Heliyon 6 (2020) e04088

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Towards the investigation of shooting incidents: evaluation of fracture pattern on polymethylmethacrylate sheet made by .22″ and .177″caliber air rifle

Md Alim, Kailash Singh Negi, Sughosh Abhyankar, Neelesh Tiwari, Abhimanyu Harshey, Ankit Srivastava *

Dr. A.P.J. Abdul Kalam Institute of Forensic Science and Criminology, Bundelkhand University, Jhansi 284128, Uttar Pradesh, India

ARTICLE INFO

Keywords:
Materials science
Mechanical engineering
Mechanics
Polymethylmethacrylate
Air rifle
Fracture pattern
Shooting incident
Physical evidence
Glassy polymer

ABSTRACT

Scientific examination of the physical evidence provides significant information beyond a reasonable doubt. Due to the increasing use of the glassy polymer i.e. polymethylmethacrylate instead of glass, the probability of the occurrence of the fractured polymethylmethacrylate sheet in a shooting incident cannot be ignored. Analysis of fracture pattern offers several analytical approaches that assist the forensic investigator. The use of air guns in criminal activities is increasing as well as these weapons have found to be fatal for living beings. This study was conducted to evaluate the fracture pattern on the polymethylmethacrylate by using an air rifle. The fracture pattern formed on polymethylmethacrylate sheets by the air guns shows some specific characteristics that may help to reconstruct the crime scene. The polymethylmethacrylate sheets were test-fired with Spring-Piston air rifles of .22″ (5.5 mm) and .177″ (4.5 mm). Data obtained from the measurements were then statistically analysed with the Chi-Square test. A consistency in hole diameter was observed. Analysis of fracture patterns may provide a lead to the investigator and may help to reconstruct a shooting incident. It can also distinguish between the standard firearm and air gun. The fracture on polymethylmethacrylate sheets gave significant findings that may efficaciously contribute to the forensic investigation of shooting incidences.

1. Introduction

A scene of occurrence is the source of different physical evidences that are produced on the commission of an offence as described by Locard's principle. Scientific examinations of the physical evidences give several leads beyond the shadow of reasonable doubts as well as provide scientific support to the Judiciary. For crime investigation, the application of scientific principles and technology is referred to as Forensic Science (Mistek et al., 2018). In the present scenario, as the scientific technology is updating, the methods of committing crime are also changed and increasing by the multiple rates. Both have impacted a major global concern for the Law enforcement agencies.

The engagement of firearms in illegal activities is well reported (Alper and Glaze, 2019). Retrospective studies show a huge number of victims murdered by the use of firearms in criminal activity (Crime in India, 2017 (2019); Crime in India, 2018 (2019); Morgan et al., 2019). From the investigating point of view, a firearm is one of the crucial evidences associated with shooting incidences. It becomes more important to look towards air operated guns with the forensic point of view as these are being used by criminals (Burnt and Packey, 1979; Harshey et al., 2017). It is a special class of firearms that does not involve any kind of chemical reaction for the firing of a projectile. It hurls small metal pellets by the means of majorly three mechanisms i.e. Spring piston mechanism, Pneumatic and Compressed gas (CO2) (Abhyankar et al., 2018). In common perception, Air guns (pistol and rifle) are considered to be safe and also available in the open market. Apart from the perception, it is evident from the available literature that air gun is enough capable to cause fatal injuries (Lal and Subrahmanyam, 1972; DiMaio et al., 1982). From the medico-legal point of view, the air gun has attracted various researchers towards the study of wound ballistics phenomenon, and it was found that air gun may cause bone micro-fractures, ocular injuries and even death also occurred (Schein et al., 1994; Wightman et al., 2010; Kieser et al., 2013; Stankov et al., 2013; Hsiao and Meng, 2018a; Simon et al., 2019). Along with this, terminal ballistic literature of air guns also experimented which strengthened the available literature and forensic

* Corresponding author.
E-mail address: ankit_forensic81@rediffmail.com (A. Srivastava).

https://doi.org/10.1016/j.heliyon.2020.e04088
Received 16 January 2020; Received in revised form 18 February 2020; Accepted 26 May 2020

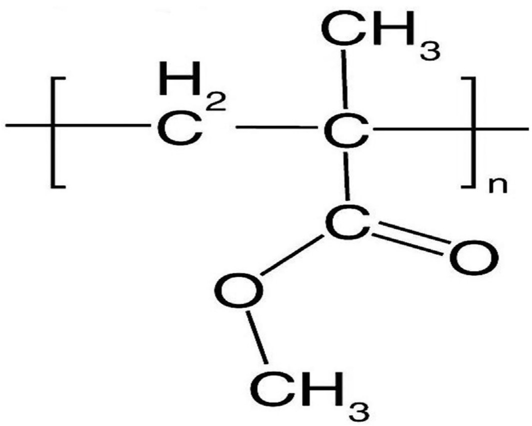


Figure 1. PMMA molecule.

investigation perspective (Wightman et al., 2013; Tiwari et al., 2019; Hsiao and Meng, 2018b).

Glass is significantly involved in the life of a common man e.g. several households such as window panes, bottles, etc. are made of glass (Nadarajan et al., 2020). Since, the evidential value of glass has been described by several researchers (Mcjijnkins and Thornton, 1973; Stoney and Thornton, 1985; Curran et al., 2000; Caddy, 2001; Copley, 2001; Gogotsi and Mudrik, 2010). The brittle nature of glass also poses a number of complications. Polymethylmethacrylate (PMMA) is a quasi-commodity thermoplastic resin, which is transparent, stronger, more durable, shockproof, weather resistance, etc (Ibeh, 2011). That's why the sheets of PMMA were introduced as a better substitute for the glass. PMMA is the polymer of the methyl methacrylate (MMA-C5H8O2). PMMA is the most frequent by-product of acrylic acid. The structure of PMMA is illustrated in (Figure 1). PMMA is additionally acknowledged through the name: Plexiglass, Lucite, Perspex, Rhoplex, Dicalite and Crystallite (Olabisi and Adewale, 2016). Detailed insights on PMMA have been reported by various researchers (Ibeh, 2011; Pawar, 2016; Ali et al., 2015; Thomas and Visakh, 2011). The PMMA sheet is now being used in windows, doors, furniture, streetlight cover, motorcycle headlights, aquarium, etc. The extensive use of PMMA is also escalating the probability of its presence at the crime scene in the form of physical evidence.

Fractography is the acronym for the study of fractures. Fracture analysis is the subject of interest for the forensic echelon for a very long time. As compared to glass fractography, forensic analysis of PMMA sheet fracture is less explored. While analysing the fracture, stress or rib marks, cone, radial, and concentric fractures are the most commonly referred

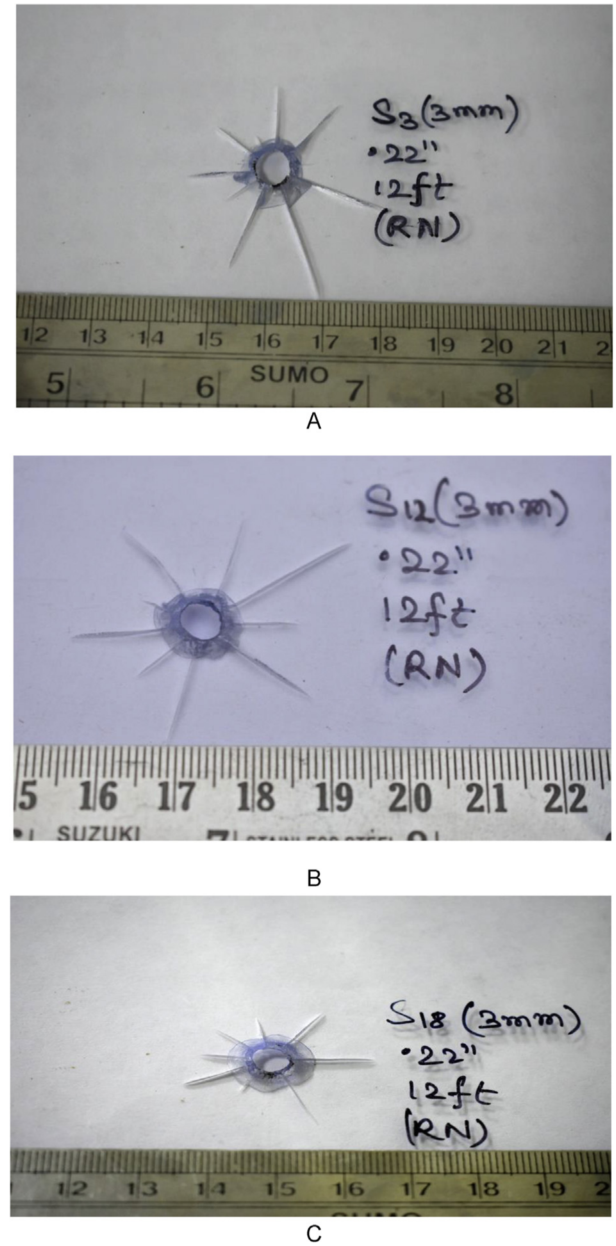
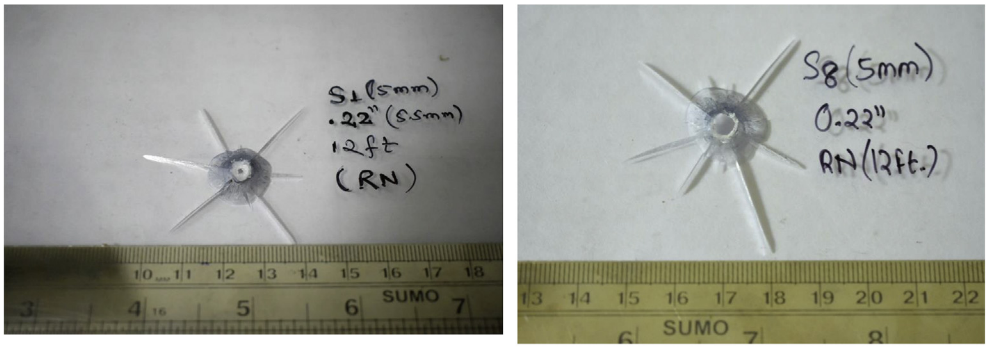


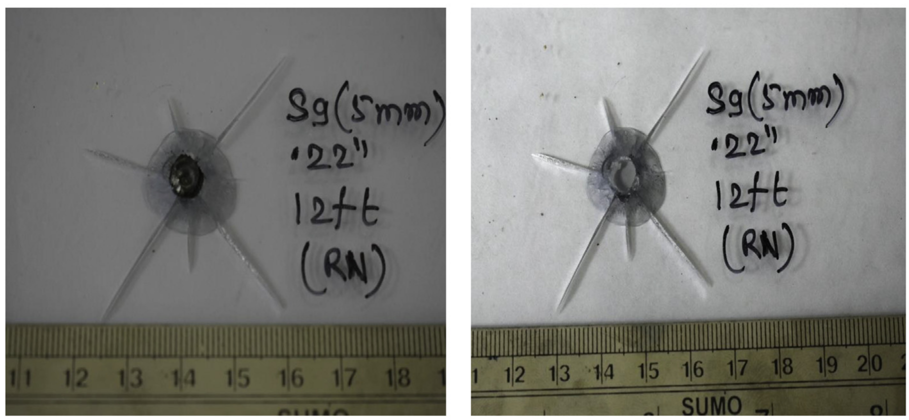
Figure 2. Fracture pattern on 3mm PMMA sheet by .22″ Air rifle. A, B, C shows sheets with short radial cracks and differences in features.

Table 1. Specification of tools and materials used and sample size description.

Sr. No.	Tools/Materials used	Purpose of use	Specification
1	PMMA sheets	Target sheet	Manufactured by Plastech Innovations, New Delhi- INDIA
2	Air Rifle	Firing	Caliber - 0.22″ (5.5 mm) 0.177″ (4.5mm)
3	Pellet	Projectile	Shape - Round head Caliber – 0.22″ & 0.177″ Average weight - 0.703 g for 0.22″ 0.41g for 0.177″
4	Vernier Caliper	Measurement	Aerospace digital Vernier Caliper
5	Camera	Photography	Nikon Digital camera D3400
Design of Sample Size			
Sr. No.	**Thickness of PMMA sheets**	**Calibers Used**	**Test Fired Pellets**
1.	3mm	.22″ (5.5mm)	45
2.	5mm		45
3.	3mm	.177″ (4.5mm)	45
4.	5mm		45
Total Samples			**180**



(A)



(B)

Figure 3. (A)Fracture pattern on 5 mm PMMA sheet by .22″ Air rifle. (B) Fractured PMMA sheets with stuck pellet and after the removal of pellet.

characteristic features. Fracture analysis may provide different significant information i.e. the cause of the fracture, the direction of impact, nature of force, angle of impact, etc. Earlier, generation and the propagation of the fracture have been pronounced by various researchers (Harshey et al., 2017). In fracture mechanics, basically, there are three modes of crack propagation i.e. Mode I, Mode II and Mode III. Mode I "tensile stress" act normal to the crack plane (opening mode). Mode II, "shear stress" is acting perpendicularly to the crack front and parallel to the plane of crack (sliding mode), and Mode III, "shear stress" is acting parallel to the plane of crack and crack front (tearing mode) (Anderson, 2017; Nie et al., 2020). Mode II type of crack propagation was observed in the present study. As far as the PMMA sheet is concerned, the formation of the fracture pattern mechanism is influenced by many factors like strength of the bond, stress, tensile stress and tension on the sheet surface, etc (Pawar, 2016; Ali et al., 2015).

Theoretically, the strength of a material depends upon the forces of inter-atomic bonds. Furthermore Overend et al. (2007) stated that the tensile strength affects by a number of factors i.e. environmental condition, surface condition, the duration of load, etc. rather than being a material constant. According to Griffith, the pre-existing flaws (also known as Griffith flaws) are the initiating points of the fractures (Griffith, 1920). The hitting of a projectile on a PMMA sheet causes a slight bending of the PMMA sheet. As the limit of tensile stress is crossed, it breaks and the projectile passes through the PMMA sheet (Saferstein, 2006). It is well established that the kinetic energy, transferred from projectile to PMAA sheet, propagates along the path of least resistance followed by the formation of cracks (Grady, 2010). At the opposite side of the impact point, radial cracks initiate outwards and crater shaped hole (cone fracture) is formed due to the penetration of the projectile (Mcjijnkins and Thornton, 1973). The absence of the concentric fracture is the prominent feature of PMMA fractography. Detailed insights over the PMMA fracture have outlined by Anderson (2017); Rittle and Brill (2008); Dorogoy et al. (2010); Faye et al. (2016); Mbarek et al. (2018); Rittle and Dorogoy (2014). Previously, in the forensic context, fracture on PMMA sheets due to high-velocity projectile impact was studied. The available literature on the fractography reveals that there is no clear correlation of the caliber of the firearm with the size and appearance of the crater. It indicates that the form of the crater is a function of the velocity of crack propagation rather than the velocity of the projectile or its diameter (Thornton, 2001).

In the light of above facts, the present study was aimed to analyse the fracture pattern on the PMMA sheets made by air rifle of two different calibers i.e. .22″ (5.5 mm) and .177″ (4.5 mm). The findings of this work may significantly assist in crime scene investigation and ultimately will serve the society.

2. Materials and methodology

In this study,.22″ (5.5 mm) and .177″ (4.5mm) caliber air rifle of the spring piston mechanism were used to cause a fracture. Air rifles are generally available in different calibers i.e. .177″, .20″, .22″, .25″, .30″, etc. But only .22″ and .177″caliber's air rifle are frequent and were available to us in the market. That's why these two particular calibers were taken into consideration. Notably, air rifles with spring-piston mechanisms have maximum velocity in the range of 230–240 m/s (Stankov et al., 2013). Round Nose (RN) also called as Round head lead pellets of 5.5 mm and 4.5 mm caliber were used with their respective caliber air rifles. The test-firing was performed to simulate the firing from

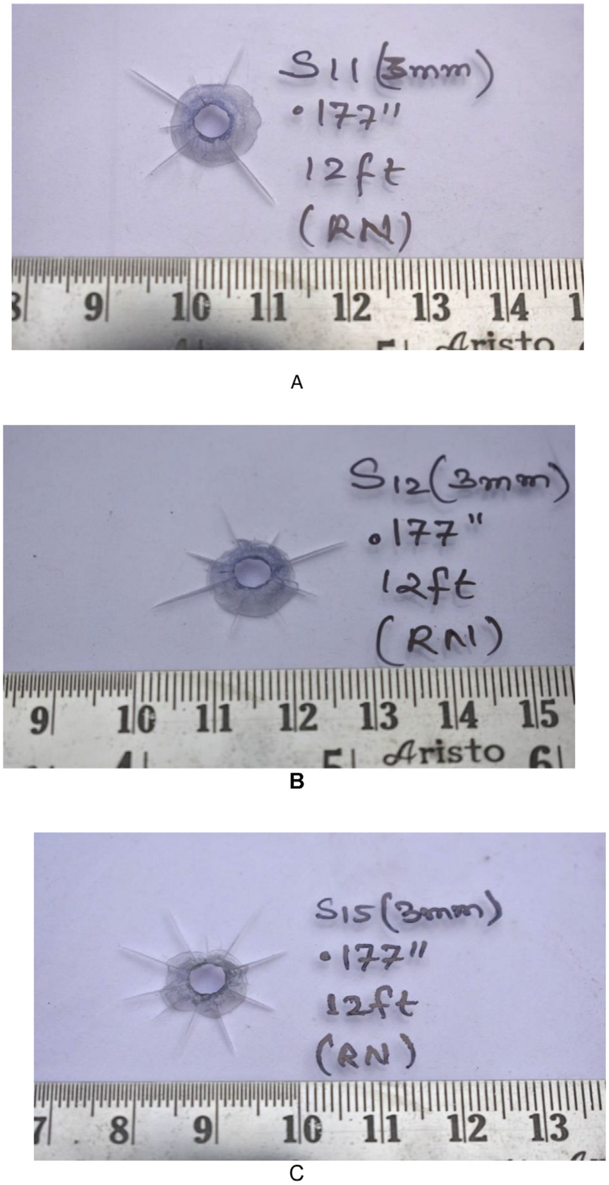


Figure 4. Fracture pattern on 3 mm PMMA by .177″ Air rifle. A,B,C shows different fracture sheets with similarities in fractures.

long range (beyond 7ft) therefore firing was conducted at a fixed distance of 12 feet and perpendicular to the target. PMMA target sheets (Dimension:1 square ft) were categorized into two classes i.e. 3 mm and 5 mm thickness. A total of 180 samples were test-fired. The design of the sample size and the specifications of the materials and tools used in this study have described in (Table 1). After the firing, samples were photographed, Radial and concentric cracks were counted directly. Hole diameter, Diameter of mist zone and Thickness of mist zone were measured by digital Vernier Caliper as discussed by Harshey et al. (2017) and Tiwari et al. (2019). For the validation of the hypothesis, statistical calculations i.e. Chi-Square test was performed.

3. Results

In case of .22″caliber, PMMA sheets of 3 mm thick produced short radial fracture pattern as shown in Figure 2. Cone fracture was observed on the opposite side to the direction of impact. Around the hole, the mist zone with a small thickness was formed. Contrary to this, most of the 5 mm thick sheets were not completely penetrated by the .22″caliber

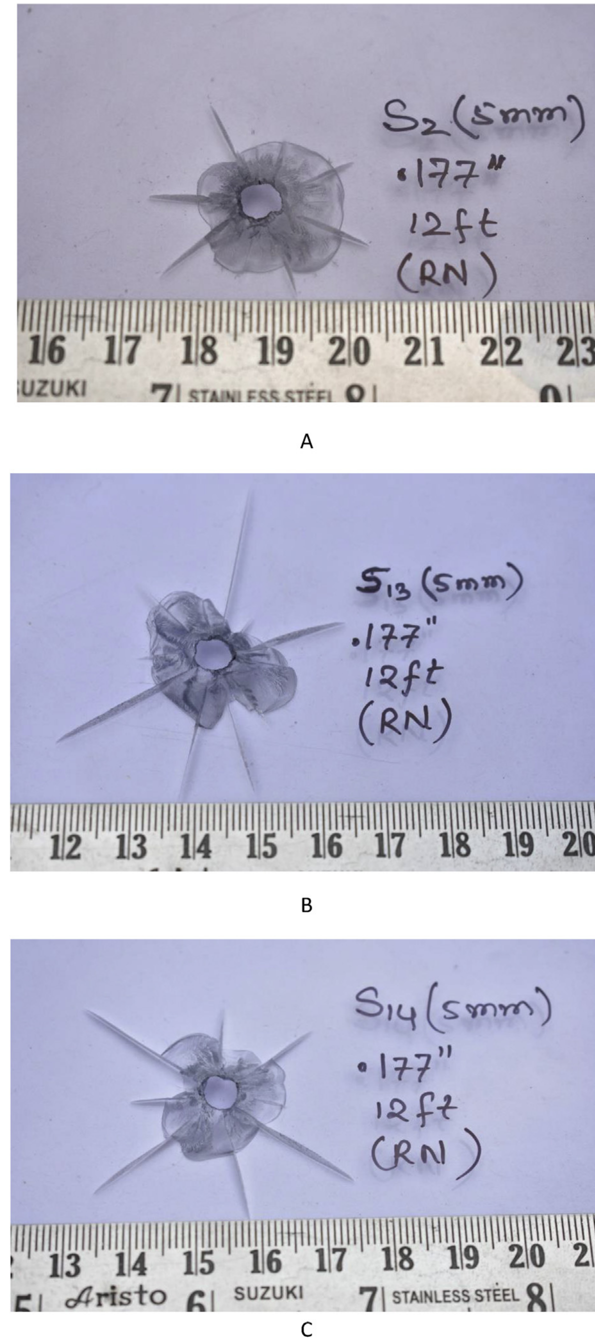


Figure 5. Fracture pattern on 5 mm PMMA by .177″ Air rifle. A,B,C shows variations in the Mist zone.

pellet. It is noteworthy that at the point of impact some damage was caused where the pellet was found to be stuck, as well as pellet impact caused the formation of cone fracture on the opposite side. Removal of the pellet did not cause any other changes to the fracture pattern (Figure 3). No concentric cracks were observed in both categories, the absence of concentric cracks in PMMA is well outlined by Caddy (2001). Stress marks were also visible in both cases but more prominently in 5 mm sheets. The fracture patterns produced on 5mm & 3mm thick PMMA sheet by .22″ and .177″caliber air rifle has shown in (Figure 3, Figure 4, Figure 5). The comparison of the fracture pattern made by .22″ and .177″caliber air rifle revealed significant differences in 5 mm thick sheet. However, a 3 mm thick PMMA sheet does not show any type of significant difference. It was seen that the distance travelled by radial cracks in .22″caliber was greater than that of travelled by .177″caliber. On the side

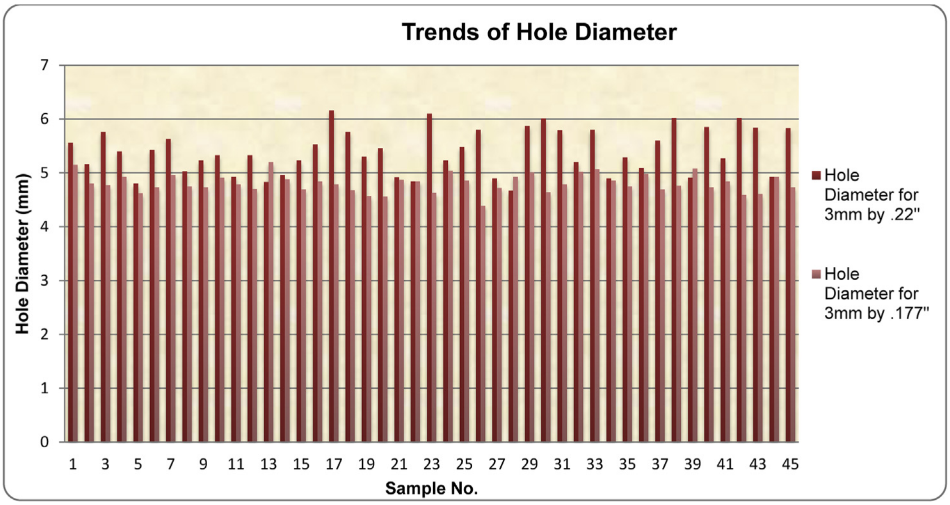


Figure 6. Trends of hole diameter in 3 mm PMMA sheet.

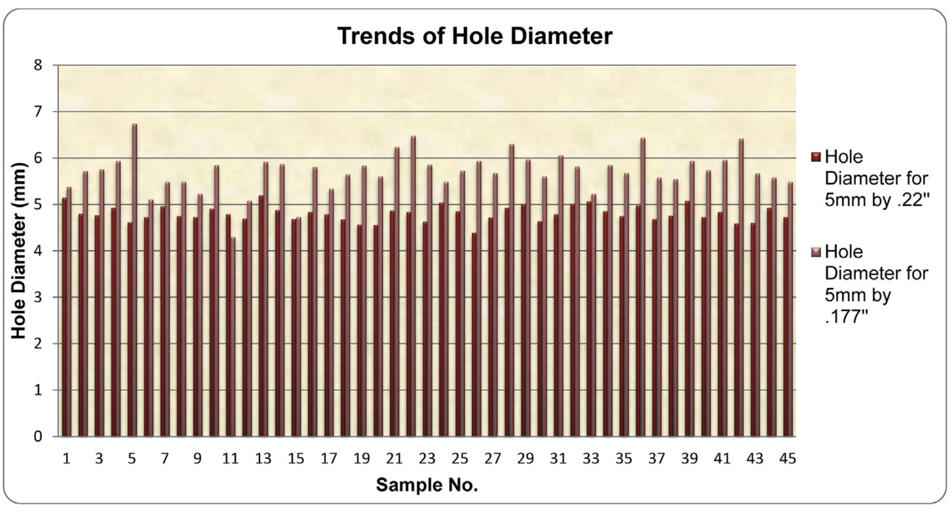


Figure 7. Trends of hole diameter in 5mm PMMA sheet.

Table 2. Values of mean and standard deviation of the measurement for PMMA sheets of different thickness.

Thickness of Sheet	Hole Diameter (in mm)		Thickness of Mist zone (in mm)		Diameter of Mist zone (in mm)		Radial Fracture Count		Concentric Fracture Count	
	.177″ Cal.	.22″ Cal.	.177″ Cal.	.22″ Cal.	.177″ Cal.	.22″ Cal.	.177″ Cal.	.22″ Cal.	.177″ Cal.	.22″ Cal.
Mean Values										
3 mm	4.80	5.39	4.00	3.44	11.48	11.20	10	10	0	0
5mm	5.71	5.53	8.72	5.45	19.24	16.47	8	9	0	0
Standard Deviation (S.D.)										
3 mm	0.168	0.412	0.350	0.416	1.011	1.241	-	-	-	-
5 mm	0.44	0.407	1.568	0.511	2.544	1.2	-	-	-	-

by side analysis, the notable difference was seen in thickness of the mist zone and area covered by the mist zone, it was greater when made by .22″caliber air rifle on a 5 mm thick sheet. However, the .177″ air rifle caliber made a hole of greater diameter than that made by .22″caliber air rifle in 5mm thick PMMA sheet. Probably, the impact fluence (basic concept of pressure) is the reason responsible for this. Impact fluence of .177″ pellet is about 54% greater than the fluence of .22″ calibre pellet. Similarly, the sticking of the .22″ pellet in the 5 mm thick PMMA sheet may be explained in the terms of fluence. The trends of hole diameter, made by both the calibers on 3 mm and 5 mm thick PMMA sheets, have been shown in (Figure 6 and Figure 7) respectively. In this study, it was revealed that the hole diameter was ranging between 4.4 mm–6.44 mm when made by .177″ caliber air rifle and in case of .22″ caliber it ranges from 6.16 mm -6.7 mm. Data derived from the measurements were then statistically analysed. The mean values and Standard Deviation (S.D.) of the measurements for the PMMA of different thickness is described in (Table 2). The goodness of Fit (Chi-Square test) was applied with the Null Hypothesis that all the values of hole diameter are consistent. On the hypothesis testing, null hypothesis was accepted (since, calculated value is less than tabulated value of Chi- Square at (n-1) degree of freedom) in

Table 3. Description of Chi-Square test.

Chi Square Observations		
Null Hypothesis: All the values are consistent i.e. equals to the mean value.		
For 3mm thickness for .22″ caliber		
Total no of observations	**45**	
Calculated value of chi square	**1.387**	
Tabulated value For 44 degree of freedom	**At 1% level = 25.1**	**At 5% level = 29.8**
Conclusion	Calculated value of x_2 < tabulated value; null hypothesis accepted	Calculated value of x_2 <tabulated value; null hypothesis accepted
For 5mm thickness for .22″ caliber		
Total no of observations	**45**	
Calculated value of chi square	**1.3401**	
Tabulated value For 44 degree of freedom	**At 1% level = 25.1**	**At 5% level = 29.8**
Conclusion	Calculated value of x_2 < tabulated value; null hypothesis accepted	Calculated value of x_2 < tabulated value; null hypothesis accepted
For 3mm thickness for .177″ caliber		
Total no of observations	**45**	
Calculated value of chi square	**3.137**	
Tabulated value For 44 degree of freedom	**At 1% level = 25.1**	**At 5% level = 29.8**
Conclusion	Calculated value of x_2 < tabulated value; null hypothesis accepted	Calculated value of x_2 < tabulated value; null hypothesis accepted
For 5mm thickness for .177″ caliber		
Total no of observations	**45**	
Calculated value of chi square	**2.4207**	
Tabulated value For 44 degree of freedom	**At 1% level = 25.1**	**At 5% level = 29.8**
Conclusion	Calculated value of x_2 < tabulated value; null hypothesis accepted	Calculated value of x_2 < tabulated value; null hypothesis accepted

all the cases at 1% and 5% level of significance. The description of a Chi-square test for 3 mm and 5 mm PMMA sheets are summarized in (Table 3).

4. Discussion

Nowadays, at various places, PMMA sheets are being used in place of glass. Therefore, in this study fractographical analysis was conducted. Consistency in the hole diameter was observed while analysing the PMMA sheets of various thicknesses. Previously, some terminal ballistics studies related to air gun in connection with fracture analysis have been conducted. Waghmare et al. (2016) proposed an approach distinguishing among the fractures made by different firearms (.303 rifle, .315 rifle, 9 mm pistol, AK-47 and improvised pistol of 8 mm). According to this approach, the diameter of the hole made by standard weapons is somewhat double to the caliber of the weapon. While an irregularity may be observed in the case of Improvised or country-made firearms. Harshey et al. (2017) analysed the fracture pattern on the glass of different thickness (3 mm, 4 mm and 5mm) by the air rifle of .177″ (4.5 mm) caliber. Consistency in the trends was observed.

Later, Tiwari et al. (2019) evaluated the multiple glass fractures that were also made by .177″ (4.5 mm) caliber air rifle. In this study, the range of hole diameter was 4.5 mm–6.7 mm that was following the trends of Harshey et al. (2017). In order to analyse the multiple fractures, Tiwari et al. (2019) outlined a condition in which sequence of shots may not be determined by the rule of thumb. The same condition is very probable to be occurring in the case of PMMA as the radial cracks are of short length and may not intercept each other on multiple firing.

PMMA is a glassy polymer (structure has showed in Figure 1) i.e. molecules are not in definite geometry that's why it is amorphous in nature. Keeping this in mind, in this study count of radial cracks was not taken as any parameter to draw any conclusion. Findings of Harshey et al. (2017) and Tiwari et al. (2019) indicated the determination of kind of weapon i.e. whether it is standard weapon or an air rifle. The findings of this presented study indicate that caliber differentiation may not be possible in the case of an air gun as both calibers do not produce any significant difference. Characteristics and some differences that have marked in this study are not enough to determine the caliber of the air rifle. The findings of Waghmare et al. (2016) provides a clue to determine the caliber on the basis of hole diameter.

In the light of above facts, it is obvious that this kind of study may be extended further to analyse the impact of coating with Sun control film, various thicknesses of PMMA sheets, different pellet shapes, the weapon of different caliber and different mechanism along with the effect of variable range. The findings of this study are significant and may support the criminal investigation by means of interpretation of the facts.

5. Conclusion

The use of PMMA sheets is increasing with time due to its properties such as durability, high impact resistance, robustness and less risk of damage. The probability of the appearance of the fractured PMMA sheet at the scene of shooting incidence cannot be denied. The present study involves the analysis of fractured PMMA sheets. The analysis leads to the conclusion that trends of hole diameter are consistent. This may help to determine the type of weapon by which the fracture has been caused. In the future, thisstudy may be extended further. The findings were found to be significant and have directed the future possibilities of research in fracture analysis as well as have the potential to assist the criminal investigation.

Declarations

Author contribution statement

Md Alim: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Kailash Singh Negi: Performed the experiments.

Sughosh Abhyankar, Neelesh Tiwari: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Abhimanyu Harshey: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ankit Srivastava: Conceived and designed the experiments; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

Abhyankar, S., Srivastava, A., Yadav, V., Nigam, K., Harshey, A., 2018. Glass fractures made from different pellet shapes- A preliminary study. J. Forensic Sci. Criminal investigation 8, 1–7.
Ali, U., Karim, K.J., Buang, N.A., 2015. A review of the properties and applications of Poly (Methyl Methacrylate) (PMMA), 55. Taylor and Francis, pp. 678–705.
Alper, M., Glaze, L., 2019. Source and Use of Firearms Involved in Crimes: Survey of Prison Inmates, 2016. U.S. Department of Justice, Office of Justice Programs, Bureau of Justice Statistics. NCJ 251776.
Anderson, T.L., 2017. In: Fracture Mechanics: Fundamental and Applications, 4. CRC Press. Taylor & Francis Group Boca Raton London New York, pp. 27–34.
Burnt, G.R., Packey, A.J., 1979. The criminal use of air weapons. J. Forensic Sci. Soc. 19.
Caddy, B., 2001. Forensic Examination of Glass and Paint Analysis and Interpretation. Taylor and Francis, London, pp. 106–130.
Copley, G.J., 2001. The composition and manufacture of glass and its domestic and industrial applications. In: Caddy, B. (Ed.), 2001. Forensic Examination of Glass and Paint Analysis and Interpretation. Taylor and Francis, London, pp. 106–130.
Crime in India, 2017. 2019.National Crime Records Bureau. (Ministry of Home Affairs) Government of India. http://ncrb.gov.in.
Crime in India, 2018. 2019. National Crime Records Bureau. (Ministry of Home Affairs) Government of India. http://ncrb.gov.in.
Curran, J.M., Hicks, T.N., Buckleton, J.S., 2000. Forensic Interpretation of Glass Evidence. CRC press LLC, Boca Raton London New York Washington, D.C.
DiMaio, V.J., Copeland, A.R., Besant, P.E.M., Fletcher, L.A., Jones, A., 1982. Minimal velocities necessary for perforation of skin and air gun pellets and bullets. J. Forensic Sci. 27, 894–898.
Dorogoy, A., Rittel, D., Brill, A., 2010. A study of inclined impact in polymethylmethacrylate plates. Int. J. Impact Eng. 37, 285–294.
Faye, A., Parameswaran, V., Basu, S., 2016. Dynamic fracture initiation toughness of PMMA: a critical evaluation. Mech. Mater. 94, 156–169.
Gogotsi, G.A., Mudrik, S.P., 2010. Glasses: new approach to fracture behavior analysis. J. Non-Cryst. Solids 356, 1021–1026.
Grady, D.E., 2010. Length scales and size distributions in dynamic fragmentation. Int. J. Fract. 163, 85–99.
Griffith, A.A., 1920. The phenomena of rupture and flow in solids. Philos Trans RSocLond A 221, 163–198.
Harshey, A., Srivastava, A., Yadav, V.K., Nigam, K., 2017. Analysis of glass fracture pattern made by .177″ (4.55mm) caliber air rifle. Egypt. J. Food Sci. 7, 1–8.
Hsiao, Y.T., Meng, H.H., 2018a. Evaluation of wounding potential of airguns using aluminium witness plates. Aust. J. Forensic Sci. 1–11.
Hsiao, Y.T., Meng, H.H., 2018b. Estimating the impact velocity of airgun pellet via terminal ballistics experiments. Forensic sci. J. 17 (1), 27–36.
Ibeh, C.C., 2011. In: Thermoplastic Materials Properties Manufacturing Methods and Application, 117–123. CRC Press, Taylor and Francisgroup Boca Raton, pp. 389–404.
Kieser, C.D., Riddel, R., Kieser, A.J., Theis, J., Swain, V.M., 2013. Bone micro-fracture observations from direct impact of slow velocity projectiles. J. Archive Military Med. 2, 1–6.
Lal, R.C., Subrahmanyam, B.V., 1972. Accidental death by air rifle. Forensic Sci. 1, 441–443.
Mbarek, I.A., Boumbimba, R.M., Rusinek, A., Voyiadjis, G.Z., Gerard, P., 2018. The dynamic behaviour of Poly (methyl methacrylate) based nano-rubbers subjected to impact and perforation: experimental investigations. Mech. Mater.
Mcjijnkins, S.P., Thornton, J.I., 1973. Glass fracture analysis- a review. Forensic Sci. 2, 1–27.
Mistek, E., Fikiet, M.A., Khandasammy, S.R., Lednev, I.K., 2018. Toward Locard's exchange principle. Recent developments in forensic trace evidence analysis. Anal. Chem.
Morgan, A., Aqil, N.A., Okeil, N.A., Ghaleb, S.A., Otaibi, A.F., Alashqar, H.M., Ghuwainem, S.O.A., Qahtani, M.A.M., 2019. Firearm injuries in rural Saudi Arabia: incidence, patterns, management, and cost. Egypt J Forensic Sci 9, 1–7.
Nadarajan, D., Daud, S.M., Shariff, N., 2020. Analysis of fracture pattern on soda lime and tempered glass caused by shotgun bullet impact. Malaysian J. Med. Health Sci. 16, 131–135.
Nie, D., Chen, X., Wu, Q., 2020. Mixed-mode fracture behaviors of AISI 1045 and AISI 5140 steels in compressor crankshafts – Part II: Mode II-III. Eng. Fail. Anal. 110 (2020), 104407.
Olabisi, O., Adewale, K., 2016. In: Handbook of Thermoplastics, 2. CRC Press Taylor and Francis Group, Boca Raton London New York, pp. 169–192.
Overend, M., Gaetano, S.D., Haldimann, M., 2007. Diagnostic interpretation of glassfailure. Struct. Eng. Int. 2, 151–158.
Pawar, E., 2016. A Review article on acrylic plastic. IOSR J. Mech. Civ. Eng. 13, 1–4.
Rittel, D., Brill, A., 2008. Dynamic flow and failure of confined polymethylmethacrylate. J. Mech. Phys. Solid. 56, 1401–1416.
Rittel, D., Dorogoy, A., 2014. Impact of thick PMMA plates by long projectiles at low velocities. Part I: effect of head's shape. Mech. Mater. 70, 41–52.
Saferstein, R. (Ed.), 2006. Criminalistics an Introduction to Forensic Science, ninth ed. Prentice Hall, Englewood Cliffs New Jersey.
Schein, O.D., Enger, C., Tielsch, J.M., 1994. The context and consequences of ocular injuries from air guns. AJO (Am. J. Ophthalmol.) 117, 501–506.
Simon, G., Heckmann, V., Toth, D., Kozma, Z., 2019. Brain death of an infant caused by a penetrating air gun injury. Leg. Med. 39, 41–44.
Stankov, A., Jakovski, Z., Pavlovski, G., Muric, N., Dwork, A.J., Cakar, Z., 2013. Air gun injury with deadly aftermath – case report. Leg. Med. 15, 35–37.
Stoney, D.A., Thornton, J.I., 1985. The forensic significance of the correlation of density and refractive index in glass evidence. Forensic Sci. Int. 29, 147–157.
Thomas, S., Visakh, P.M., 2011. In: Handbook of Engineering and Specialty Thermoplastics, 3. Scrivener Publishing LLC. Wiley, New Jersey, pp. 429–491.
Thornton, J.I., 2001. Interpretation of physical aspects of glass evidence. In: Caddy, B. (Ed.), 2001. Forensic Examination of Glass and Paint Analysis and Interpretation. Taylor and Francis, London, pp. 106–130.
Tiwari, N., Harshey, A., Das, T., Abhyankar, S., Yadav, V.K., Nigam, K., Anand, V.R., Srivastava, A., 2019. Evidential significance of multiple fracture pattern on the glass in forensic ballistics. Egypt. J. Food Sci. 9, 1–5.
Waghmare, N.P., Lal, A., Anand, V.R., 2016. Investigation of forensic glass Fractography made by different ammunition. Austin J. Forensic Sci. Criminol. 3 (1), 1–5.
Wightman, G., Beard, J., Allison, R., 2010. An investigation into the behavior of air gun pellets in ballistic gel and their interaction with bone. Forensic Sci. Int. 200, 41–49.
Wightman, G., Cochrane, R., Gray, R.A., Linton, M.A., 2013. Contribution to the discussion on the safety of air weapons. Sci. Justice 53 (3), 343–349.