THE EFFECTS OF A RANGE OF PROJECTILES ON BULLET RICOCHET EVIDENCE FROM 1 MM SHEET METAL

1. Introduction

Sheet metal is a popular industrial material used in construction throughout history and refers to a metal shaped into thin, flat piece using hot or cold rolling processes [1]. It is commonly used in commercial and industrial construction due to its flexibility, resilience, and low price. The standard thickness of sheet metal is below 6.35 mm [2]; however, mild steel sheets of 0.45 mm to 1.2 mm (gauge 18, 20, 22, 24) are more typically used in modern urban environments [3], with 1 mm being the most commonly available gauge used for applications such as roofing sheets, signposts, walls and partitions, major appliances, and particularly for the construction of light vehicle bodies [4,5,6,7]. Owing to its availability in urban settings, sheet metal is a frequently reported surface with bullet holes and ricochet marks, particularly in urban shooting incidents [5, 7].

Sheet metal usually has homogeneous material properties, and its production involves standard industrial processes [1,8,9]. For these reasons, the findings of sheet metal-related terminal ballistic studies usually have better reproducibility than the other non-homogeneous and natural target types [5,10-19]. Bullet holes and ricochet marks on sheet metal are the most highlighted evidence and studies have shown how these features could be used to determine the trajectories of fired bullets (bullet' angle of incidence) and the shooter's location during practical reconstructions [5,7,14].

Most of these forensic studies have focused on exploring the evidential value of bullet holes (during bullet perforation) in sheet metal, except for a single study that examined the ricochet marks [5]. This previous ricochet study presents statistical evidence that ricochet-related evidence on 1 mm sheet metal by AK bullets (7.62 × 39 mm, M 43) has an excellent reconstructive value to indicate corresponding angles of incidence while presenting currently unreported complex ricochet phenomena. This highlights the significance of further exploring the reported findings with different bullet types/ configurations.

Building on the above-mentioned previous ricochet study [5], this empirical investigation explores the ricochet-related scientific evidence on flat 1 mm sheet metal with various bullet types (9 mm Luger, 5.56× 45 mm, and 7.62 × 51 mm). These bullet types are commonly reported in crime scene shootings around the world and represent various bullet configurations, geometries and velocities to understand how bullet-related factors affect ricochet evidence. The findings of this study are also of use to impact scientists to help understand the diverse terminal ballistic phenomena related to sheet metal and associated evidence production under varying conditions.

2. Methodology

This study used the same general methodology employed in most of the ricochet experiments [5, 20-23]. Four firearm types (9 mm Browning HP pistol, 9 mm Uzi Sub-machine gun, SLR assault rifle, M16 assault rifle) were each firmly mounted on a stable steel firing platform. The firing platform was designed and fabricated using L-angle (50.8 mm × 50.8 mm) steel bars to hold the guns firmly. Once mounted on the firing platform, barrels of firearms were ensured to be parallel to the ground. The firearm positions were checked after each shot to ensure no change. A custom-made bubble level with a rod (diameter equal to the calibre of the firearm) was used for this purpose. The height above the ground for each muzzle and point of target impact was always 1.6 m.

A cubic shape steel target holder (457 mm × 457 mm × 457 mm) was designed and fabricated using 25 mm L angle bars to hold a target tray with 1 mm sheet metal samples (457 mm × 457 mm). The steel target holder was fixed onto another stable steel base, which was bolted to the ground. The frames' horizontal bars were set to parallel the floor, and the levels were checked frequently. A square-shaped frame (457 mm × 457 mm) was made using 25 mm L angle bars to hold the targets (target tray). It was hinged to the target holder having the frame from one side so that it could be lifted and locked in place to set each angle of incidence. The sheet metal samples (457 mm × 457 mm) could then be fixed to the tray from the four corners using nuts and bolts. The sheet metal samples were not supported underneath. Set angles were checked after each shot to ensure no changes occurred due to bullet impacts. Paper witness screens were placed at the target tray's far end to capture the ricocheting bullets' silhouettes. A box filled with Kevlar fabrics was placed behind the paper screen to soft capture the ricocheting bullets for analysing their deformations.

The mounted firearms were fired at sheet metal samples placed 10 m from the muzzle end of the guns. Sheet metal samples were held at different angles to the bullet's trajectory on a steel target tray. 10 x shots were fired at each angle, starting at 5 degrees. The angle increased in two-degree intervals until the critical angle of the bullets was achieved (firing stop when all 10 shots perforated a sheet metal sample with no ricochets). The same procedure was repeated for each firearm type. The tests were conducted in an open environment.

The ricochet angles of the bullets were calculated in this study to explore any relationship between the ricochet marks/ angle of incidence of the bullets. Basic trigonometry was used to calculate the ricochet angles as done with previous ricochet experiments [5, 21-23]. Each bullet's velocity was measured in meters per second using a LabRadar velocity radar (LabRadar - v.1.3 with +/- 0.1% accuracy) placed parallel and 30 cm away from the muzzle of each firearm. All ricochet marks on the sheet metal samples and witness screens were numbered and photographed. The lengths of the ricochet marks were measured using a digital calliper with 0.02 mm accuracy (an explanation of how the measurements were taken is given in section 3.4). The experimental arrangement is shown in Figure 1, with some of the pictures taken of the target holders and gun mounts with mounted firearms in Figure 2. Details of the ammunition used for the experiment are shown in Table 1. The pictures depicting the shape of the bullets and head stamps of the ammunition used are also provided in Figure 3.

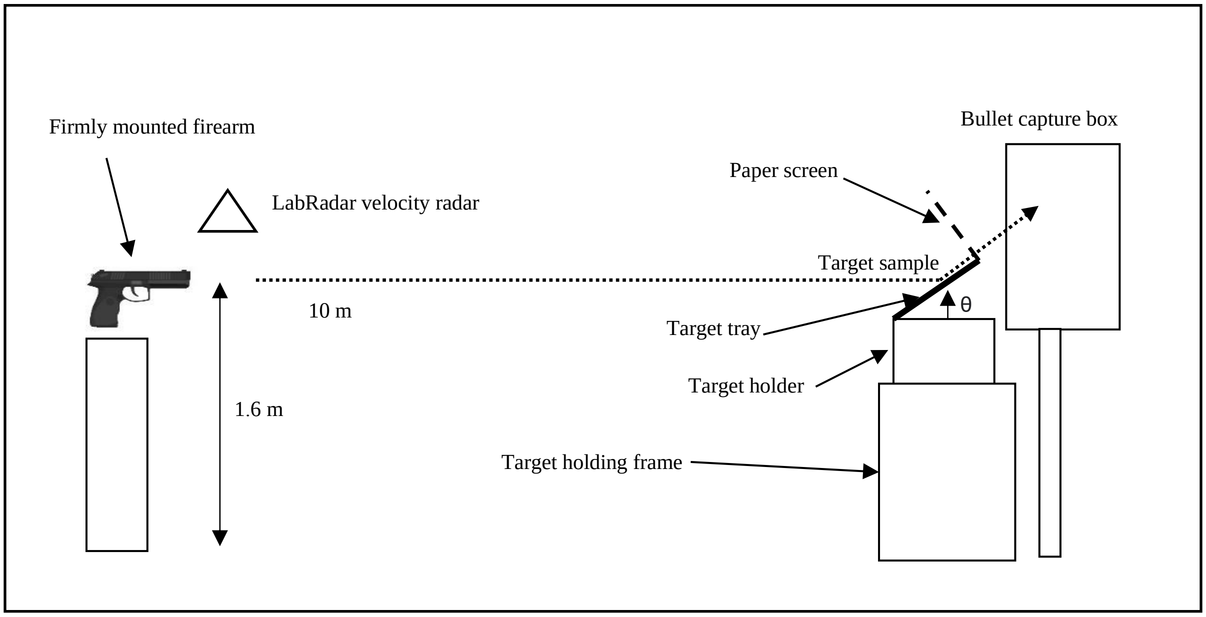

Figure 1: The experimental ricochet setup. θ refers to the angle of the target tray, which is equal to the incident angle of bullets.

Figure 2: Photographs of the gun mounts and target holder used during the study.

Table 1: Firearms and ammunition used for the experiment.

Firearm type	Ammunition type
9 mm Browning HP pistol	9 × 19 mm Luger Ammunition (round/ parabolic nose) with a lead core and copper jacket .The ammunition batch was produced in 2018 at Norinco Ammunition Factory, China .
9 mm Uzi sub-machine gun	The same 9 mm ammunition used for the Browning HP pistol was used with the Uzi Submachine gun.
SLR assault rifle	7.62 mm × 51 mm, M43-type ogive nose FMJ bullets with a steel rod, lead core and copper jacket (ogive nose) . The batch was produced in 1996 at the production facility of China North Industries Corp.
M16 assault rifle	5.56mm × 45 mm ogive nose FMJ bullets (M43-type with a steel rod, lead core and copper jacket). Produced in Birmingham Metals & Munitions Company, Birmingham, UK.

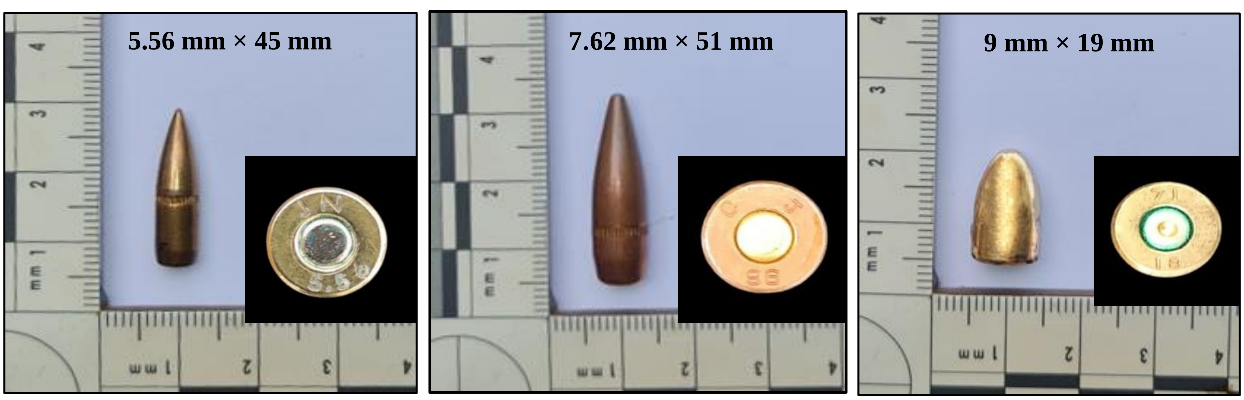

Figure 3: Bullets and head-stamps of the ammunition used for the study.

The sheet metal samples used for the study were zinc-coated standard, 1.0 mm (+/- 0.006 mm) thick mild core steel sheets (457 × 457 mm) used for general construction and as automotive sheet metal. A room temperature uniaxial tensile strength test [24] was employed to understand the mechanical behaviour of sheet metal samples used for the study. A Universal Testing Machine

(HSM58, PA Hilton) was used for the test to give a tensile strength of c. 325 MPa with elongation (strain) equal to 0.25. Furthermore, X-ray fluorescence (XRF) analysis was conducted to determine the elemental composition of the sheet metals tested during this study (Horiba XGT-5200 X-ray Analytical Microscope). This revealed the sheets consist of 47 % iron (Fe), 43 % zinc (Zn), 7 % phosphorus (P), 3 % aluminium (Al), and 1 % silicon (Si).

Correlation coefficient statistical analysis was performed using Excel to understand the relationships between the variables [25]. Cumulative failure plot analysis using MINITAB software [26] was employed to estimate the critical angle of the bullets and the probability of ricochets. In the software, ricochet angles were modelled as a function of the angles of incidence to estimate the critical angle. This method is commonly used to calculate the critical angle of bullets in most ricochet studies [5,20-23]. A one-way ANOVA (Analysis of Variance) was used to decide whether there were any statistically significant differences between the means of three or more independent groups [27]. The Eta Squared method was employed to calculate the effect size for each ANOVA model. It is a standardised estimate of effect size and is comparable across outcome variables measured using different units [28]. Effect size explains how meaningful the relationship between variables or the difference between groups is [29].

3. Results and Discussion

3.1 Critical Angle of the Bullets and Average Velocity

260 shots were fired to analyse the ricochet evidence of different bullet-target combinations. The average velocity of the bullets reported with each firearm type is given in Figure 4, with the standard deviations. The critical angles reported for different bullet types are shown in Table 2, including the calculated average kinetic energies of the bullets using the standard formula, $KE = \frac{1}{2} mv^2$ [30] (KE= Kinetic Energy, m = mass of the projectile, v =velocity of the projectile). The critical angle estimated through cumulative failure plot analysis for 9 mm Luger bullets fired from 9 mm Browning pistol

(with 50 percent probability) is given in Figure 5 to demonstrate how the critical angle values were obtained. This method has been used in many ricochet experiments to estimate the probability of ricochet [5, 20-23].

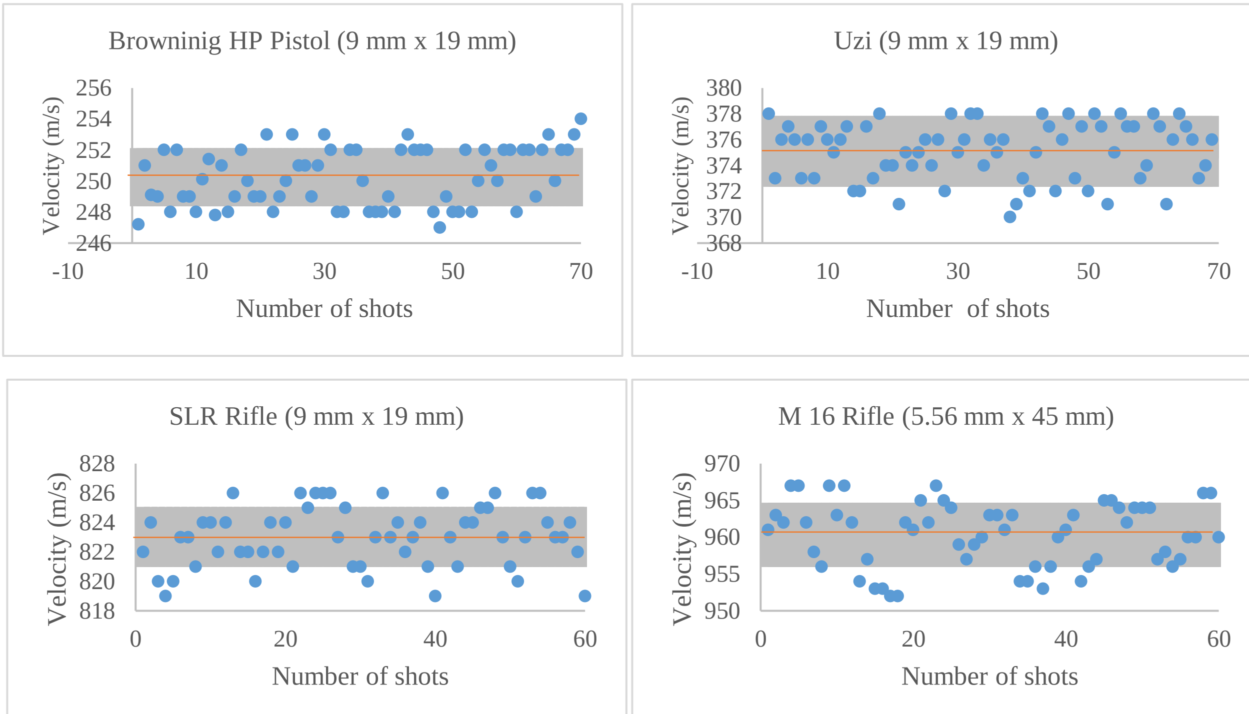

Figure 4: The average velocity of the bullets and standard deviations reported with each firearm type

Table 2: The critical angles reported for different bullet types.

Gun type	Ammunition type	Average velocity (m/s)	Kinetic Energy (Jouls)	Critical angle (degrees)
Browning HP pistol	9 × 19 mm	250	249.3	15.9
9 mm Uzi sub-machine gun	9 × 19 mm	375	561.1	15
SLR assault rifle	7.62 × 51 mm	823	3166.5	11.4
M16 assault rifle	5.56 × 45 mm	960	1797.1	Bullet fragmentation observed from 5 degrees onwards

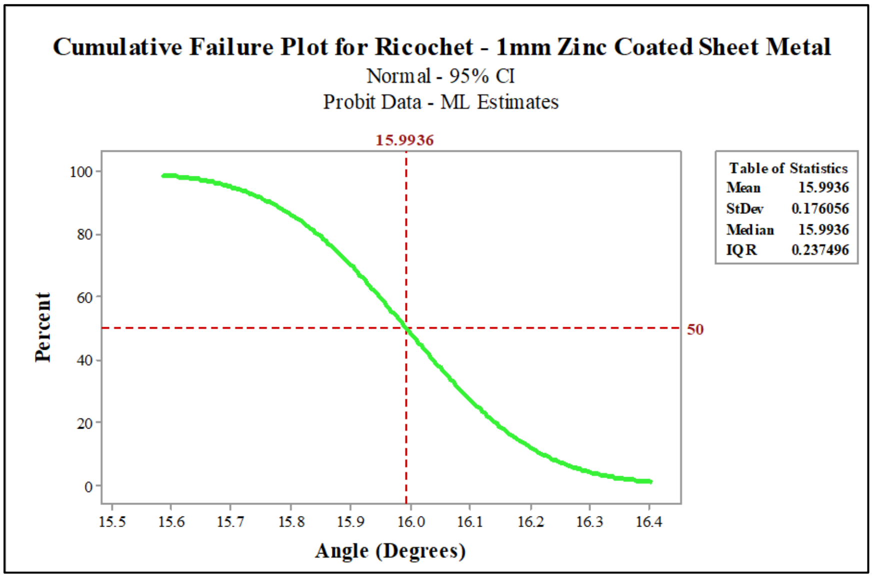

Figure 5: Cumulative failure plot generated in MINITAB software to estimate the critical angle for the 9 mm bullets fired by the Browning HP pistol (with a 50% probability of ricochet).

The critical angles observed generally comply with the current understanding of the bullet velocity and critical angle in that high-velocity bullets (with high kinetic energy) achieve critical angles earlier than lower-velocity bullets [16]. The velocity difference observed between the same type of 9 mm bullets (with Browning HP pistol and 9 mm Uzi sub-machine gun) also complies with the current understanding that longer barrels (9 mm Uzi Submachine gun) produce higher velocities than shorter barrels (Browning HP pistol). This occurs because the propellant burns more entirely in longer barrels than in shorter ones leading to a longer acceleration phase [31, 32] and due to the increased rifling length of longer barrels and the difference in rifling geometry. All 5.56 × 45 mm bullets fragmented on impact from 5 degrees onwards, indicating that their critical angle (the angle the bullet states to fragment) is likely below 5 degrees. Although the 5.56× 45 mm bullets had the highest velocity, their kinetic energy was less than 7.62 × 51 mm due to their comparatively low mass. Based on the finding, the velocity causes more severe deformation of the bullet than the kinetic energy, and the same phenomenon has been previously reported [33].

3.2 Ricochet Angles of the Bullets

The ricochet angles for the three ricocheting bullet types were reported between 3 to 11.3 degrees. Generally, a fair degree of consistency was observed in each data set with relatively small standard deviations, particularly for lower angles of incidence. Although different trends have been reported with ricochet angles of bullets and incident angles in previous ricochet studies [5, 20, 22], no such specific ricochet trends between angles of incidence and ricochet could be identified from the data of these three bullet types. The ricochet angles/ average ricochet angles with standard deviations reported (for 10 shots) are given in Figure 6.

Gun	Incident angle (degrees)	Average Ricochet Angle (degrees)	Standard Deviation (degrees)
Browning HP	5	5.7	1.6
	7	5.1	1
	9	6.2	1
	11	6.2	1.4
	13	7.6	0.9
	15	6.6	3.3
SMG UZI	5	4.9	0.6
	7	5.7	1.5
	9	5.0	1.4
	11	7.4	0.1
	13	6.2	0.8
	15	4.8	1.7
SLR	5	4.3	0.7
	7	6.6	0.6
	9	8.7	3.2
	11	6.3	0.6
	13	4	0.7

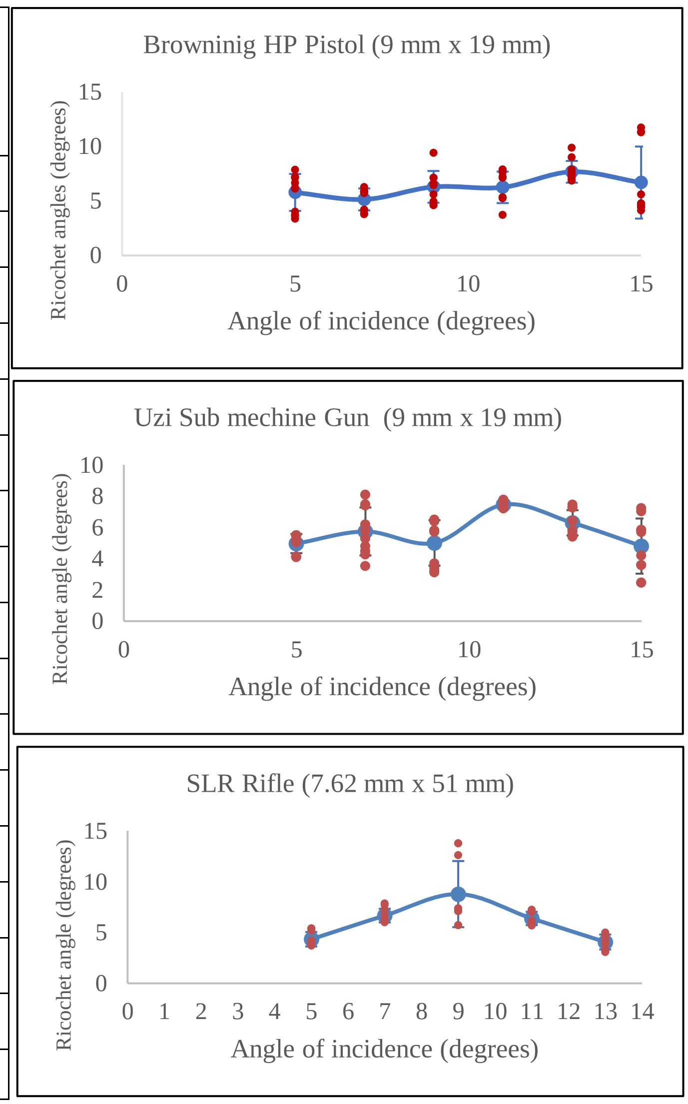

Figure 6: Average ricochet angles with standard deviations reported (for 10 shots). Red dots in the graphs indicate ricochet angles reported at each angle of incidence, and blue dots indicate the average ricochet angles for 10 shots.

True ricochets (bullet ricochet intact) were observed with 9 mm bullets fired from Browning HP and Uzi Sub-Machine Gun at all angles of incidence. Half ricochet-half perforation phenomena (bullet fragment on impact, jacket portion ricochet, and lead core perforating the sheet metal) were observed with 7.62 × 51 mm bullets and 5.56× 45 mm bullets from 11 degrees onwards (11 to 13 degrees with 7.62 mm bullets and 11 to 15 degrees with 5.56 mm bullets. A previous study reported the same phenomenon (AK bullets- 7.62× 39 mm with 1 mm sheet metal) from 8 to 20 degrees [5]. The findings strongly suggest that half ricochet-half perforation can be common to all rifle bullets ricocheting off 1 mm sheet metal and can begin to observe at different angles of incidences. Bullet-related factors such as velocity, bullet construction, geometry and the reaction of the sheet metal to the impacts of different bullets can be assumed as the contributing factors for this phenomenon to observe at different angles with different bullets. These factors have also been highlighted in the bullet ricochet-related literature as factors affecting the ricochet behaviour of bullets [5, 19]. The summary of the ricochet phenomena observed is given in Table 3.

Table 3: A summary of ricochet phenomena observed for different bullets.

Bullet / gun type	True ricochets?	Half perforation / half ricochet	Remarks
9 mm (Pistol)	Yes	No	-
9 mm (SMG)	Yes	No	-
7.62 mm (SLR)	Yes (5 to 9 degrees)	Yes (11 to 13 degrees)	-
5.56 mm (M 16)	No	Yes (11 to 15 degrees)	Bullets fragmented on impact from 5 degrees onwards.

The average ricochet angles reported for each bullet were generally similar to or less than the corresponding incident angles. Similar observations have also been reported in a previous study with 7.62 mm AK bullets [5]. This strongly suggests that any bullet ricocheting off 1 mm sheet metal produces ricochet angles equal to or less than the corresponding incident angles. This finding is significant as it contrasts with the existing theory on bullet ricochet, which suggests that for yielding target surfaces, the ricochet angle is greater than the angle of incidence [19]. It is likely that the comparatively low thickness of sheet metal compared to other target types may create a more complex and less elastic bullet-target interaction, leading to the observed phenomenon. This finding is further analysed with the ricochet evidence in the following sections.

3.3 Ricochet mark profiles

3.3.1 9 mm bullets fired from Browning HP pistol and Uzi sub-machine gun

Ricochet mark profiles observed with 9 mm bullets/ Browning HP pistol are given in Figure 7. These features were similarly observed for 10 shots fired at each angle and for both weapon types. Bullets ricocheted off sheet metal samples at 5 to 9 degrees and 11 to 15-degree incident angles displayed two different ricochet mark profiles for these ranges. From 5 to 9 degrees, three-dimensional creases were produced on the surface, with widths and depths increasing towards the furthest end from the initial impact. At this furthest end, semi-circular dents were also formed. These dents were similar to the deformed bullet profiles collected from the bullet capture box. Notable holes were produced at the end of these semi-circular dents for the 13 and 15-degree impacts, demonstrating a complete failure of the sheet metal with some metal loss due to the bullets' relatively high energy transfer than at lower angles.

For the recovered bullets, one side consistently experienced flattening, with the degree of flattening increasing with the angle of incidence. When the angle of incidence increases, a greater surface area of the bullets comes into contact with the sheet metal and the level of energy transmitted to the surface by the bullet subsequently increases. From 5 to 11 degrees, the bullet's energy is sufficient only to produce a permanent deformation on sheet metal, with strains sufficient to exceed the elastic limit. From 11 degrees onwards, craters had been produced, indicating that the failure point of the material had been reached.

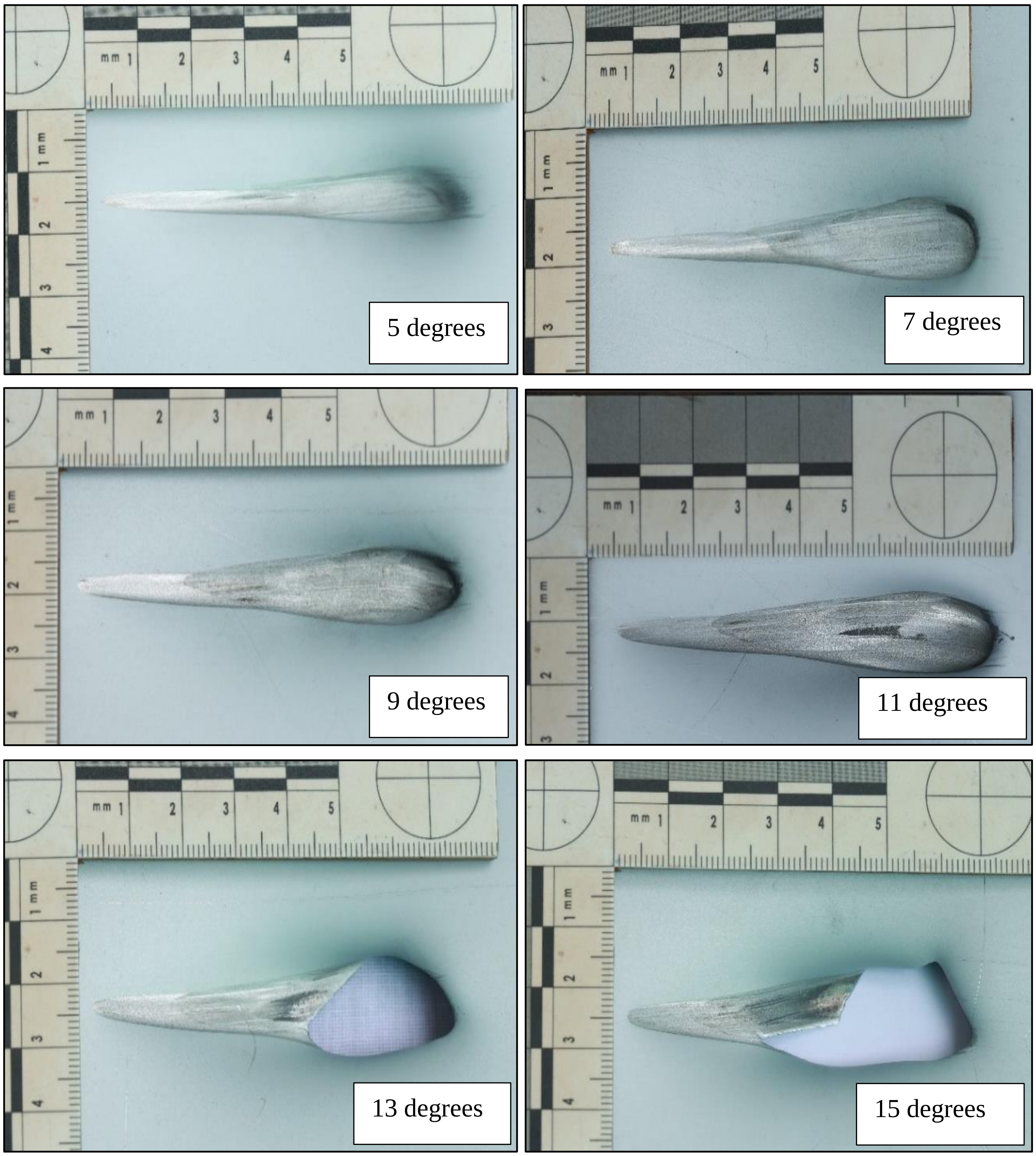

Figure 7: Ricochet crease profiles at each angle of incidence for 9 mm bullets fired from the Browning HP pistol. The initial impact point is on the left side of each mark.

illustration of the finding is given in Figure 8 with a recovered bullet at 9 degrees). The deformation features (including the bullets' D-shaped profiles) could perfectly fit in the corresponding dents produced at each angle of incidence. These dent profiles at each angle of incidence had different and unique shapes corresponding to the deformation withstood by the bullets at each angle. The dent profiles and their occurrence at 7 to 11 degrees suggest a forensically significant phenomenon to help identify the approximate angles of incidence for 9 mm bullets ricocheting off this particular 1 mm sheet metal [5]. The evidence also emphasised the possibility of matching a recovered 9 mm bullet to its ricochet mark based on the bullet's land and groove imprints visually observed on the ricochet marks. Although this is not a currently practised method, further exploration of the possibility of matching the bullet to a sample taken from a ricochet surface is suggested using comparison microscopy.

Figure 8: A recovered 9 mm bullet from a 9-degree angle of incidence placed into the corresponding ricochet dent. As shown in the picture, the recovered bullet placed on the far end of the ricochet dent could not be further moved beyond the dent. The bullet's land and groove mark imprints can also be seen within the ricochet marks (black circle).

3.3.2 5.56 × 45 mm and 7.62 × 51 mm bullets

Different ricochet mark profiles to those for the 9 mm ammunition were observed for bullets fired from rifles. From 5-degree angles of incidence upwards, cratering effects on the sheet metal surfaces were observed from ricocheting 7.62 mm bullets and 5.56 mm bullet fragments. This started from a much lower angle than the 9 mm bullets due to the relatively higher velocity and energy transfer to the sheet metal surfaces at the same angles of incidence. A double-headed ricochet mark (a ricochet mark with two heads or craters) and first introduced during a previous 7.62 mm AK bullet study with 1 mm sheet metal [5], started to appear at 5 to 13 degrees with the 7.62 mm bullets in this study too. (This mark appeared in the previous study [5] with AK bullets at 8 degrees). The same was observed only at 11 degrees with the 5.56 mm bullets, demonstrating the difference in the appearance of this mark on sheet metal at various angles of incidence. Bullet-related factors such as mass, velocity and geometry contribute to the different observations of each bullet type. A picture of a double head mark reported in the previous AK study and the same produced with 7.62 mm and 5.56 mm bullets in this study are shown in Figure 9.

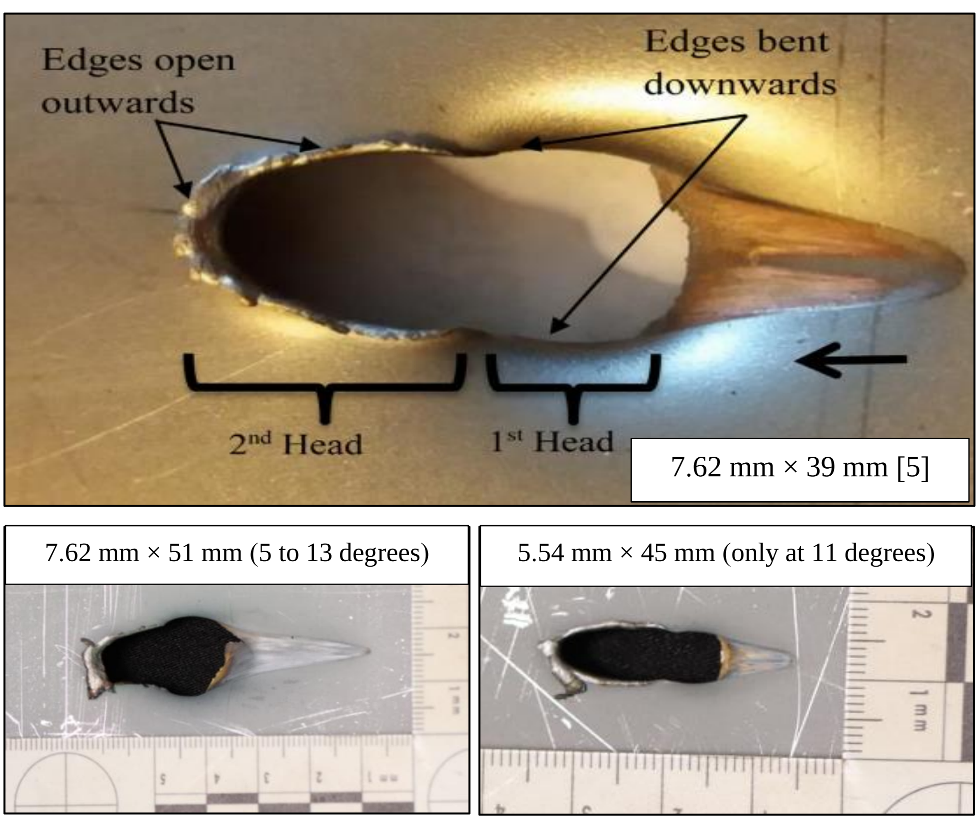

Figure 9: Double-headed ricochet mark with two heads produced with AK bullets (7.62 mm × 39 mm (top picture [5]) and the same produced with 7.62 mm × 51 mm bullets (bottom left) and 5.56 mm × 45 mm (bottom right) in this study.

3.3.3 New ricochet mark profile of 5.56 mm × 45 mm bullets on sheet metal

A currently unreported different ricochet mark profile was observed with all 5.56 mm bullets fired at 5, 7 and 9 degrees. The 5.56 mm bullets fragmented at these angles, with the resulting fragments ricocheting. A new ricochet mark feature consisted of three visible craters, and the shape was similar to a guitar. The lengths of the craters of the 10 ricochet marks at each angle of incidence seemed to be unique to the particular angle, with clearly observable differences in the three angle groups. The bullet's fragmentation seemed to have increased with increased angle of incidence (large patches at these angles were observed on paper screens instead of clear ricochet marks, as seen in the top picture in Figure 9). Clear impacts of the steel rod within the 5.56 mm bullets before impact could be seen among the ricocheting bullet fragments at a 9-degree angle of incidence (bottom picture in Figure 10).

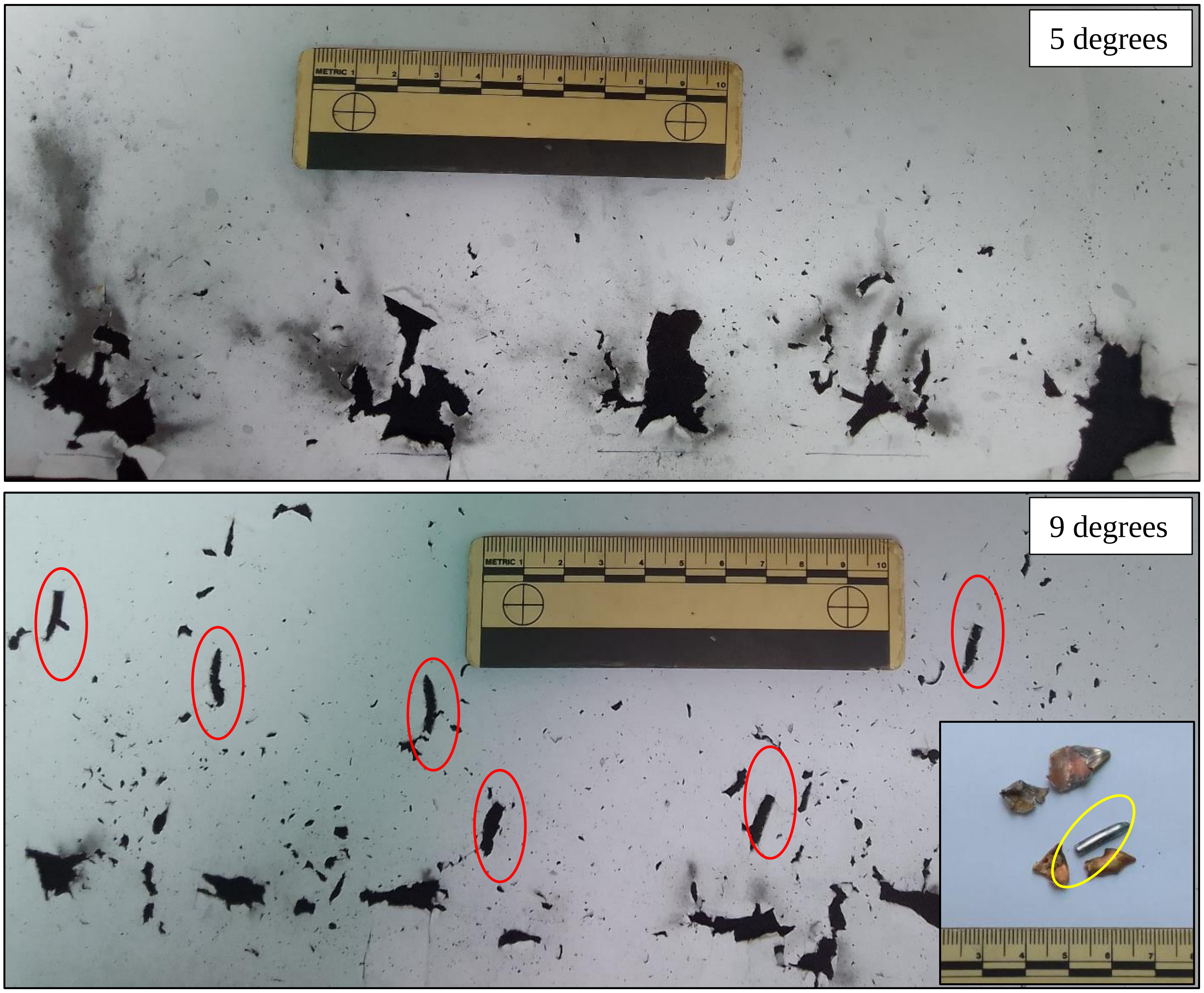

Figure 10: Impacts from the fragmented 5.56 × 45 mm bullet at 5 degrees (top) and 9 degrees (bottom). Steel rod impacts from the fragmented bullets (red circles) were clearly visible at 9 degrees upwards. A recovered steel rod from the bullet capture box is also shown in a yellow colour circle.

The new ricochet mark on sheet metal consisted of a lead-in mark and three heads, contrasting with the double-head ricochet mark reported in the AK study [5] with a lead-in mark and two heads (craters). Consistent observations here strongly suggest that this new mark is a clear feature of 5.56 mm × 45 mm bullets ricocheting off 1 mm sheet metal. A picture of the new ricochet marks at 5, 7, and 9 degrees is shown in Figure 11, along with the sheet metal sample with the new ricochet marks at 5 degrees.

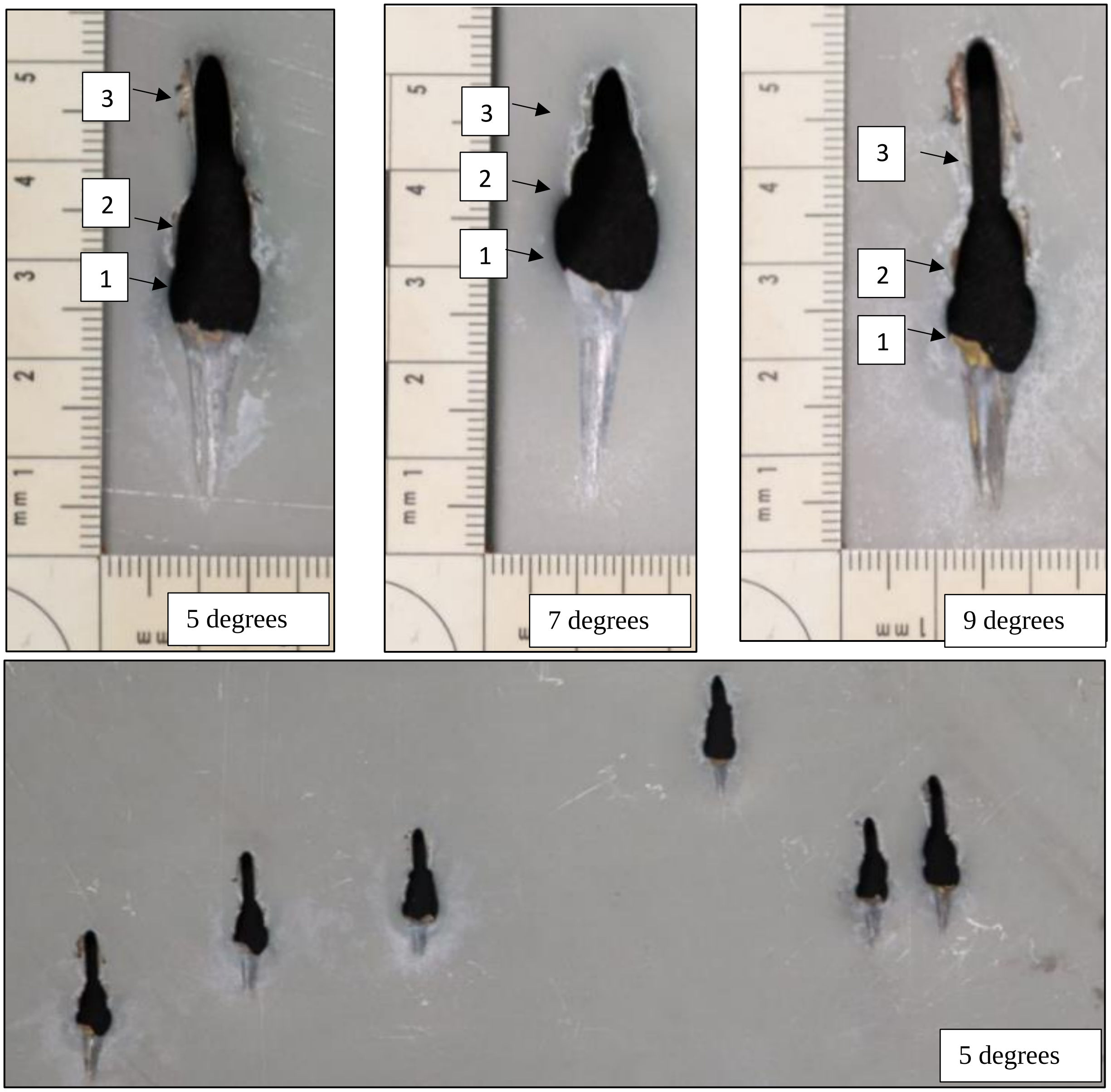

Figure 11: New guitar-shaped ricochet marks at 5, 7 and 9 degrees with three heads (top) and a sheet metal sample at 5 degrees to show the consistency.

The ricochet profile was further examined along with the cross-section of the 5.56 mm bullets used for this experiment (Figure 12). The M16 projectile used for this experiment consists of three segments: a steel rod penetrator, a lead sleeve, and a copper jacket, as seen in a typical M43-type bullet design [34]. Compared to the new ricochet mark with three heads, this could suggest that the new ricochet mark has a relationship with the bullet's three-layered structure. It can also be suggested that a similar mechanism produced the double-headed ricochet marks in the previous AK study (the AK bullets used had two layered compositions with lead core and copper jacket) [5]. The evidence suggests that the ricocheting steel rod penetrators that separated from the bullets produced the third crater at the far end of each ricochet mark. Separation has occurred due to the initial impact forces acting on the bullets during the production of the second crater. The dimensions and the shape of the steel rod penetrators recovered from the bullet capture box were observed to be similar to the dimensions of the third heads of the new ricochet mark, supporting this argument (bottom picture of Figure 10. The separating steel rods were prominently observed on paper screens at 9 degrees. Bullet fragments and steel rods were also collected from the bullet capture box at 5 and 7-degree angles of incidence. However, the clear impact of the steel rods was only visible on paper screens at a 9-degree angle of incidence. An impact-related mechanism is believed to have been responsible for the ricochet patterns of bullet fragments and separated steel rods. All evidence suggests an occurrence of complex and novel ricochet phenomena when 5.56 × 45 mm bullets ricochet off 1 mm sheet metal.

This finding is novel and significant as the current literature does not indicate any terminal ballistics examples of bullets producing characteristic defects directly related to their layer composition.

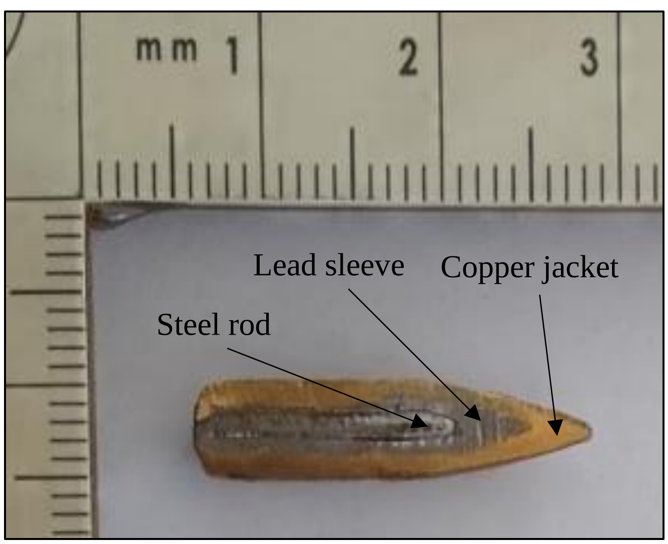

Figure 12: The cross-sectional profile of the 5.56 × 45 mm bullet used for the experiment.

However, interestingly at 11 degrees, the three heads disappeared, and the standard double-head mark started to appear. No evidence was available to explain this change, so it is likely a combined effect of the angle of incidence, bullet construction and the reaction of the sheet metal. Additionally, the new ricochet feature with three heads was not observed for the 7.62 × 51 mm bullets with the same structural composition. The kinetic energy difference between the two ammunition types and the larger size of the 7.62 mm bullet, making it overall more structurally stable likely combine here to explain this observation.

3.4 Lengths of the ricochet marks

The length of the ricochet mark on sheet metal is another critical measurement that can be used to understand the angle of incidence of the ricocheted bullets [5]. This relationship has been explored in many forensic-related studies with different bullet-surface combinations (during bullet ricochet, penetration and perforation events) [7, 14, 15, 35, 36]. Consequently, the average lengths of the bullet ricochet mark on sheet metal samples were also considered to observe any possible relationships. Average values and standard deviations are presented in Figure 13. An explanation of how the measurements were taken is in Figure 14.

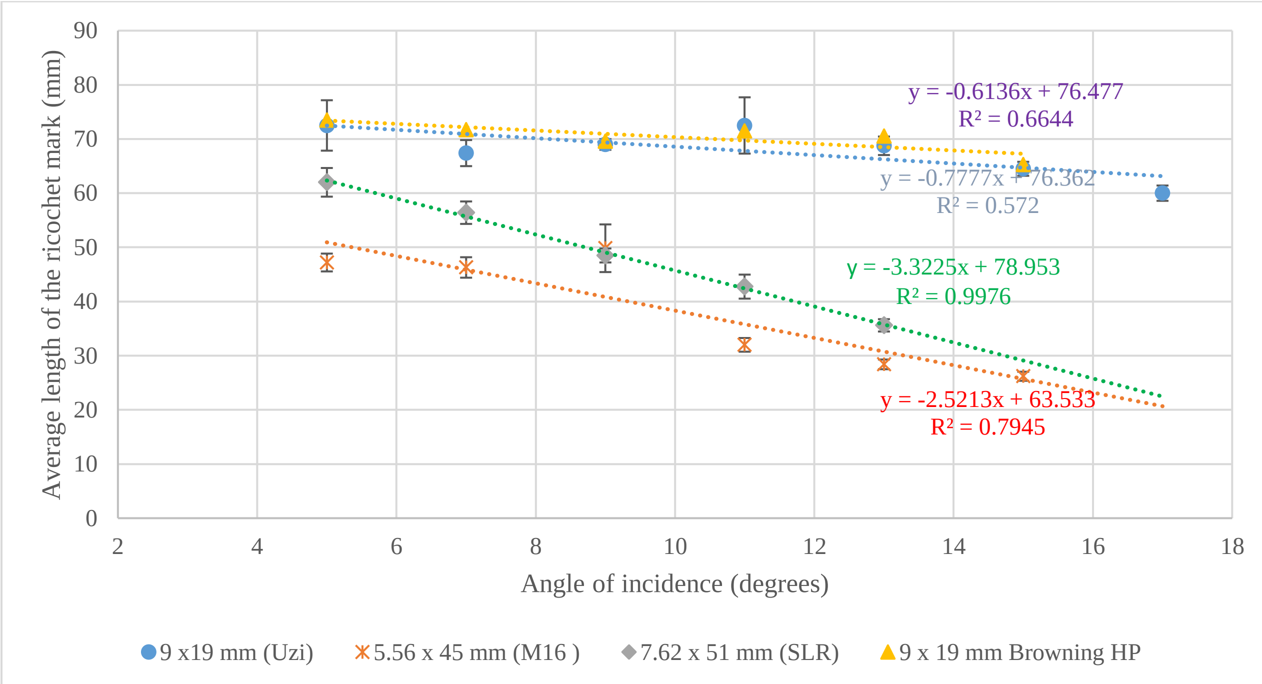

Figure 13: The average length of the bullet ricochet marks for different ammunition.

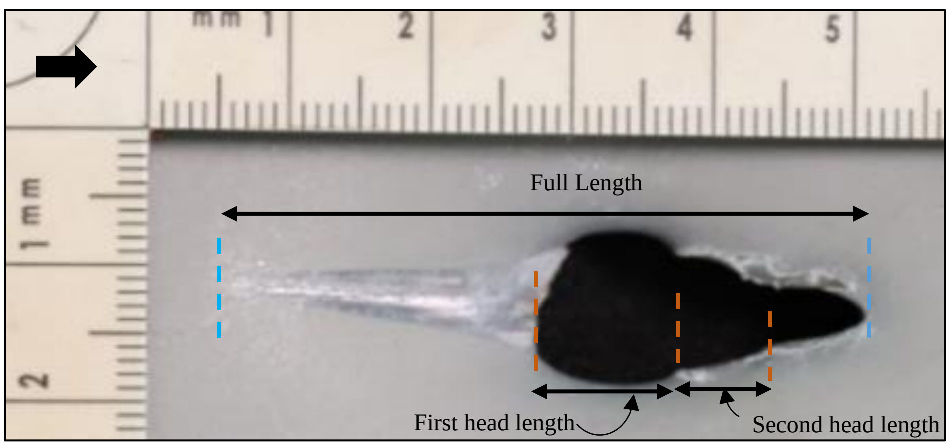

Figure 14: A picture explaining how the measurements were taken. The full lengths were recorded by measuring the distance between the first contact point of the bullet (lead-in mark) to the end of the bullet defect. The longest edges of the first and second heads (craters) were measured when recording the lengths of the first and second heads (craters). The same method was used in the previous ricochet study [5] to measure the lengths of ricochet marks/ heads. The black arrow indicates the direction of the bullet's impact.

The data indicate a general negative trend between the length of the ricochet mark and angles of incidence. The finding complies with the current understanding of the relationship between the angle of incidence of bullets and the length of the bullet ricochet mark [5] and bullet impact marks [7,14,15,35]. A significant relationship was observed with the rifle-calibre bullets, in that the relationship between the length of the ricochet marks of 7.62 × 51 mm bullets and the angle of incidence was significant (with a correlation coefficient value almost close to 1 (0.9976). The evidence compared to the previous AK experiment with a similar relationship (correlation – coefficient value 0.998) [5] suggests a phenomenon that the lengths of the ricochet mark on 1 mm sheet metal with 7.62 mm calibre bullets can be used as an accurate indicator of the corresponding angle of incidence for the bullets.

The lengths of the newly discovered ricochet mark with the three heads (for 5.56 × 45 mm bullets) were measured. The results are presented in Figure 15 with the lengths of the first, second, and third heads with each incidence angle. The lengths of the respective heads were consistent with low associated standard deviations, suggesting that they also could possibly be used to identify the angle of incidence of M16 bullets ricocheting off 1 mm sheet metal. However, there was no clear trend in the measurements of the three different head marks with angle of incidence.

One-way ANOVA performed separately for the lengths of the first, second and third heads using 5, 7, and 9-degree angles of incidence (data set for these three parameters aligned with the assumptions for a parametric ANOVA test). The results revealed that the group means of the length of the second [$F(2,27) = 597.468$, $p < 0.001$] and third heads [$F(2,27) = 328.550$, $p < 0.001$] are statistically significant than the length of the first head [$F(2,27) = 1.106$, $p = 0.346$]. Partial Eta Squared tests conducted for the lengths of the first, second and third heads using 5, 7 and 9-degree angles of incidence revealed that large effects are observed between the mean lengths of the second (0.978) and third heads' lengths (0.961) for each incidence angle. A medium effect (0.076) is observed between the mean head lengths of the first heads' length (0.961) to each angle of incidence. For reference, a small effect = 0.01, a medium effect = 0.06 and a large effect = 0.14 or higher.

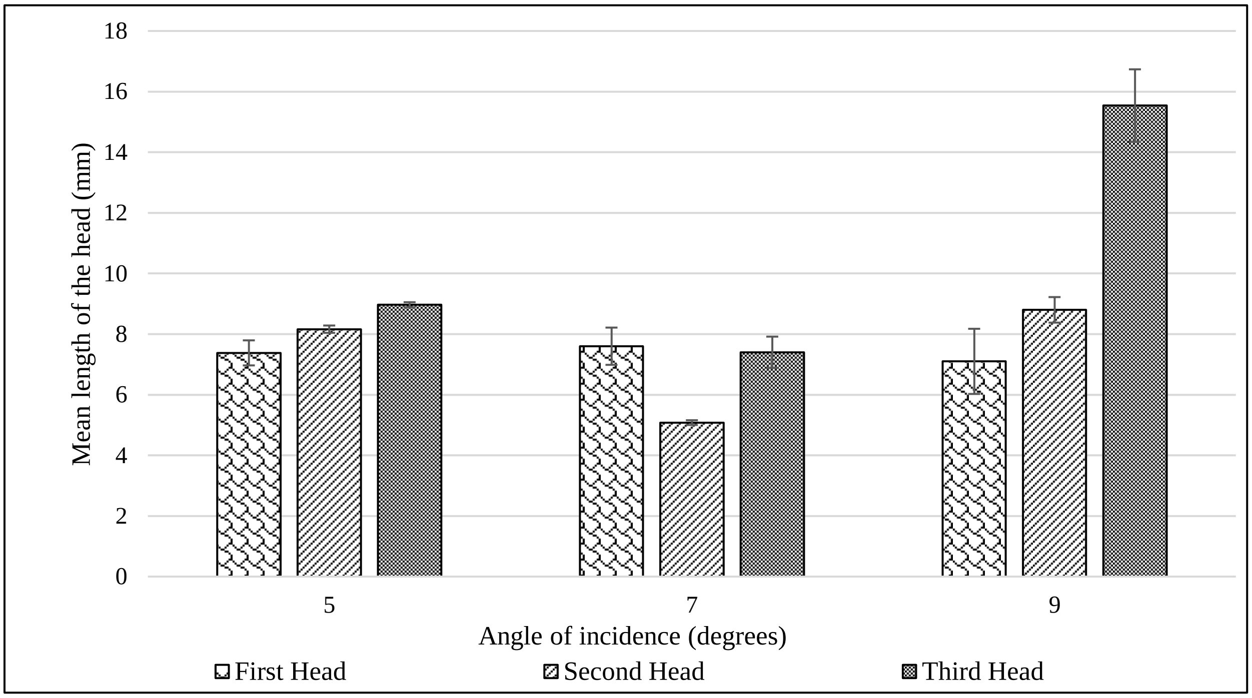

Figure 15: Mean lengths of the first, second and third heads with each angle of incidence.

4. Conclusion

The forensic significance of ricochet marks on 1 mm sheet metal was examined with four firearm types discharging either 9 x 19 mm Luger, 5.56 mm × 45 mm, or 7. 62 mm × 51 mm bullets. The critical angles reported were 15.9 degrees, 15 degrees, and 11.4 degrees, respectively, for Browning HP (9 mm × 19 mm), Uzi SMG (9 mm × 19 mm), and SLR rifle (7.62 mm × 51 mm). The critical angles reported complied with the current bullet velocity and critical angle understanding. No ricochet angles could be reported for the 5.56 mm× 45 mm bullets as they fragmented upon impact from 5 degrees onwards.

True ricochets were observed with 9 mm bullets fired from both a Browning HP and an Uzi submachine gun from 5 to 15-degree angles of incidence. For 7.62 mm × 51 mm bullets, true ricochets were reported from 5 to 9 degrees and half ricochet/half perforation phenomena were observed from 11 to 13 degrees, with the bullet fragmenting on impact. In the latter case, the jacket portion ricocheted and the lead core perforated the sheet metal. Compared with a previous ricochet study using 7.62 mm × 39 mm ammunition [5], it suggests that half ricochet/half perforation events are common to rifle bullets ricocheting off 1 mm sheet metal. The reported ricochet angles from all bullet types suggest that bullets ricocheting off 1 mm sheet metal generally produce ricochet angles equal to or less than the corresponding angles of incidence. This finding was also similarly observed in a previous study with AK bullets [5] and is significant as it contrasts with the existing theory on bullet ricochet with yielding target surfaces that ricochet angles are typically greater than angles of incidence [9].

For the 9 mm bullets, dent profiles observed at 7 to 9-degree angles of incidence suggest they may be of forensic value for predicting the angle of incidence in unknown situations. Guitar-shaped, three-headed ricochet marks on sheet metal samples were observed with ricocheting 5. 56 × 45 mm bullet fragments at 5, 7 and 9 degrees. This ricochet mark had not been reported in any terminal ballistic studies previously. The evidence suggests that the new ricochet mark is associated with 5.56 mm × 45 mm bullets and relates to the bullet's three-part structural composition (M 43 type configuration). The finding is significant as the current literature does not highlight any terminal ballistics examples of bullets producing characteristic defects on the impact surface directly related to their layer composition.

A significant relationship was observed between the length of the ricochet mark of 7.62 × 51 mm bullets and angle of incidence with a correlation coefficient value almost close to 1 (0.997). The evidence compared to the similar results in the previous AK study (R^2 =0.998) strongly suggest that the length of the ricochet marks produced by 7.62 mm calibre bullets on 1 mm sheet metal can be used as useful indicators of the ricocheted bullet's angle of incidence during crime scene reconstructions. The measured lengths of different heads of the newly introduced ricochet marks with three heads were consistent for each angle of incidence, although no trend was observed across the range of angles investigated. This study's newly reported ricochet mark feature highlights the diversity of ways that different bullets interact with sheet metal and produce such varied ricochet evidence.

The study's findings present complex phenomena and associated scientific evidence of different bullet–target combinations that can be observed in urban shooting incidents. As highlighted, the findings may have much reconstructive value due to the prevalence in urban settings of sheet metal with similar homogeneous properties to that used in this study. Further studies with various rifle and pistol bullets and sheet metal combinations are also recommended to observe any significant ricochet evidence and relationships as demonstrated in this study.

References

1. James, B. (2022, December 8). *6 Ways To Utilise Sheet Metal For Construction*. CivilSeek. https://civilseek.com/sheet-metal-for-construction/

2. Smith, C. B., & Mishra, R. S. (2014). Fundamentals of Formability. *Friction Stir Processing for Enhanced Low-Temperature Formability*, 7–9. https://doi.org/10.1016/b978-0-12-420113-2.00002-7

3. Sheridan, M. (2018b, September 19). *About Sheet Metal Gages*. NorthClad. https://northclad.com/articles/about-sheet-metal-gages/

4. Hovorun, T. P., Berladir, K. V., Pererva, V. I., Rudenko, S. G., & Martynov, A. I. (2017). Modern materials for the automotive industry. *Journal of Engineering Sciences*, *4*(2), f8–f18. https://doi.org/10.21272/jes.2017.4(2).f8

5. Nishshanka, B., Shepherd, C., & Paranirubasingam, P. (2020). A forensic-based empirical study on ricochet behaviour of Kalashnikov bullets (7.62 mm × 39 mm) on 1 mm sheet metal. Forensic Science International, 312, 110313. https://doi.org/10.1016/j.forsciint.2020.110313

6. How Are Steel Sheets Used in Automotive Industry? (2021, December 17). HVR MAG. Retrieved February 3, 2023, from https://www.hvrmagnet.com/blog/how-are-steel-sheets-used-in-automotive-industry/

7. Nishshanka, B., Shepherd, C., & Ariyarathna, R. (2021). AK bullet (7.62 × 39 mm) holes on 1-mm sheet metal: A forensic-related study in aid of bullet trajectory reconstruction. Journal of Forensic Sciences, 66(4), 1276–1284. https://doi.org/10.1111/1556-4029.14717

8. Schader, M. (2019b, March 2). *How Is Sheet Metal Made?* Sciencing. https://sciencing.com/how-does-4899623-how-sheet-metal-made.html

9. Goode, O. (2020, November 10). *A Guide To How Sheet Metal Is Produced*. Radshape Limited. https://www.radshape.co.uk/how-sheet-metal-is-produced/

10. Eksinitkun, G., Phungyimnoi, N., & Poogun, S. (2019). The analysis of the perforation of the bullet 11 mm. on the metal sheet. *Journal of Physics: Conference Series*, *1380*(1), 012085. https://doi.org/10.1088/1742-6596/1380/1/012085

11. Jankowiak, T., Rusinek, A., Kpenyigba, K., & Pesci, R) .2014 .(Ballistic behavior of steel sheet subjected to impact and perforation .*Steel and Composite Structures*, *16*)6(, 595–609 . https//:doi.org/10.12989/scs.2014.16.6.595

12. Li, C., Rasheed, S., Malik, A., Nazeer, F., & Long, J) .2022 .(Study on ballistic impact behavior of Al alloys against two different shapes of steel core projectiles .*Journal of Materials Research and Technology*, *20*, 2489–2500 . https//:doi.org/10.1016/j.jmrt.2022.08.052

13. Yamada, H., Tateyama, K., Naruke, S., Sasaki, H., Torigata, S., Honda, R., Kubo, T., Yoshimoto, M., & Fujii, T) .2021 .(Impact resistance of steel materials to ballistic ejecta and shelter development using steel deck plates .*Journal of Applied Volcanology*, *10*)1 .(https//:doi.org/10.1186/s13617-021-00105-8

14. Nishshanka, L. C. B., Shepherd, C., Ariyarathna, M. R., Weerakkody, L., & Palihena, J. (2021). An android-based field investigation tool to estimate the potential trajectories of perforated AK bullets in 1 mm sheet metal surfaces. Forensic Science International: Digital Investigation, 38, 301267. https://doi.org/10.1016/j.fsidi.2021.301267

15. Nishshanka, B., Shepherd, C., & Ariyarathna, R. (2020). A software-based solution to estimate the angles of incidence of AK bullets using the bullet hole features on 1 mm sheet metal. In KDU. 13th International Research Conference - KDU, Colombo, Sri Lanka. http://ir.kdu.ac.lk/bitstream/handle/345/2937/FOC%20107-113.pdf?sequence=1&isAllowed=y

16. Liscio, E., & Imran, R. (2020). Angle of impact determination from bullet holes in a metal surface. Forensic Science International, 317. https://doi.org/10.1016/j.forsciint.2020.110504

17. Siso, R., Bokobza, L., Hazan-Eitan, Z., Gronspan, A., & Schecter, B. (2016). Firing Distance Estimation From Bullet Impact Characteristics On Thin Sheets Metal. AFTE Journal, 43(3), 178–184.

18. Mattijssen, E. J., & Kerkhoff, W. (2016). Bullet trajectory reconstruction – Methods, accuracy and precision. *Forensic Science International*, *262*, 204–211. https://doi.org/10.1016/j.forsciint.2016.03.039

19. Haag, L. C., & Haag, L. C. (2011). *Shooting Incident Reconstruction*. Elsevier Gezondheidszorg.

20. Nishshanka, B., Shepherd, C., Jayawickrama, S. M., & Ariyarathna, R. (2022). Ricochet of 9 mm pistol bullets on glazed ceramic tiles: An empirical study in support of shooting incident reconstruction. Journal of Forensic Sciences, 68(1), 101–112. https://doi.org/10.1111/1556-4029.15180

21. Nishshanka, B., Shepherd, C., & Punyasena, M. (2022). Ricochet of AK bullets (7.62 MM × 39 MM) on glazed ceramic tiles: An empirical study in support of shooting incident reconstructions. Forensic Science International, 332, 111179. https://doi.org/10.1016/j.forsciint.2022.111179

22. Nishshanka, L. C. B., Shepherd, C., Punyasena, M., & Ariyarathna, M. R. (2021). Ricochet of AK bullets (7,62 × 39 mm) on concrete and cement surfaces; a forensic-based study. Science &Amp; Justice, 61(5), 467–476. https://doi.org/10.1016/j.scijus.2021.06.004

23. Nishshanka, B., Shepherd, C., Koene, L., Punyasena, M., & Ariyarathna, R. (2022). An empirical study on the close-range post-ricochet orientation of AK bullets (7.62 mm × 39 mm). Science &Amp; Justice, 62(5), 569–581. https://doi.org/10.1016/j.scijus.2022.08.004

24. Hickey, K. (2021, March 23). *Tensile Testing*. AHSS Guidelines. https://ahssinsights.org/forming/testing-characterization-forming/tensile-testing/

25. Bhandari, P. (2022, December 5). *Correlation Coefficient | Types, Formulas & Examples*. Scribbr. https://www.scribbr.com/statistics/correlation-coefficient/

26. *Solutions | Minitab*. (2023). https://www.minitab.com/en-us/solutions/

27. *One-way ANOVA - An introduction to when you should run this test and the test hypothesis | Laerd Statistics*. (2018) https://www.statology.org/eta-squared/

28. Statology. (2021, December 14). *What is Eta Squared? (Definition & Example)*. Scatology. Retrieved February 6, 2023, from https://www.statology.org/eta-squared/

29. Bhandari, P. (2023). What is Effect Size and Why Does It Matter? (Examples). *Scribbr*. https://www.scribbr.com/statistics/effect-size/

30. The Editors of Encyclopaedia Britannica. (1998, July 20). *Kinetic energy | Definition, Formula, Units, Examples, & Facts*. Encyclopedia Britannica. https://www.britannica.com/science/kinetic-energy

31. Boddington, C) .2020, October 16 .(*How Barrel Length Can Affect Shooting Performance* . RifleShooter .https//:www.rifleshootermag.com/editorial/how-barrel-length-can-affect-shooting-performance/385361

32. National Rifle Association (2021) *NRA Shooting Sports Journal | Pistol Barrel Length And Velocity* .An NRA Shooting Sports Journal .https//:www.ssusa.org/content/pistol-barrel-length-and-velocity/

33. Gao, Y., Feng, S., Huang, G., Feng, Y. P., & Huang, Q. (2022). Experimental study of the oblique impact and ricochet characteristics of cylindrical fragments. *International Journal of Impact Engineering*, *170*, 104334. https://doi.org/10.1016/j.ijimpeng.2022.104334

34. Kurzawa, A., Pyka, D., Jamroziak, K., Bajkowski, M., Bocian, M., Magier, M., & Koch, J. (2020). Assessment of the Impact Resistance of a Composite Material with EN AW-7075 Matrix Reinforced with α-Al2O3 Particles Using a 7.62 × 39 mm Projectile. *Materials*, *13*(3), 769. https://doi.org/10.3390/ma13030769

35. Nishshanka, M. B., Paranirubasingam, P., & Shepherd, C. (2020). A forensic-based study on low-angled AK rifle bullet entry wounds using a porcine model. Journal of Forensic and Legal Medicine, 74, 102025. https://doi.org/10.1016/j.jflm.2020.102025

36. Nishshanka, B., & Shepherd, C. R. (2021). AK bullet (7,62 × 39 mm) ricochet off flat, wooden targets; A forensic-based study. Forensic Science International, 326, 110903. https://doi.org/10.1016/j.forsciint.2021.110903