramid target plate using digital image correlation (DIC). Since the influence of experimental parameters, such as projectile nutation or target properties, on the projectile trajectory and, therefore, the ricochet event, might be higher than the influence measured due to the surface coating, the BFD was also measured. If the projectile ricochets earlier, it does not penetrate the target plate so extensively. As a result, there is less deformation on the back face. This experiment is a feasibility study to determine if the surface coating has an influence and, if so, if the measurement might be able to quantify it.

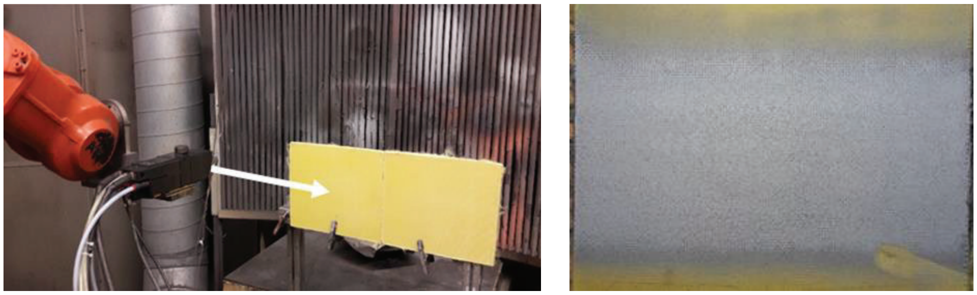
2. CERAMIC SPRAY-COATING

2.1 Sample preparation

For the ceramic spraying and ballistic testing, aramid plates were used, which are made from the same material and average thickness as combat helmets. The surface was roughened using a pneumatic sandblaster with pressure set at 3.5 bar to avoid damaging the fibres. The aramid plates were cleaned with ethanol to remove grease and other contamination to assure better adhesion of the ceramic coating during the projectile high-speed impact.

2.2 Binding layer

A layer of a zinc (Zn) binder was sprayed on the prepared and cleaned aramid plate surface for better adhesion between the aramid plate and its final ceramic layer. Zn was used due to its low melting temperature, which causes less surface damage on the aramid target strike face. The applied spray technique is called arc wire spray, wherein an electrical arc discharge is the source of energy melting the Zn (Figure 3, a). A 100 µm-thick layer of Zn was applied (Figure 3, b). This was the thinnest possible layer as the parameter was adhesion between the aramid plate and ceramic layer, which can be expected. The Zn layer was applied with a width of 100–150 mm over the full length. On average, an increase of mass of about 25–30 g was considered. A thorough investigation of the influence of the binder material, its thickness and the probable influence of different spraying techniques and settings was not part of this study. As a starting point, materials were chosen due to their availability.



a) Spray coating at the UBTM b) Zn-layered sample

Figure 3. Arc-wired Zn coating

2.3 Ceramic coating

Two available zirconium oxide (zirconia, ZrO_2) powders were tested between 10–40 µm grain sizes. They were tested to determine if there was an influence of grain size on adhesion. A thickness from 300–1100 µm was applied (**Table 1**), where the larger grain size of ZrO_2 was deemed better for higher thicknesses. Other influences of the two different powders were not observed, which might be due to the limited sample size and primary test set-up.

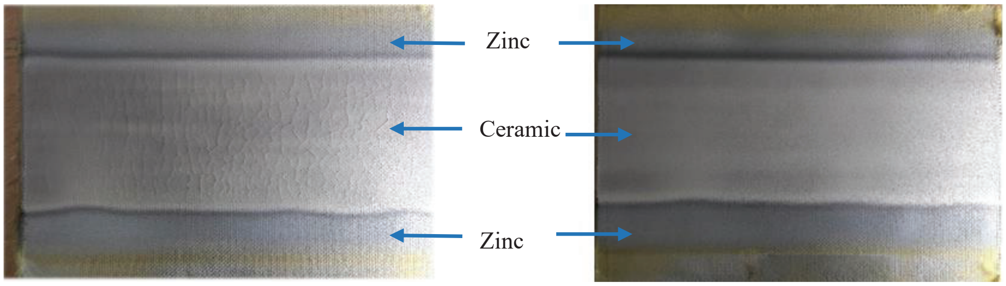


Figure 4. Plates coated with ZrO_2: (left) cracks and (right) after correction

To apply the ceramic coating on top of the Zn layer, atmospheric plasma spraying was chosen, as it is suitable to reach the high melting temperature of ceramics. In order to decrease the high temperature interacting with the aramid plate surface, the spray nozzle was placed further away, from the previous 110 mm distance to 165 mm. Additional fan cooling was applied. However, if the ceramics were cooled too fast, cracks appeared upon coming in contact with the Zn-layered composite plate (Figure 4).

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2.4 Additional mass on combat helmet

The ceramic material had a density of 5.7 g/cm^3, which added a mass of 50–180 g to the roughly 750 g mass of those plates (Figure 4). To estimate the increase of helmet mass due to the added ceramic layers, the outer shell surface of a combat helmet was measured. The helmet was 3D-scanned, and its computer model was analysed. A complete spray coating of the outer shell surface was assumed. The 3D model was taken from a medium-sized helmet, keeping in mind that different sizes and models yield different results in terms of the mass increase. An outer shell of this type has an area of 1160 cm² (Figure 5). For ceramic coating of 300–1100 µm, the increase in mass was 200–700 g, where the radial increase of a rounded surface was neglected. In relation to a medium combat helmet with interior, the increase was 15–50%, depending on the thickness of the layer. This primary study did not consider the ergonomic aspects of additional helmet mass.

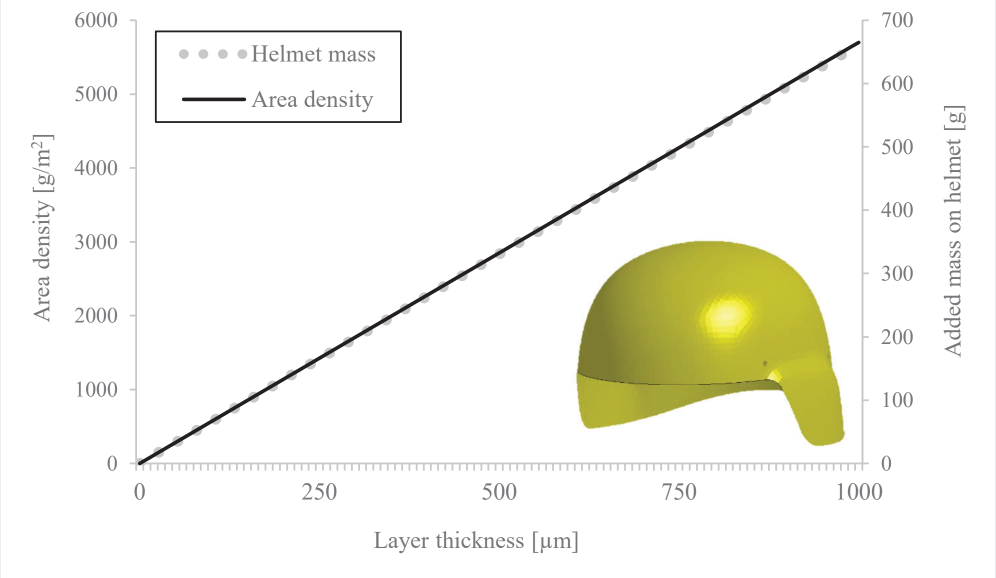

Figure 5. Increase in combat helmet mass based on the simulation model

3. BALLISTIC TESTS

3.1 Setup

The 7.62x39 mm projectile was launched at a constant initial velocity of v_i=610 m/s, simulating a shot from approximately a 100 m distance. The plates were inclined at 65° and 80° (NATO). These oblique angles were chosen based on previous studies, having 65°close to the critical ricochet angle and 80° being a grazing shot with as little deformation as possible. The DIC measurement technique was applied to quantify the BFD of the plates. Additionally, a high-speed camera was placed on the strike face to capture the fracture of the ceramic coating (Figure 6).

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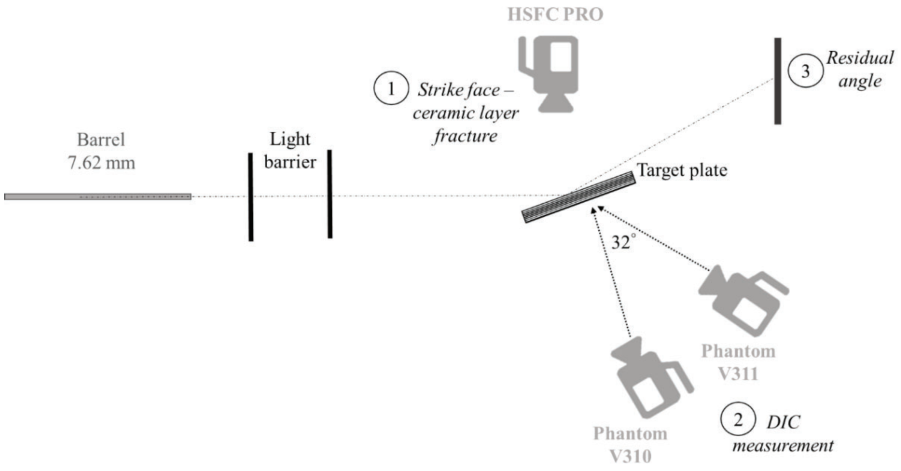

Figure 6. The experimental test setup

Table 1 summarises the test matrix of the investigated aramid plates. The plates were taken from one batch of 50 plates in order to decrease the potential influence of the production process as reference data were taken from plates with no layers. Plates at the upper 12 and 13 were chosen deliberately, and the middle ones were taken from the available samples. Four plates with only the Zn layer were tested in order to determine if the layer process had an influence on the ballistic plate performance. The twelve ceramic-layered plates and the type of powder utilised are presented in Table 1 with their different thicknesses.

Table 1. Test matrix of differently layered plates with initial conditions and residual properties

Layer	Plate number	Impact angle θ [°]	Ceramic thickness [µm]	Initial velocity [m/s]	Reflection angle ξ [°]	Max BFD [mm]	Note
No layer	22	80		606	77	7.0	
No layer	12	80		611	77	6.3	
No layer	13	65		615	58	11.0	
Zinc	8	65	100	613	-	12.0	D
Zinc	23	65	80	620	-	13.6	P
Zinc	24	65	80	621	66	12.1	
Zinc	25	65	160	615	-	-	P
ZrO_2 Y2O3	10	80	400	617	78	6.7	
ZrO_2 Y2O3	11	80	500	605	76	6.5	
ZrO_2 Y2O3	15	80	400	606	76	5.9	
ZrO_2 Y2O3	14	65	460	601	61	10.6	
ZrO_2 Y2O3	16	65	950	612	61	10.1	
ZrO_2 Y2O3	17	65	350	603	-	11.0	P
ZrO_2 Y2O3	18	65	290	606	61	-	
ZrO_2	9	80	400	606	76	5.9	
ZrO_2	19	65	350	606	57	-	
ZrO_2	20	65	620	605	-	12	B
ZrO_2	21	65	1100	611	-	10.7	P
ZrO_2	26	65	160	613	62		

Perforation P; Influence of boundary conditions B and Penetration D; else ricochet

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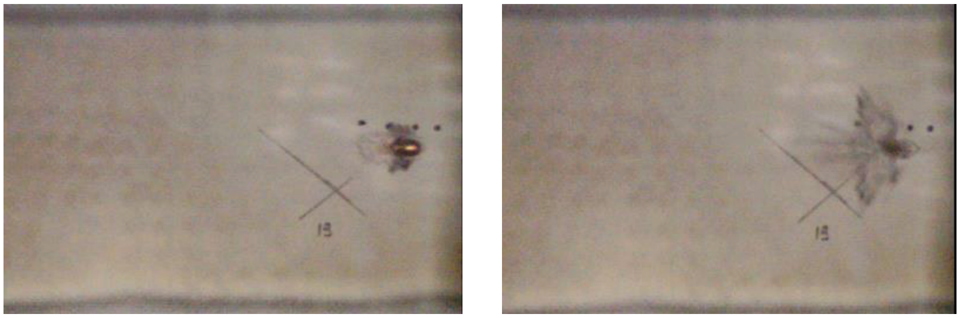
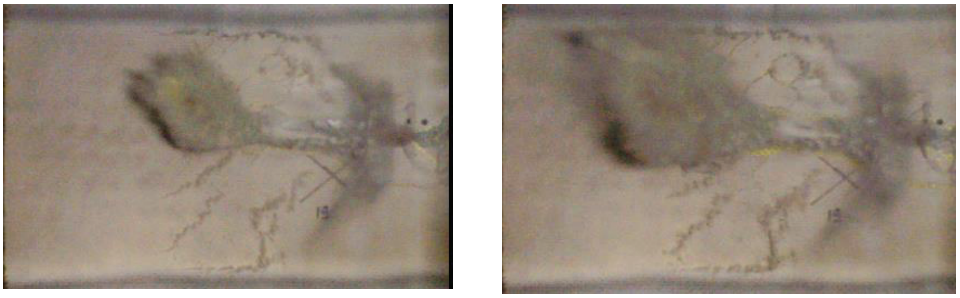
3.2 Results

3.2.1 Ceramic layer fracture

Figure 7 shows plate impact at the two different angles with similar layer material, powder size, and layer thickness. Independent of the impact angle, the ceramic layer spalled after projectile penetration. Further investigation is required to determine if the additional ceramic layer reduces the impulse transition from the impacting projectile on the aramid plate.



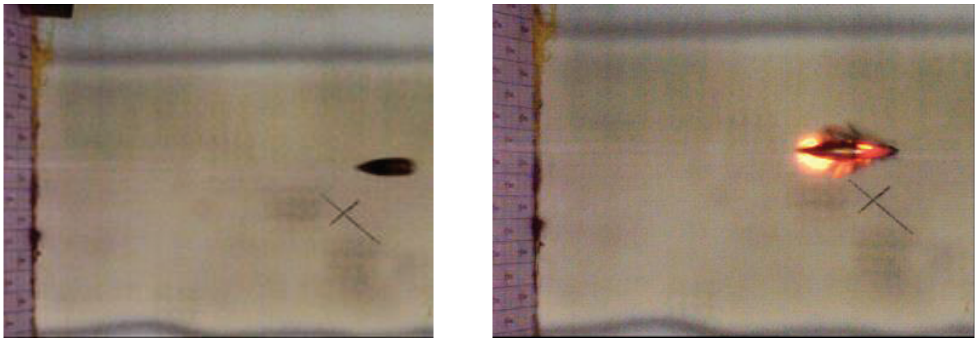
a) t=70 μs b) t=140 μs



c) t=270 μs d) t=330 μs

Figure 7. Strike face of Plate 19 at 25°and 350 µm

Also, independent of the initial powder, at the true ricochet with θ=80°impact scenario, the pyrophoric material behaviour of the ceramic layer was observed (Figure 8). A burned surface on the remaining aramid plate was not observed.



a) t=0 μs b) t=70 μs

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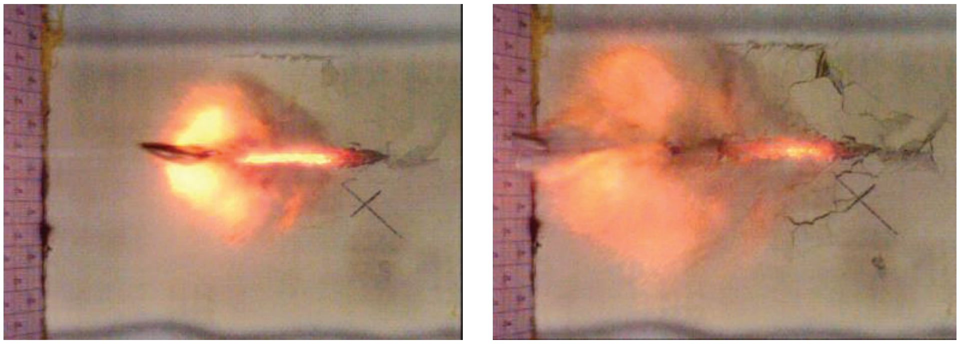
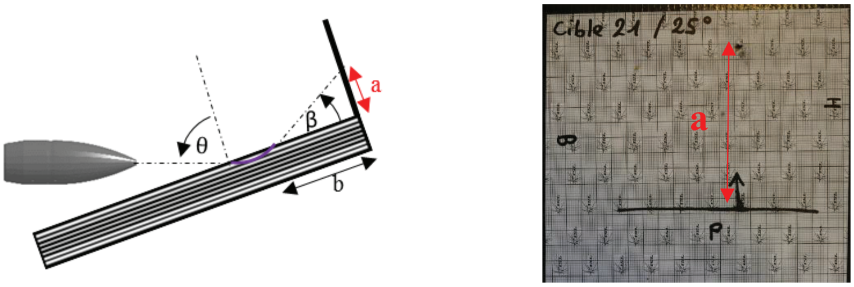


c) t=270 μs d) t=410 μs

Figure 8. Strike face of Plate 10 at 10° and 400 µm

3.2.2 Determination of the deflection angle

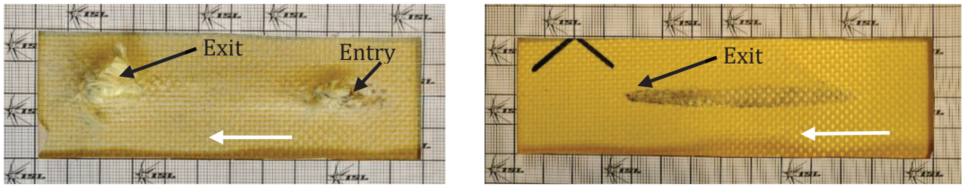
In order to determine the value of the refection angle β, a cardboard witness plate was positioned at the edge perpendicular to the aramid plate strike face (Figure 9a). Figure 9b shows the cardboard of Plate 21 with an impact angle θ of 65°.



a) Sketch of impact b) Cardboard of Plate 29

Figure 9. Determination of residual angle β

Determining length b from the aramid target plate to the cardboard poses a challenge. The projectile penetrates or comes in contact with the plate for some distance before it ricochets [3]. Figure 10a shows the projectile penetration as it was observed for an impact angle θ=65°. The white arrow marks the direction. For an angle θ=80°, the projectile is in contact with the first aramid layer.



a) Oblique impact angle θ=65° b) Oblique impact angle θ=80°

Figure 10. Projectile trajectory on an aramid plate (arrow indicates impact direction)

The exit point is where the projectile leaves contact with the strike face and until the plate edge is defined at length b. Length a is perpendicular to the plate edge until the projectile perforates the witness cardboard. The angle β is shown in Equation 1.

$$\beta = \arctan \frac{a}{b} \tag{1}$$

Equation 2 shows the exit angles ξ. In cases without a value, the projectile did not ricochet – either they perforated or they were stuck in the plates.

$$\xi = 90° - \beta \tag{2}$$

An uncertainty of about ξ ± 2-4°, depending on the impact case, was seen. The impact angle θ=65° is close to the critical ricochet angle θ_c [4]. In general, the impact θ and residual angle ξ correspond, as has been observed in previous works [5].

3.2.3 BFD

The dynamic BFD measurement was conducted with digital image correlation. As shown in Table 1, and as described in the previous section, the Zn layer seems to have an effect on the plate performance. However, more data is needed to confirm this statement. So far, several tests over a period of months have shown that all Zn-layered plates result in higher BFD. Perforation could also be observed under initial conditions in the case of untreated plates [3].

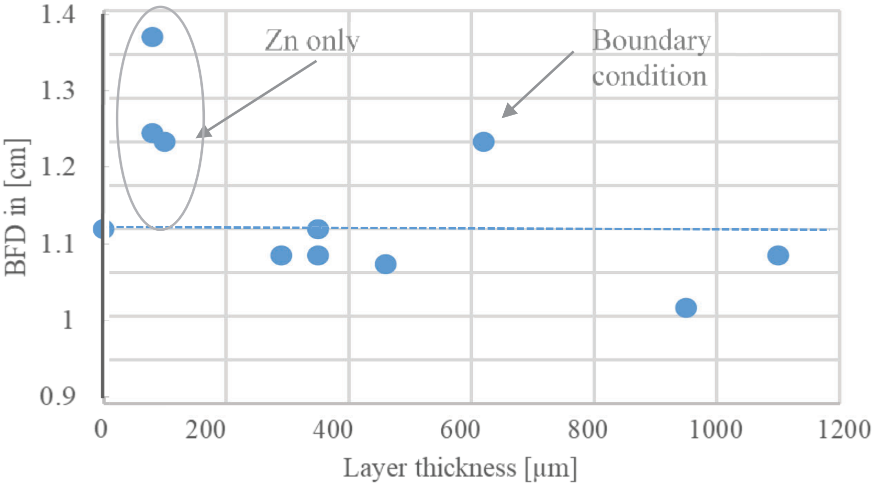


Figure 11. BFD depending on the ceramic thickness for θ=65°

When taking the average BFD from original plates to coated, a decrease of about 5% is achieved (Figure 11). For the impact angle of θ=65, at 0 µm layer thickness, the measurement of the original plate is shown as a reference state. This value aligns with previous experiments [3]. The 100 µm layer thickness comes from the Zn coating only, and the higher layer thicknesses came from Zn + ceramic coating. Although the Zn-coated plates showed less protective capability for the four tested cases than the untreated plates, if covered again with ceramic, all tests showed a reduction in BFD. The question that arises is that if the Zn layer showed less influence in the protective performance, would the ceramic layer BFD be even lower? Moreover, there seems to be an ideal coating thickness – at about 400 µm – for all tested initial conditions. The measurement error is too high to capture the influence of the thickness 700–1100 µm on the BFD. However, if the influence of the layer thickness was debatable, the additional mass chosen could be lower (Figure 5). The plate coated with 620µm in Figure 11 had a high BFD value due to the influence of boundary conditions. The projectile came in contact with the frame during the impact. Also, the influence of the different powder was not observed with the current testing capability. For the impact of θ=80° in Figure 12, fewer impact tests were conducted due to the pyrophoric behaviour of the ceramic layer (Figure 8). Two BFD values of the untreated plates were taken, and their middle value was used as a limit.

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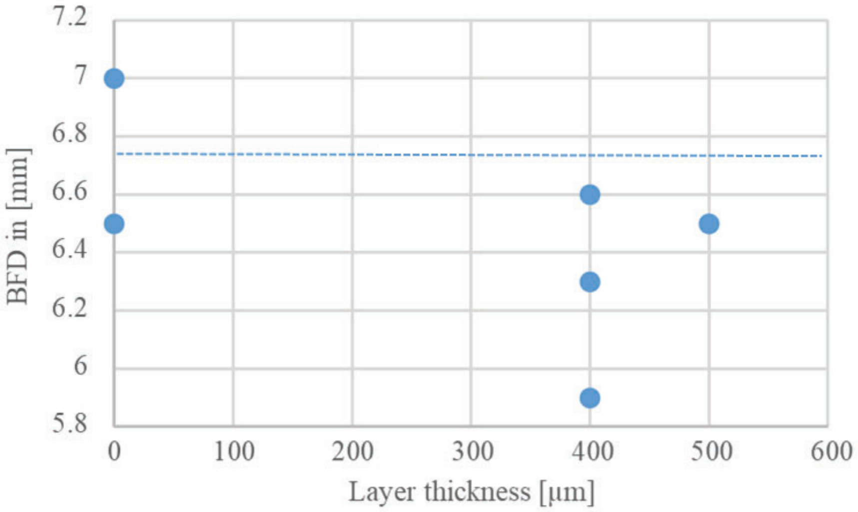

Figure 12. BFD depending on the ceramic thickness for θ=80°

4. CONCLUSION

This work shows a primary test on the ceramic spray-coating of aramid plates using an oblique impact and ricochet of a 7.62x39 mm projectile. Various parameters were measured: the BFD using DIC, the residual angle, and a high-speed video capturing the fracture of the ceramic coating. Two different impact angles – θ=65° and θ=80° (NATO) – were tested with a constant initial velocity 610 +/-10 m/s. The high-speed videos showed that the ceramic layer on the strike face for the higher θ showed pyrophoric behaviour. The influence of the surface coating on the residual angles could not be determined. The measured BFD showed that the Zn layer acted as an adhesive between the aramid plate and the ceramic layer and seemed to decrease their protective performance when compared to the original plates. The ceramic layer thickness showed repeatedly less measurable BFD. For a thorough investigation of the influence of spray technique, powder and thickness, a less complex target material is needed. However, the primary test showed better results than were initially expected in terms of the adhesion between the ceramic coating and the aramid plates.

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