Defence Science Journal, Vol. 62, No. 3, May 2012, pp. 153-158, DOI: 10.14429/dsj.62.1467

Ultrasonic Assessment of Bullet Inflicted Damage in Aramid Laminated Composites

N. Nayak*, A. Banerjee, and D. Datta†
Proof and Experimental Establishment, Chandipur, DRDO, Balasore–756 025
†Bengal Engineering and Science University, Shibpur–711 103
**E-mail: nnayakpxe@yahoo.com*

ABSTRACT

Immersion type ultrasonic C-scan has been performed on Twaron-epoxy (T-E) and Twaron-polypropylene (T-PP) composite laminates impacted by 7.62 mm armor piercing (AP) projectile with different striking velocities to assess the bullet inflicted damage area. Square zones of size 72 mm by 72 mm around each impact area are subjected ultrasonic C-scan in pulse echo mode. Ultrasonic features are extracted and processed to estimate the damage area in the laminates due to each impact. The variation in internal damage area is correlated with ballistic properties of composite laminates. It is observed that in the similar range of impact velocity, the damage area is invariably higher in composites made from thermoplastic polypropylene (PP) resin compared to the thermoset epoxy resin. The internal damage area of impacted panel is found to decrease with increase in impact velocity for both the types of resin matrix which corroborated the trend in experimental ballistic curve. The internal damage area, however, increases substantially when shot lodging takes place inside the laminate below ballistic limit or upon excessive yawing.

Keywords: Ultrasonic C-scan, ballistic limit, impact velocity, damage pattern, composite

1. INTRODUCTION

Light weight armors are usually made up of fibre reinforced plastic composites to suit the requirements of human shields in view of their high strength and stiffness to weight ratio. During use, these armors are expected to face projectile or splinter impacts and as such, it is necessary that such composites achieve the desired protection capability against impact. The extent of damage is possibly one of the important areas of interest to both the designer as well as the test and evaluation agencies. Estimation of severity and extent of damage zone due to such impacts can provide valuable inputs for effective fabrication of composite laminates, in terms of selecting the constituents like fibre and resin as well as structural issues like number of plies, ply orientation, stacking sequence, etc. Non-destructive evaluation (NDE) of composites is really challenging due to the fact that apart from being anisotropic and heterogeneous, these materials may involve different damage modes simultaneously. Several investigators have carried out experimental and numerical investigations to study the behavior of composite materials. Henneke[1] and Jones[2] developed a computer controlled ultrasonic scanning and data collection system for NDE of composites. Preuss and Clark[3] used the time of flight of ultrasonic C-scanning for detection, sizing and characterization of defects in carbon-fibre composite components. Abrate[4,5] comprehensively reviewed the response of the material, evaluation of damage and prediction of residual properties. Hosur, *et al.*[6] presented the results of experimental work on damage of carbon fibre reinforced impacts carried out at energy levels varying from 3 to 30 J where the resulting de lamination damage was determined by immersion type ultrasonic C-scans conducted in pulse echo mode. Datta, *et al.*[7] performed immersion type C-scans on impacted composite specimens. The impact was created by repeated dropping of weights on the glass fibre reinforced plastic (GFRP) panels. For automated image generation, grouping of signal amplitude data set was done by un-weighted pair group method of arithmetic averages (UPGMA) linkage method, but-based on a pre-selected number of clusters.

The problem faced with all composite materials used for ballistic protection is how to evaluate the damage area after impact. In spite of the availability of different test methods such as liquid penetrant, C-scan ultrasonic, radiographic analysis and digital image analysis in transparent materials, it has not always been possible to discriminate between the main failure modes of a composite material such as fibre breakage, fiber de-bonding, delamination and matrix cracking. However, the size and geometry of the damage area if determined accurately can give reliable information about the ballistic performance of these materials[8]. In an earlier study effect of resin matrix on the ballistic response of aramid laminated composite was reported[9] where the composites made using PP matrix

Received 25 January 2012, revised 2 April 2012, online published 3 May 2012

showed higher ballistic limit compared to epoxy ones. The damage pattern was different with a larger back bulging in case of the former. The observations like the lower energy absorption at higher impact energy, higher energy absorption for cases in which projectiles got lodged inside the composite laminate on penetration and higher ballistic limit (BL) of polypropylene (PP)-based composites compared to epoxy ones needed more insight into the impact induced damage to composites. Therefore, there was a desire to look for qualitative trends in the internal damage induced by ballistic impact over a range of impact velocities for each type of resin to compare the findings with the ballistic test results. Hence, both Twaron-epoxy (T-E) and Twaron-polypropylene (T-PP) composite laminates were subjected to ultrasonic C-scan analysis after ballistic impact by 7.62 mm AP projectile. The primary focus remained to study the damage pattern and determine the internal damage areas in the laminates impacted by varying striking velocities. The ultrasonic C-scan of impacted composite laminates was performed in an immersion type set up with stepper motor controlled probe scanning. Grouping of ultrasonic data was done by adopting UPGMA algorithm[7,10]. The internal damage area is then quantified and correlated with the corresponding strike and residual velocities of the projectile.

2. EXPERIMENTAL SETUP

2.1 Materials Used

Plain weave aramid fabric with trade name Twaron T-750 from DSM, Netherlands was used for making composite laminates. The epoxy resin used is modified with 20 phr carboxyl terminated poly (ethylene glycol adipate)[11.] Commercially available polypropylene films of 80 μm thickness were used for fabrication of thermoplastic composites. Composite laminates of 30 cm x 30 cm size used for ballistic testing were fabricated by keeping each ply of fabric oriented in the same directions (0/90) and placed in a base plate of mould. Thin films of PP (80 μm thickness) were placed on each Twaron ply. Number of plies and PP sheets were adjusted to obtain laminates of desired thickness. The ratio of fiber to PP was 70:30 by weight. Composite laminate fabrication was carried out by compression molding machine at 200 ^{O}C with pressure of 30 MPa. The molding temperature was maintained for 20 min and cooled to room temperature at same pressure. Twaron-epoxy composite was fabricated following similar procedure. Measured quantities of modified epoxy resin mixed with hardener were applied on each ply of 300 mm x 300 mm using a brush. These plies were then stacked over each other on a steel mould in (0/90) direction. Number of plies was varied to obtain the desired thickness. The ratio of fiber to resin was maintained at 70:30 by weight. The gel time of resin mixture was one hour and curing was carried out for 8 h in a preheated oven at 100 ^{O}C under 30 MPa pressure. It was furnace cooled and then removed as laminates for use.

2.2 Ballistic Testing Setup

The composite laminates were mounted on specially designed holders where two sides were clamped for rigid holding and placed in line of fire of a 7.62 mm military rifle. A high speed video camera, (Speed Cam Visario), with a speed of 10,000 frames/s was used to observe the pre and post impact phenomena. An artificial light source using flash bulbs used for illumination which was synchronized with camera and a trigger was generated by short circuiting aluminum foil at appropriate distance depending on the velocity of projectile. A schematic of the set up is given as Fig. 1. The picture was stored in a PC and frame-by-frame analysis was made in time domain to study the impact response of laminates and calculate SV and RV (in case of perforated ones).

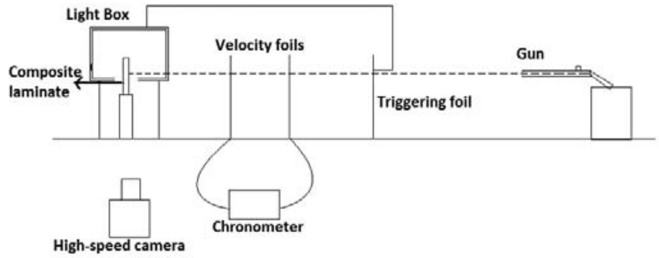


Figure 1. Experimental lay out for ballistic impact test.

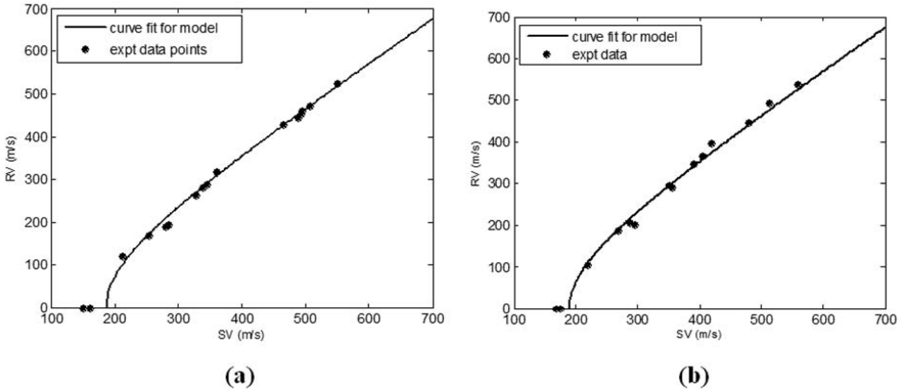
2.3. Ultrasonic C-scan Setup and Imaging

The facility comprised of an immersion tank made of acrylic glass and a mounting frame furnished with two lead screws, driven by stepper motors, in mutually perpendicular directions. The transducer, fitted in the probe holding device, can move along two mutually perpendicular directions in precise steps and is capable of scanning any predefined two dimensional region. The transducer is connected to an ultrasonic board that acts as the pulsar, receiver and digitizer of the ultrasonic waveform. The board[12], seamlessly interacts with the controlling software[13], that has the capability to condition, gate and zoom the digitized signal. A square region of 72 mm by 72 mm around the impact point was first selected. The impacted plate is placed in the immersion tank and probe is adjusted for scanning sequence in raster fashion by normal incidence type pulse echo method. Generally, probe frequency of 1 MHz and gain of 31dB were used. Different ultrasonic features were extracted from the digitized waveform for all the locations of a particular zone, but data pertaining to Peak Amplitude feature were subjected to clustering for automated imaging in this case, with number of clusters restricted to three[10,14].

3. RESULTS AND DISCUSSION

3.1 Ballistic Test Data

For different target and projectile combination, ballistic limit and SV-RV relationship have been identified to be crucial to assess energy absorption capability. The SV-RV data generated during ballistic impact of the two types of composite laminates were fitted with the help of Jonas-Lambert model[15] and presented elsewhere[9]. The same for 10 mm thick laminates is presented here in Fig. 2 to illustrate the ballistic performance of the two types of laminate material. The composite laminates were found to have typical behavior in their energy absorption around BL. For a 10 mm thick laminate, for example, when the striking velocity (SV) is 162 m/s, the RV is zero and the projectile is stopped by laminate. But if the impact velocity increases slightly above BL, the projectile residual velocity (RV) increases more. As the impact velocity increases up to BL, the amount of absorbed energy increases but when the SV is more than BL, the energy absorbing capacity of the system drastically reduces[16]. The damage area has a direct bearing on the energy absorption and hence the remaining velocity.



(a) (b)

Figure 2. SV-RV relationship of 10 mm thick composite laminates on impact of 7.62 mm projectile: (a) T-E and (b)T-PP.

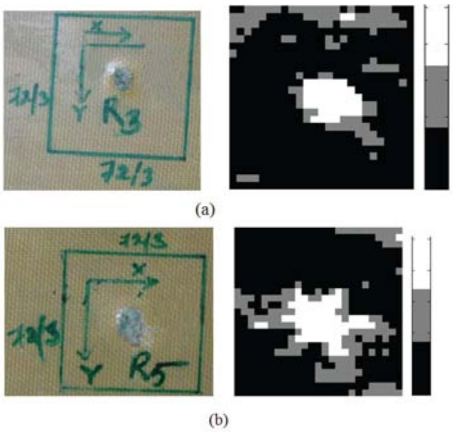
3.2 C-scan Images and Damage Area

Ultrasonic C-scan was conducted on post-impacted T-E and T-PP composite laminates of 10 mm and 15 mm thickness. Due to the inherent heterogeneity in composites, its interaction with acoustic waves results in unwanted variations. Therefore, systematic grouping technique was employed to group the data set pertaining to a particular ultrasonic feature. Of the different grouping algorithms[10], three cluster UPGMAA with peak amplitude as the ultrasonic feature was found to produce consistent and reliable results. In this method the images are seen to consist of three distinct regions in varying order of severity of damage and the central white area represents the most severely damaged region and is reported as internal damage area/damage area subsequently in the text. The black region represents the least damage/ unaffected area and the grey is in between in terms of severity.

The visual impression of the impact zone in the laminate and the corresponding C-scan images are compared in Figs. 3 and 4. It is observed that a localized circular impact area (R3) in T-E laminate (Fig. 3(a)) corresponds to an almost symmetric internal damage area in the C-scan image compared to a more widespread distorted internal damage area for impact zone (R5) representing an asymmetric elliptical shape on laminate (Fig. 3(b)). Similarly, two impacted zones of 10mm PP laminate and their C-scan images are shown in Fig. 4. When impacted with a lower velocity of 268.9 m/s, a star shaped impact zone (R4) resulted [Fig.4(a)] compared to a more compact impression in R1 impacted at a velocity of 479m/s (Fig.4(b)). Thus, the damage in impacted laminates physically observed were clearly comparable with the internal damage area in C-scan images generated.

The PP-based laminates invariably showed a higher damage area for similar impact velocities which indicated a relatively global damage mode with higher delamination/ de-bonding compared to epoxy laminates and this contributed to observed higher BL for the former. A damage area of 460 mm^2 was observed for 10mm PP laminate compared to 265 mm^2 for 10 mm epoxy laminate, impacted with a velocity in the range of 350 m/s.

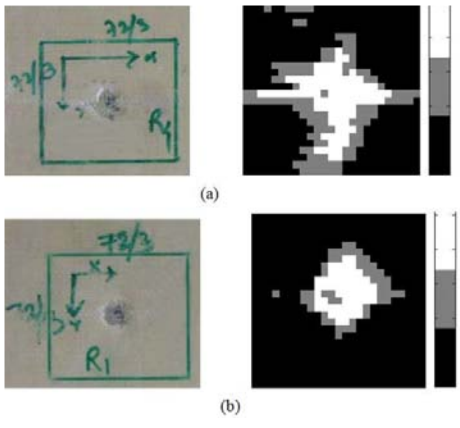
Once the application of C-scan technique for estimation of damage area in the composite laminate was established, attempt was made to quantify and correlate it with ballistic parameters. Impacted 10mm thick T-E and T-PP



(a)

(b)

Figure 3. Impact zone and corresponding C-scan images of a 10 mm T-E laminate (a) zone R3, (b) zone R5.



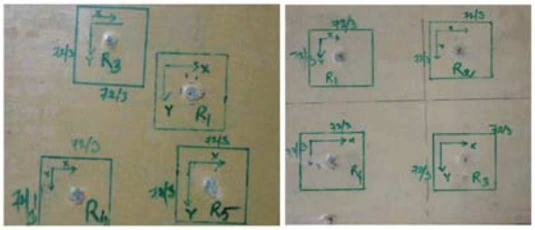
(a)

(b)

Figure 4. Impact zone and corresponding C-scan images of a 10mm T-PP laminate (a) zone R4, (b) zone R1.

laminates marked in different zones viz., R1, R2, etc. around the impact points are shown in Fig. 5.

Each zone representing an impact area corresponding to a projectile velocity was subjected to C-scan analysis. The C-scan images of the impacted zones for T-E laminate are given in Fig. 6 and those for T-PP in Fig. 7.

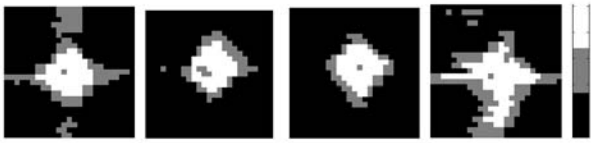


(a) (b)

Figure 5. Impacted (a) T-E AND (b) T-PP composite laminates with marked zones prior to C-scan.

(a) (b) (c) (d)

Figure 6. C-scan images of zones (a) R1, (b) R3, (c) R4, and (d) R5 in impacted 10 mm thick T-E laminate from Fig. 5(a).



(a) (b) (c) (d)

Figure 7. C-scan images of zones (a) R1, (b) R2, (c) R3, and (d) R4 in impacted 10 mm thick T-PP laminate from Fig. 5(b).

Table 1. Impact velocity and corresponding damage area in 10 mm Twaron-epoxy composite laminate

Scanned zone	V_s (m/s)	Internal damage area (mm^2)
Zone-1 (R1)	360.8	165.80
Zone-3 (R3)	253.7	339.89
Zone-4 (R4)	550.1	149.22
Zone-5 (R5)	238.1	555.43

Table 2. Impact velocity and corresponding damage area of 10 mm Twaron-PP composite laminate.

Scanned zone	SV (m/s)	Internal damage area (mm^2)
Zone-1 (R1)	479.0	464.24
Zone-2 (R2)	405.0	489.11
Zone-3 (R3)	559.4	497.40
Zone-4 (R4)	268.9	754.39

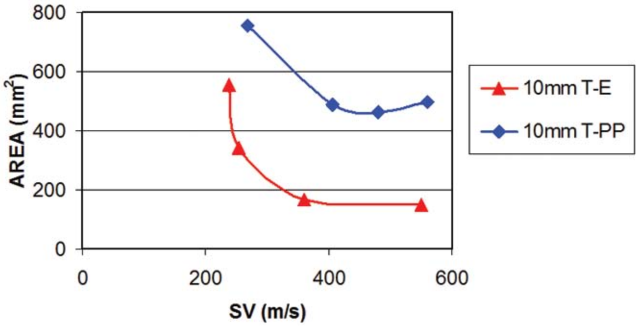
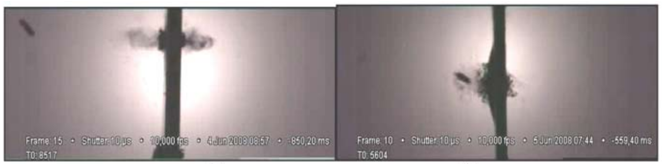


Figure 8. Variation of damage area with SV for 10mm thick Twaron®-epoxy and Twaron®-PP laminates.

The quantified core damage areas with corresponding SVs are summarized in Tables 1 and 2. The variation of internal damage area with different SVs for both the types of laminates is shown in Fig. 8.

A reduction in internal damage area with increasing SV is observed and for similar range of impact velocity, the damage area of PP laminates is observed to be higher than that in the epoxy-based ones. The trend could be reproduced in multiple panels impacted with different SV. This observation corroborates the findings presented in the ballistic curves in terms of SV-RV relationship for the two types of laminates of 10 mm thickness as shown in Fig. 2. The ballistic limit of the PP-based laminates was found to be higher than the epoxy-based laminates. It can be inferred that the higher damage area contributes to higher energy absorption and leads to higher BL of PP-based laminates.

Typical high speed video images of the perforation process for laminates with the two types of matrices are shown in Fig. 9. The back face damage of epoxy laminate can be seen to be localized and circular compared to PP-based laminates where the damage is global and bulging in transverse direction before returning back to original position. This observation also supplements the visual and C-scan finding of larger damage area in T-PP laminate for the same SV.



(a) (b)

Figure 9. High-speed images of perforated (a) T-E and (b) T-PP laminates.

The variation in core damage area with SV for 10 mm and 15 mm thick Twaron-epoxy composite laminates is given in Fig. 10. A similar trend of decrease in damage area with increase of SV is also followed for 15 mm thick laminate. At the same time, a higher damage area is observed in 15 mm laminate compared to 10mm thickness.

It was also found that the measure of damage area is highly sensitive to projectile attitude on impact and exit in addition to SV. Damage area was observed to be

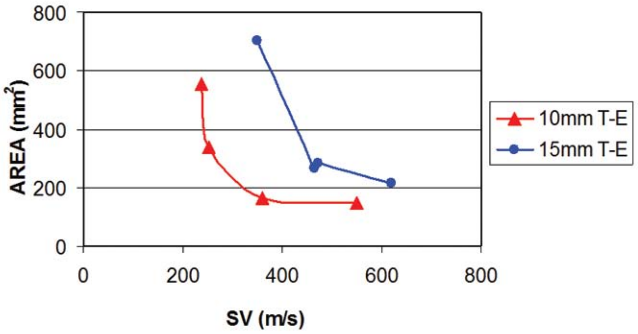


Figure 10. Variation in damage area with SV for 10mm and 15mm thick Twaron®-epoxy laminate.

abruptly high for SV around BL or impacts with yawed projectiles. The observation can be explained by the fact that during the embedding of projectile inside the laminate, separation between layers takes place leading to larger delamination and the rearward layers displaced by projectile do not come back to original position. In the cases of impact below BL, the deviation of projectile path inside the laminate takes place due to the resistance offered by non-penetrated layers from rear side of laminate which ultimately creates more delamination / de-bonding and produces higher damage area as detected in C-scan analysis. Marked difference in damage area for normal and yawed projectile at same range of SV, i.e. much higher damage area for the yawed one can also be explained in the above light.

Though the variation in damage area with SV could be generally correlated, a clear trend of variation of damage area with energy absorbed by laminates was not found. In some of the impact cases, higher energy absorption resulted in higher core damage area but the same was not always followed. This might be due to the complexities associated with the path the projectile followed, energy dissipation mechanism and fiber interaction with the tip of the projectile[17], which was evident from its exit angle after perforation.

4. CONCLUSIONS

The ultrasonic normal incidence pulse echo immersion type C-scan technique was found suitable for identification of defects induced by impact in aramid fabric laminated composites. Imaging with peak amplitude as ultrasonic feature and three cluster grouping-based on UPGMAA was found to be most appropriate technique for determining internal damage area. C-scan images generated were able to extract relevant information of the damage state in the impacted composite laminates. The internal damage areas derived by C-scan technique are found to be sensitive to the loss of energy of the projectile and increased rapidly in case of shot lodging. PP-based composites invariably showed higher impact damage than the epoxy-based composites in the similar range of striking velocity. The higher damage area of PP-based composites corroborated the observed higher BL due to higher energy absorption during the impact.

5. ACKNOWLEDGEMENTS

The authors express their sincere thanks to Maj Gen P Mathur, Director, PXE, Chandipur for encouragement and permission to publish this paper. Thanks are also due to Director, NMRL, Ambernath for facilitating composite laminate fabrication.

REFERENCES

1. Henneke EG II. Ultrasonic nondestructive evaluation of advanced composites. *In* Non-destructive Testing of Fibre-reinforced Plastics Composites, edited by John Summerscales, 1990, **2**, 55-159.
2. Jones, T.S. Inspection of composites using the automated ultrasonic scanning system (AUSS). *Materials Evaluation*,1985, **43(6)**, 746-53.
3. Preuss T.E. & Clark, G. Use of time-of-flight C-scanning for assessment of impact damage. *Composites*, 1988, **19**(2), 145-48.
4. Abrate, S. Impact on laminated composite materials. Transactions of the ASME. *Appl. Mech. Rev.*, 1991, **44**(4), 155-90.
5. Abrate, S. Impact on laminated composites: recent advances. Transactions of the ASME. *Appl. Mech. Rev.*, 1994, **47(**11), 517-43.
6. Hosur M.V.; Murthy, C.R.L.; Ramamurthy, T.S. & Shet A. Estimation of impact induced damage in CFRP laminates through ultrasonic imaging. *NDT&E International,* 1998, **31**(5), 359-74.
7. Datta, D.; Samanta, S. & Maity, P. Automated imaging of composite specimens, *J. Non destructive Test. Eval.,* 2004, **3**(3), 21-27.
8. Hazell, P.J.; Cowie, A.; Stennett, C. & Cooper, G. A. Penetration of a woven CRPF laminate by a high velocity steel sphere impacting at velocities of up to 1875m/s. *Int. J. Impact Engg.,* 2009, **36**(9), 1136-142.
9. Nayak, N.; Sivaraman, P.; Banerjee A.; Dutta, A.L.; Madhu, V.; Mishra, V. S. & Chakravorty, B. C. Effect of matix on the ballistic impact of aramid fabrics composite laminates by armor piercing projectiles. *Polymer Composites*, 2012, **33**(3), 443-50.
10. Samant, S.; Samanta, S.; Banerjee, A.; Nayak, N. & Dutta, D. Ultrasonic Assessment of Bullet inflicted Damage in composites. *In* the Proceedings of National Seminar on Non-destructive Evaluation. NDE-2009, Trichy, 4-5 December 2010. pp. 104-07.
11. Ratna, D.; Samui, A.B. & Chakraborty, B.C. Flexibility improvement of epoxy resin by Chemical modification. *Polymer International*, 2004, **53** (11), 1882-887.
12. PCUS11 Ultrasonic P/R Board Manual, DOC # EBD003-1, Fraunhoffer Institute for Non-Destructive Testing, Saarbruecken, Germany.
13. Manual QUT, Ultrasonic testing software for the PCUS Ultrasonic Board, Version 4, Quality Network. Pvt. Ltd., 1999.
14. Wong, C.C.; Chen, C.C. & Su, M.C. A novel algorithm for data clustering. *Pattern Recognition*, 2001, **34** (3), 425-42.

15. Lambert, J.P. A residual velocity predictive model for long rod penetrators. Report No. ARBRL- MR-02828. Ballistic research laboratory, Aberdeen Proving Ground, MD, 1978, 3.
16. Hetherington, J.G. & Rajagopalan, B.P. An investigation into the energy absorbed during ballistic performance of composite armors *Int. J. Impact Engg.,* 1991, **11** (1), 33-40.
17. Naik, N.K.; Shrirao, P. and Reddy, B.C.K. Ballistic impact behaviour of woven fabric composites: Formulation. *Int. J Impact Engg.*, 2006, **32** (9), 1521-552.

Contributers

Dr N. Nayak, obtained his MSc (Chemistry) from Utkal University, Bhubaneswar, MTech (Materials Science and Engg.) from IIT, Mumbai and PhD in Chemistry (Materials science) from Fakir Mohan university, Balasore. He is presently working as Scientist-F and heading the Test and Evaluation Division at Proof and Experimental Establishment (PXE), Chandipur. His areas of work include: Dynamic test and evaluation of all types conventional armaments and ballistic evaluation of armour materials.

Mr Arkadeb Banerjee obtained his BE in Mechanical Engg from BE College, Shibpur, West Bengal. Currently persuing his doctoral research from Jadavpur University, Kolkata. Presently working as Scientist D in Test and Evaluation Group of PXE, Chandipur. His areas of research include: Dynamic evaluation of MBT Arjun armaments, armours, and numerical modelling of ballistic impact of armours.

Dr D. Datta obtained his Bachelor and Master degrees in Mechanical Engineering, from Jadavpur University, in 1984 and 1986, respectively. And PhD (Mechanical Engineering) from Indian Institute of Technology, Kanpur, in 1996. Presently working as Professor and Head of Mechanical Engg Department of BESU, Shibpur, Howrah. His areas of research include: Ultrasonic NDE and composite materials.