Defence Science Journal, Vol. 73, No. 2, March 2023, pp. 163-170, DOI : 10.14429/dsj.73.18637

Effect of Temperature and Ply Angle on Performance of Ultra High Molecular Weight Polyethylene (UHMWPE) Laminates Under Low Velocity Impact

T. Sreekantha Reddy, P. Rama Subba Reddy* and Vemuri Madhu

DRDO-Defence Metallurgical Research Laboratory, Hyderabad - 500 058, India

**E-mail: rsreddy.dmrl@gov.in*

ABSTRACT

Low velocity impact tests were conducted on ultra high molecular weight polyethylene (UHMWPE) laminates having different ply angle. The tests were conducted at various temperatures using steel impactor having 16mm diameter and hemi spherical shape. The selected impact energies are in the range of 50 to 250 Joule. The performance of the composites was compared with respect to peak force, maximum displacement and back face deformation. Results indicated that with increase of temperature, the contact duration increased whereas deceleration was reduced. Various failure mechanisms involved in energy absorption were also addressed.

Keywords: UHMWPE; Low velocity impact; Ply angle; Deformation

1. INTRODUCTION

The present day focus of an armour technologist is to develop light weight armour for personnel and vehicle protection systems. Heavy armour restricts the combat capability and comfort of soldiers. Further, it also reduces the maneuverability, fuel economy and overall performance of combat systems. Extensive research had been carried to increase the resistance to impact and energy absorption capability of fabric materials since 1960[1]. Cunniff conducted an exceptional work in the field of impact studies on nylon, aramid and UHMWPE based armour structures with different weave types[2-5]. Of late, Ultra High Molecular Weight Polyethylene (UHMWPE) with trade names of Dyneema® and Spectra® has come into lime light due to its excellent properties like high failure strain, superior specific strength, elastic wave speed etc.

Various studies were conducted to examine the impact response of UHMWPE composites. Hazzard[6], *et al.* studied the effect of fibre orientation on 2.2 mm thickness Dyneema composite laminates under low velocity impact at 150 J energy. Their studies concluded that the quasi-isotropic architectures exhibited 43 % lower back face deformation when compared to 0°/90° ply orientation. O'Masta[7], *et al.* examined the response of UHWMPE reinforced laminates with inter-ply angles ($\theta \leq 90^o$) and observed that laminates failed by indirect tension mechanism. It was also reported that the shear-lag length increases as θ is reduced.

Zhang[8], *et al.* conducted ballistic evaluation of UHMWPE based hybrid and non-hybrid laminates against 12.7 mm spherical projectile. It was found that the transverse expansion speed of back face deformation (BFD) was higher in hybrid panels compared to 0/90. cross-ply panels, however the lower midpoint deflection was reported for hybrid laminates. Nguyen[9], *et al.* investigated ballistic performance of thick UHMWPE laminates (9 to 100 mm thickness) when subjected to 12.7 mm and 20 mm calibre fragment simulating projectiles (FSPs). They observed that thin panels having less than 10 mm thickness failed in single stage, i.e., predominantly in fibre tension. But thick panels undergone two-stage failure like shear plugging and bulging.

Vargas-Gonzalez[10], *et al.* evaluated the effect of UHMWPE panel architecture on impact pressure and back face deformation (BFD) against 7.62 mm lead core projectile and concluded that 0/90^o. panel has 5.3 times higher average maximum pressure amplitude when compared to the panel having the hybrid architecture. Karthikeyan[11], *et al.* studied the effect of unidirectional (UD), alternating orthogonal (0°/90°), helicoidal and a hybridised 0°/90° - helicoid on ballistic performance of UHMWPE. They observed that ballistic limit and absorbed energies were highest for alternating orthogonal (0°/90°) lay-up due to the variation in failure mechanisms for different architecture.

Wang[12-13], *et al.* evaluated the influence of resin matrix on the behaviour of Dyneema® woven fabric based composite laminates that were impacted with steel projectile in a velocity range of 100 to 200 m/s. Their study discovered that the laminates made up of flexible matrices showed better perforation resistance and energy absorption at the cost of higher deformation and damage as compared to the rigid matrix based laminates.

Lässig[14], *et al.* studied the effect of curing parameters such as temperature and pressure on ballistic performance and shock wave behavior of UHMWPE laminates and concluded that higher consolidation pressures result in a better ballistic performance in terms of depth of penetration (DoP) and V_{50} velocity. Asija[15]. *et al.* investigated the effect of Shear

Received : 21 November 2022, Revised : 11 December 2022
Accepted : 02 February 2023, Online published : 06 April 2023

Thickening Fluid (STF) treatment on the high strain rate properties of UHMWPE composites. They observed that STF-treated specimens exhibited higher values of specimen peak stress, peak strain, specimen strain rate and impact toughness as compared to neat untreated specimens. Hu[16], *et al.* extensively studied the damage tolerance of 2-dimentional UHMWPE/CF hybrid woven laminates when subjected to low-velocity impact[16-18]. They found that hybrid laminates exhibited about 70 % higher penetration energy as compared to pure carbon composites.

During the manufacturing and service in the field, armour systems experience different low velocity impact loads like tool drop, flying debris, hailstones etc. Though the damage due to low velocity impact damage is not visible to naked eye, it reduces the load bearing capacity of the composites as it causes internal delamination. Hence, it can have catastrophic effect on actual performance of armour materials. Considerable research has been carried out on the behaviour of UHMWPE composites under high velocity impact. However, very limited information is available with respect to low velocity impact studies on this type of composites. Moreover, no reports were published on the effect of temperature on impact behaviour of UHMWPE composites under low velocity/low energy. Hence, the objective of the present study is to understand the effect of temperature, impact energy and laminate ply angle on UHMWPE composite performance under low velocity impact.

2. EXPERIMENTAL WORK

2.1 Fabrication of Composites

Composite panels were processed using a commercial UHMWPE prepreg namely Dyneema® HB-50 (DSM, Netherlands). Each ply of Dyneema consists of UHMWPE unidirectional fibers coated with a thermoplastic resin system and four of such plies were arranged in cross-ply configuration in a 0/90/0/90 arrangement to form a sub laminate as shown in Fig. 1. The material was cut into 320x320 mm sheets from the roll and 23 layers were stacked to get areal density (AD) of 5.0 kg/m^2. These laminates were consolidated using a hydraulic press (250 Ton Press, Orione Hydraulic Pvt. Ltd, India) as per the cycle given by the manufacturer. Three types of composites with different architecture were consolidated under the same conditions using single fabric roll. In the first configuration, named as 0/90. cross-ply, sub-laminate layers were placed in standard cross ply orientation in as received condition. The second configuration, referred as 30^o helicoidal (HC 30) was obtained by laying down with every other layer rotated 30^o clockwise with respect to the previous layer. It can be noted that with every layer rotation, there is an equivalent fiber orientation in the orthogonal direction. For instance, the layers aligned in 30^o will have lay-up in the 120^o direction also, due to the orthogonality of the fabric architecture. In the same manner, the third configuration, designated as 45^o helicoidal (HC 45) was also obtained by laying down every other layer rotated 45^o clockwise with respect to the previous layer. In general, it can be stated that repetition of layers will take place every after nth layer (n=90/θ, θ is an angle between successive layers). After fabrication of laminate, specimens were cut into the dimensions of 150 x 150 mm by using vertical band saw for low velocity impact test.

2.2 Low Velocity Impact Experiments

Instrumented drop weight impact tester having a hemispherical impactor (diameter - 16 mm) was used to conduct the impact tests. The details of instrument employed are reported elsewhere[19]. The experiments were performed at three different temperatures viz. -20 °C, 25 °C and 60 °C. The motive behind selecting these particular temperatures was to cover the maximum range of different regional conditions around the globe. The specimens were kept at experimental temperature for 1 to 1.5 hr to obtain even temperature throughout the specimen. Five different impact energies like 50, 100, 150, 200 and 250 Joule were chosen. The corresponding impact velocities were 4.35, 6.08, 7.51, 8.72 and 9.83 m/s respectively.

All the experimental conditions are mentioned in Table 1. Data acquisition system was utilized to get the force–time history at a rate of 500 kHz. From the obtained force-time data, important parameters like peak force/maximum force (F_{max}), maximum displacement (D_{max}), energy absorbed (E_a) and impact velocity were determined with the help of instrument's software[20]. A minmum of three samples were tested at each temperature and impact energy. Due to paucity of samples, comparison of ply angle effect was carried out only at 60 ^{o}C temperature.

Table 1. Experimental parameters

Temperature (^{o}C)	**-20, 25, 60**
Composite architecture	1. [0/90] cross-ply - $[(0/90)_2]_{23}$ 2. 30^o helicoidal - $[(0/90)_2(30/120)_2(60/150)_2[(0/90)_2.....]_{23}$ 3. 45^o helicoidal - $[(0/90)_2(\pm 45)_2.....]_{23}$
Impact energy (J)	50, 100, 150, 200, 250

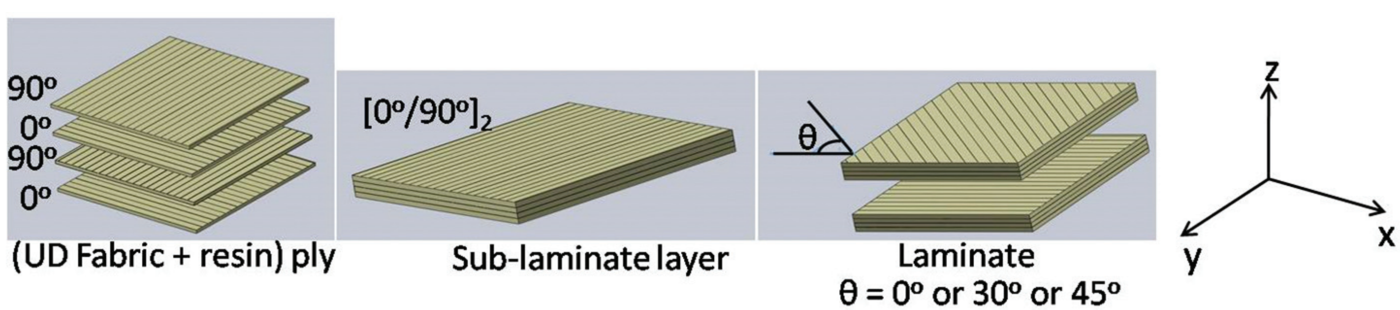


Figure 1. Schematic view of laminate construction.

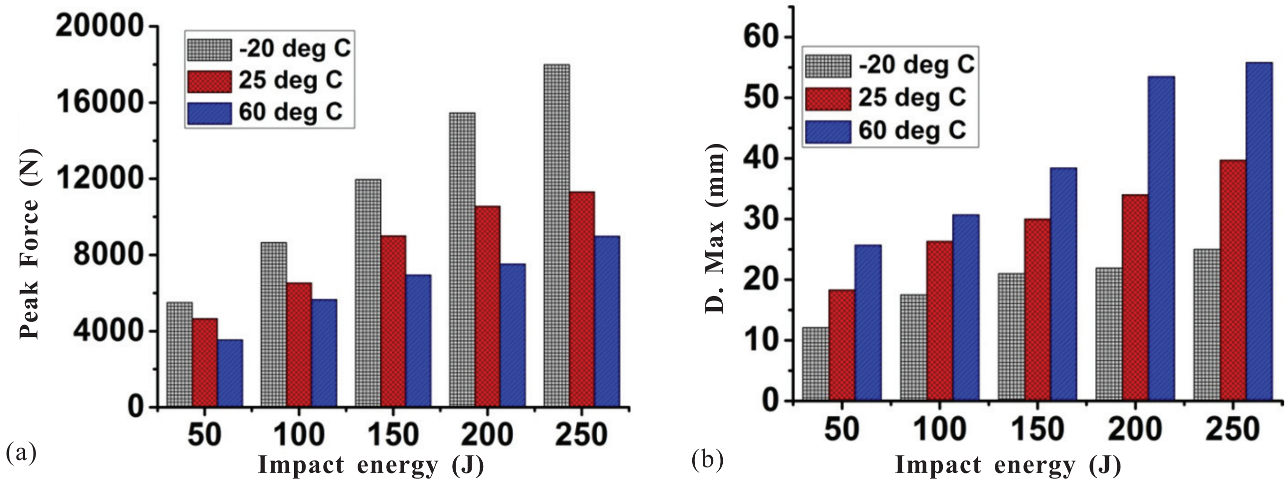


Figure 2. (a) Peak force at different impact energy and temperature (b) Variation of maximum displacement at different impact energies and temperature.

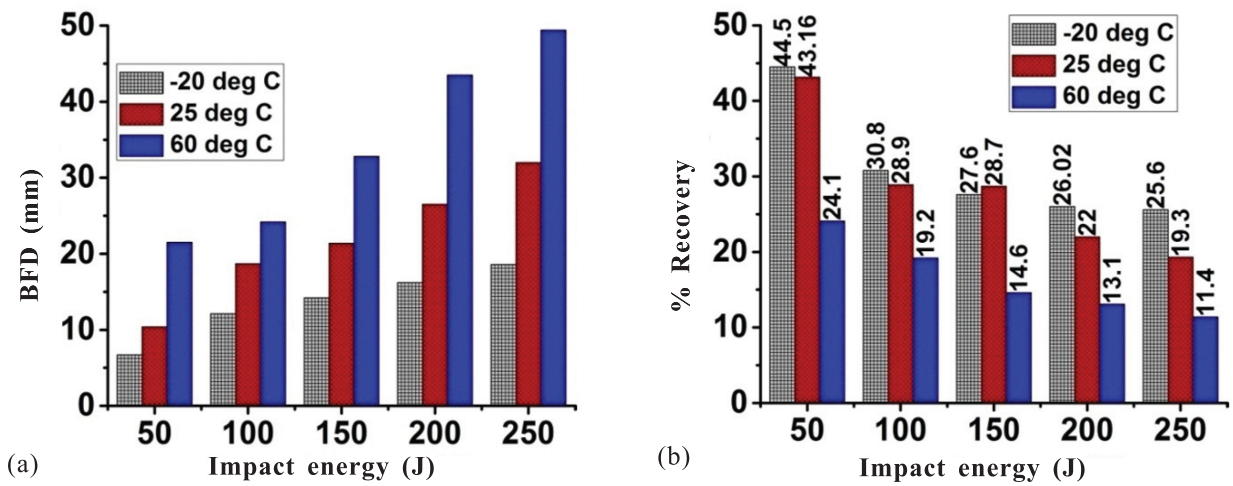


Figure 3. (a) Residual back face deformation (b) % of recovery of laminates at different temperatures as a function of impact energy.

2.3 FAILURE ANALYSIS

Damage analysis of post impacted laminates was carried out by careful visual observation to analyse the degree of failure and its mode. Residual back face deformation (BFD, the transverse displacement of laminate from the center of impact point) of laminates was measured physically after 24 hr of completion of the experiments. The difference in deformation between the dynamic displacement (D_{max}) and residual back face deformaiton was measured and percent of recovery in the deformation was estimated using equation 1.

$$\text{\% of recovery} = \frac{D_{\max} - \text{Residual BFD}}{D_{\max}} \text{X } 100 \qquad (1)$$

Selected laminates were cross sectioned along the centre line of impact in order to witness the other failure modes if any.

3. RESULTS AND DISCUSSION

3.1 Effect of Impact Energy and Temperature

3.1.1 Change in Peak Force and Maximum Displacement

Figure 2 shows change in peak force (F_{max}) and Max. displacement for different impact energies and temperature conditions. It can be seen that peak force increased with increse of impact energy irrespective of temperature conditions. However, increse in temeperature from sub zero to 60 ^{o}C resulted in reduction of peak fore as well as rate of increase in peak force at all the impact enerigeis. For instance when impacted with 150 J energy, peak force at -20 ^{o}C is 12 kN and it got decreased by 25 % and 42 % respectively at 25 ^{o}C and 60 ^{o}C temperature. UHMWPE (Dyneema) is thermoplastic material. The softening point of Dyneema is in the range of 150-160 ^{o}C. As the temperature increased from RT, the conditions are approaching the softening temperature that results in increase of ductility. As the temperature decreased towards sub zero temperatures, the molecular motion of Dyneema will be decreased due to which the material starts stiffening and consequently the ductility also decreased. Due to this, peak force is highest at -20 ^{o}C and it has come down with increase in temperature and showed lower value at 60 ^{o}C.

Figure 2(b) presents the maximum displacement (D_{max}) of laminates. It can be seen that D_{max} increased with increse of impact energy as well as temperature. It is well reported that at sub-zero temperatures, restriction of segmental motion of polymer molecules (UHMWPE) and hinderance of molecular motion takes place resulting increase in ovarall stiffness of laminate[21]. Hence the D_{max} was observed lowest at -20 °C for all impact energies.

Residual back face deformation of the laminates aginst impact energy at different temperatures is illustrated in Fig. 3a. As expected, the trend with respect to impact energy and temperature is similar to that of D_{max}. Here, our intrest is to know how the elastic deformation was recovered under different impact conditions. Figure 3b displays the per cent recovery of deformation for the laminate subjected to different impact energies and temperatures. It is clear from the Fig. 2b and 3a that, D_{max} values at 50 J are 12.1 mm, 18.3 mm & 25.7 mm and BFD values are 6.7 mm, 10.4 mm & 21.5 mm respectively at -20 °C, 25 °C & 60 °C. This indicates that D_{max} occurred at lower temperatures might be with in elastic limit of laminate which helps in maximum recovery of deformation i.e. per cent recovery is highest at -20 °C. Where as at 60 °C, polymer molecules will soften as compare to lower temperatures and stretch beyond elastic limit and resulted in lowest recovery at 60 °C. Moreover, it should be noted that test specimens were removed from the test chamber immediately after impact and final deformation was measured after 24 hours conditioning at room temperature only (not at test temperature). This also one of the probable causes for decrease in per cent recovery. It further reduced with increase in the impact energy. This can be attributed to the fact that under higher impact energy, the polymer chains are stretched to the maximum extent and upon

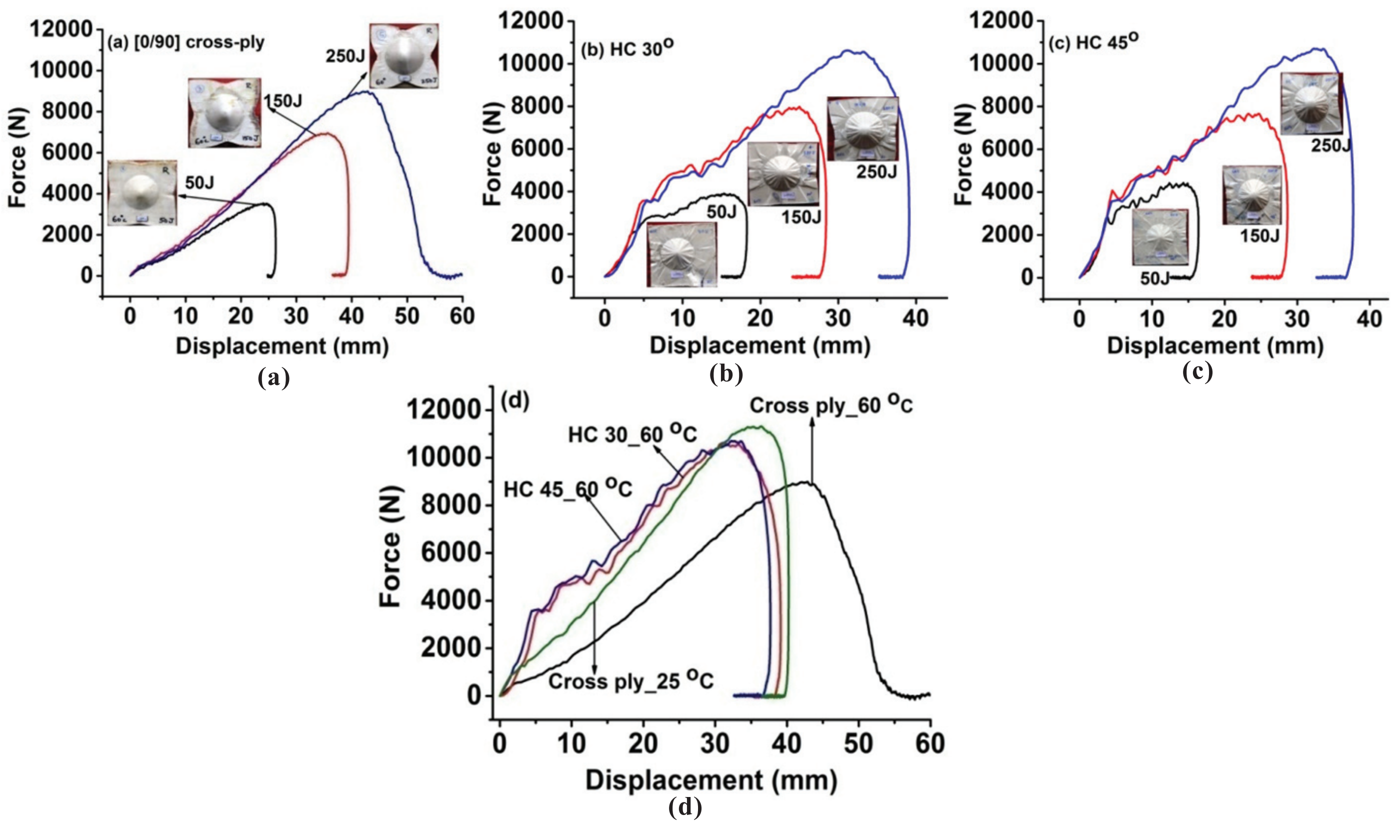


Figure 4. Effect of ply angle on force-displacement behaviour at 60 °C: (a) [0/90] cross-ply, (b) 30° helicoidal, (c) 45° helicoidal (d) Comparison of three laminates at 250 J.

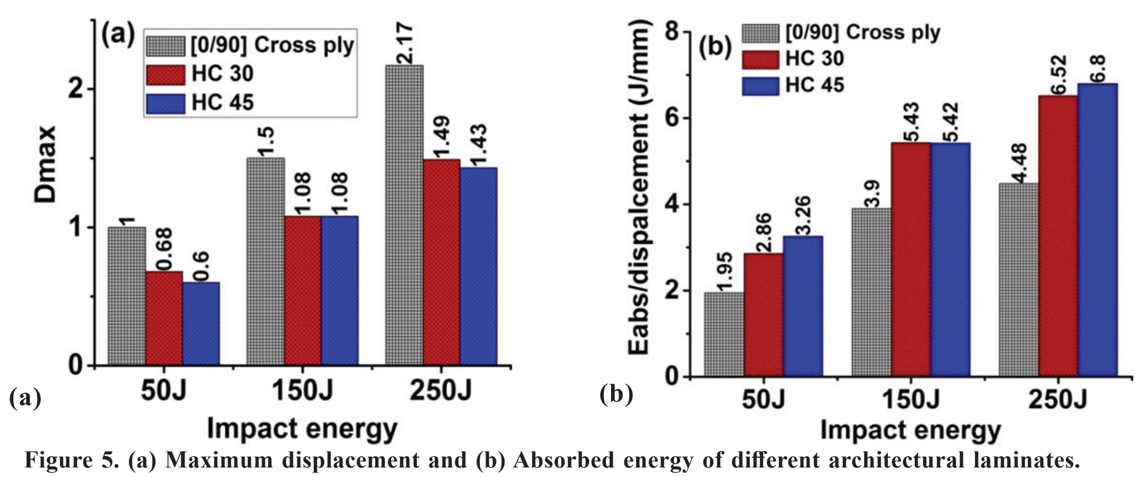
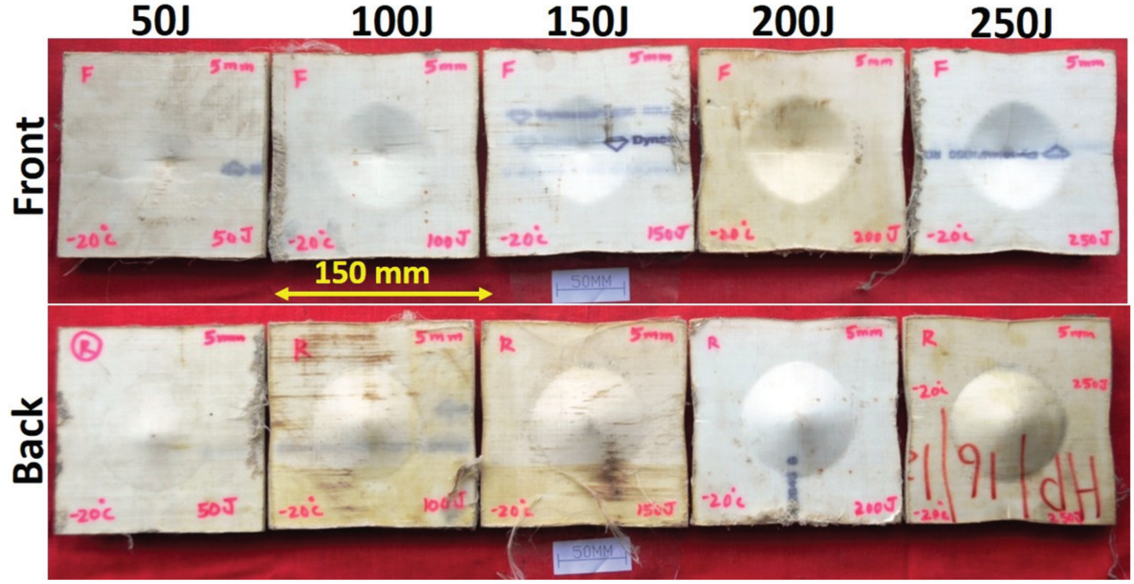
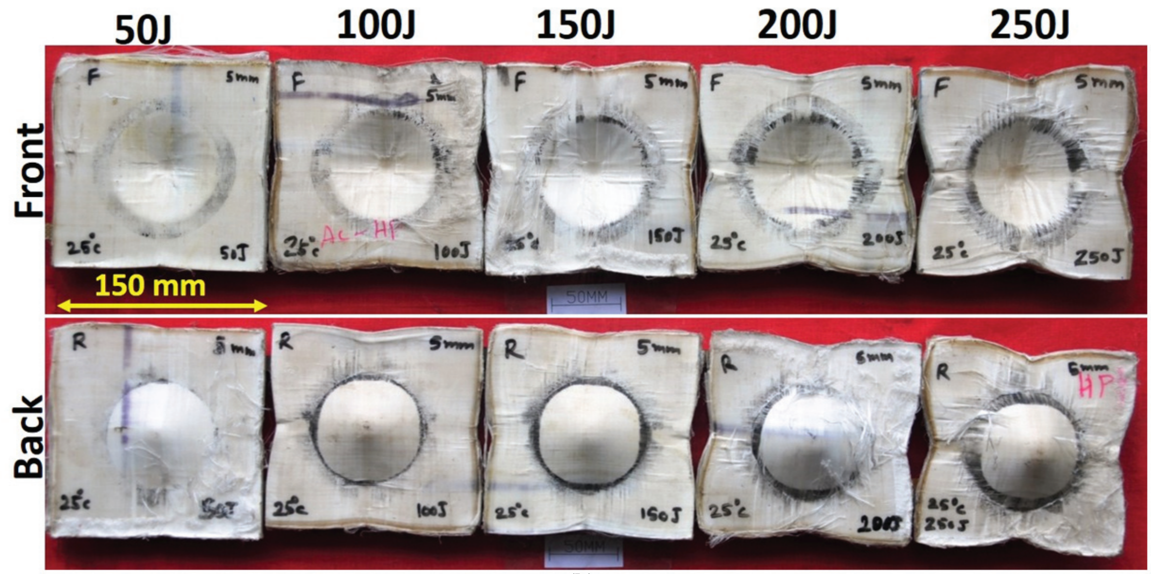


Figure 5. (a) Maximum displacement and (b) Absorbed energy of different architectural laminates.



(a)



(b)

Figure 6. Photographs of the laminates impacted at (a) -20 °C and (b) 25 °C at different energies.

relase of load, recoiling of chains will be restricted. Therefore variation in percentage of plastic deformation is observed significantly at higher testing temperature conditions.

3.2 Effect of Ply Angle

Effect of ply angle on the laminate energy absorption and its deformation behaviour was studied at temperature of 60 °C. Figure 4 shows force-displacement data of laminates impacted at three different energies. In the case of cross ply laminates, rebound of impactor was observed when impacted with 50 J and 150 J energy. When energy was increased to 250 J, the laminate deformed continually in ductile manner and no rebound was taken place.

Pull in of fibres at centre of boundaries was observed and this phenomenon has increased with increase in impact energy. Whereas in case of helicoidal laminates, rebound of impactor was observed even at 250 J impact energy, which indicates that the penetration resistance of laminates improved by changing the architecture of laminas. This can be attributed to the change in deformation mechanism of laminates. From the Fig. 4b-d it is clear that unlike cross ply laminates, deformation of helicoidal laminates took place in two stages. In the first stage sudden rise of force (increase in slope of curves) with limited displacement (0-6 mm) can be seen due to resistance for initiation of deformation. In second stage, the force got increased gradually as laminate deformed in ductile manner. Pull in of fibres took place at all directions instead of only from centre of boundaries. For comparison, F-D curve of cross ply laminate impacted at 25 °C is shown in Fig. 4(d) which clearly suggests that the penetration resistance of helicoidal laminate at 60 °C is comparable to the cross ply laminate tested at 25 °C. The study suggests that, change of ply angle led to the improvement of laminate stiffness, due to which there was no reduction in the efficiency of the laminate even at higher temperature.

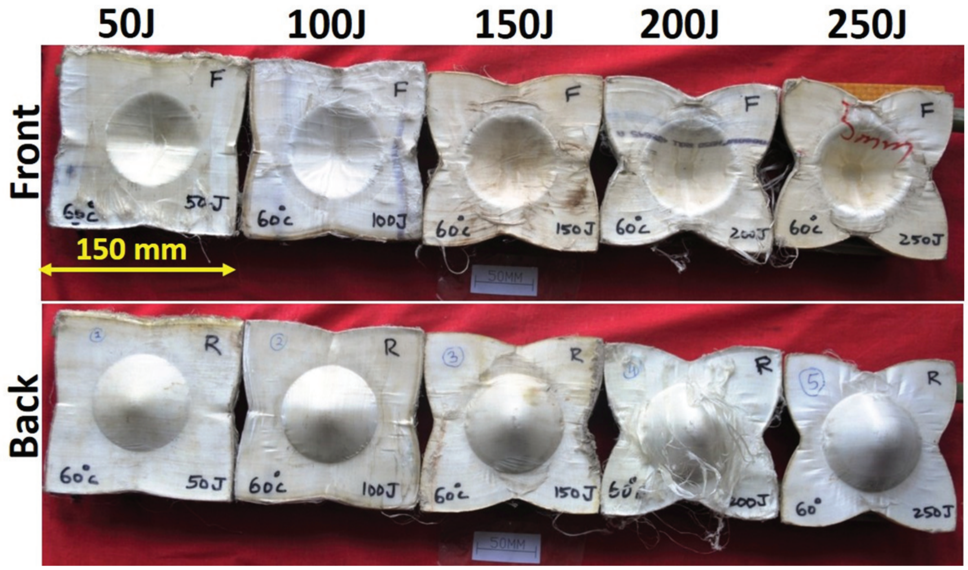


Figure 6. (c) Photographs of the laminates impacted at 60 °C at different energies.

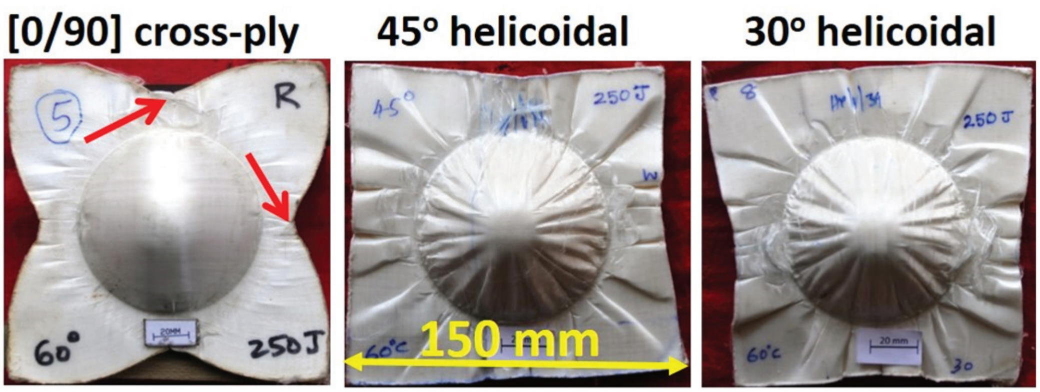


Figure 6. (d) Effect of ply angle on the damage behaviour at 60 °C.

Comparison of D_{max} at different impact energies is provided in Fig. 5. D_{max} of 0/90. cross ply laminates was taken as unity and other values were normalized for easy interpretation. From the figure it is clear that the presence of helicoidal architecture has reduced the D_{max} by about 30-40 % when compared to cross ply laminates. For instance, the D_{max} of angle ply laminates at 150 J and 250 J are comparable to cross ply laminates impacted at 50 J and 150 J respectively. Absorbed energy per unit displacement was calculated and plotted for different impact energies Fig. 5(b). It is observed from the figure that, helicoidal laminates exhibited about 40 % higher energy absorption compared to cross ply laminates for all impact energies.

In case of cross ply laminates, the primary fibres are arranged in 0° and 90° direction only. Hence the impact load was more focused in these two directions. Where as in case of helicoidal laminates, fibres are aligned in different angles (i.e. more than two directions). This has provided better bending stiffness of laminate which in turn helps in increase in resistance to deformation. Therefore, D_{max} of helicoidal laminates is lower than cross ply laminates. Higher absorbed energy of helicoidal laminates as compare to cross ply laminates can also be attributed to the increase in stiffness of laminate and thereby increase in resistance to deformation.

3.3 Failure Analysis

Photographs of impacted laminates at different temperatures and energies are shown in Fig. 6 a-c. Indentation at the point of impact (centre of the laminate) on the front surface was observed for all the laminates. Breakage of fibres was not seen in any of the experiments carried out in this study. Instead, laminates were deformed in the form of cone with the dia equivalent to the test fixture opening (i.e. 76.2 mm). As mentioned above, back face deformation increased with increase in impact energy and temperature. However, the effect of temperature was found to be more noticeable than the impact energy.

Impact of projectile induces the longitudinal stress waves in the laminate. These waves propagate along the primary fibres. On reaching the laminate free ends, these waves reflect back and effect the fibre pull-in[11,22-23]. In order to initiate the pull-in, the frictional force acting on the laminate due to pneumatic clamp must be overcome by the impact load on primary fibres. Pull-in of fibres at centre of laminate edges was observed in cross ply laminates and was diminished towards the corners of the laminate (shown with arrow in Fig. 6(d). It is obvious that in the cross ply laminates, the primary fibres are in 0° and 90° direction only. Hence the impact load was more focused on four locations where the primary fibres intersect

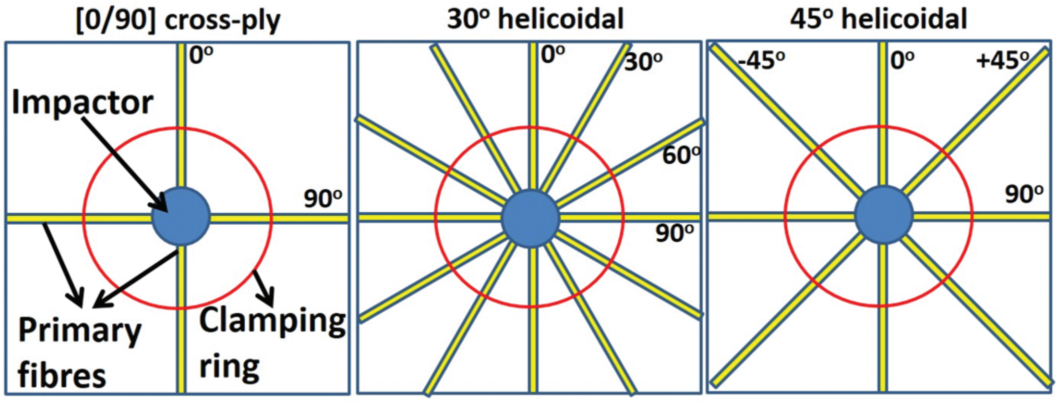


Figure 7. Schematic representation of laminates showing primary fibres in respective configurations.

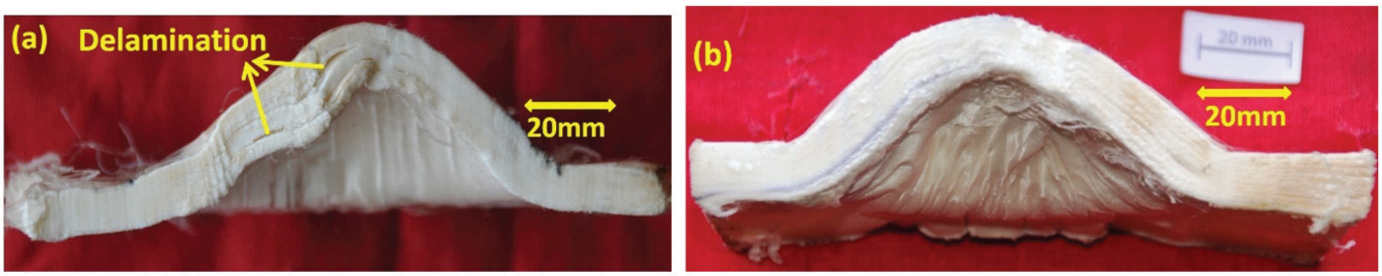


Figure 8. Cross section of impacted laminates (a) [0/90] cross-ply laminate (b) 30o helicoidal laminate.

the clamped boundary. The extent of pull-in is increased gradually with increase in impact energy which resulted in to the shape of butter-fly at highest impact energy. This effect can be seen clearly at 25 and 60 ^{o}C. Where as in the case of helicoidal laminates the pull-in of fibres was observed from different directions radially and hence more wrinkles can be seen on the laminate surface. The extent of wrinkling indicates the extent of material deflection and energy absorbed[24]. It is evident from the Fig. 5(b) that helicoidal laminates can sustain higher impact energy as compared to cross ply laminates. In helicoidal laminates, fibres are aligned in different angles and at different depth of levels in the laminate and all of them could engage the impactor in a better way while undergoing the deformation process. From the Fig. 7 it is evident that the number of primary fibres in a laminate is inversely proportional to the angle between the consecutive layers. Hence, helicoidal laminates are expected to have lower BFD and higher energy absorption capability due to the uniform distribution of load on large number of fibres. However, in the present study, no significant change in BFD and energy absorption was observed between H 30 and H 45 laminates. Hence, this needs further investigation by preparing the laminates with varying angles.

Figure 8 shows the cross section of impacted laminates. In case of cross-ply laminate (Fig. 8(a)), significant delamination (separation of layers / formation of gaps between the laminas) can be seen clearly. However, no sign of such damage was observed in helicoidal laminates with naked eye, though it might be present at microscopic level.

4. CONCLUSIONS

Ultra high molecular weight polyethylene composite laminates of 5 mm thickness were fabricated and subjected to low velocity impact at different energy levels and temperatures. It was found that peak force of laminate decreased by 25 % and 42 % respectively at 25 ^{o}C and 60 ^{o}C temperatures as compared to -20 ^{o}C due to reduction in laminate stiffness. Maximum displacement was increased linerly with increase in impact energy whereas it increased exponentially with respect to temperature due to the softening of the laminate at higher temperature and % of recovery in the deformation got reduced with increase in temperature. Presence of different ply angles in the laminate construction can significantly improve the laminate behaviour under low velocity impact conditions by increasing the energy absorption and reducing the maximum displacemnt. Post impact analysis showed that fibre pull-in, stretching of fibres, delamination and wrinkling are major deformation mechanisms. Inputs of this study are very useful for designing an armour especially for personnel protection even for those deployed in various temperature conditions.

REFERENCES

1. Hearle, J.W.S. High-performance fibres. Woodhead Publishing, Cambridge, 2001. doi:10.1533/9781855737549
2. Cunniff, P.M. An analysis of the system effects in woven fabrics under ballistic impact. *Text. Res. J.*, 1992, **62**(9), 495–509. doi:10.1177/2F004051759206200902
3. Cunniff, P.M. A semi empirical model for the ballistic impact performance of textile-based personnel armor. *Text. Res. J.*, 1996, **66**(1), 45–58. doi:10.1177/2F004051759606600107
4. Cunniff, P.M. Dimensionless parameters for optimization of textile-based body armor systems. *In* Proceedings of the 18th International Symposium on Ballistics. San Antonio, Texas, 1999. p. 1303–1310.

doi: 10.4236/ojfd.2021.112006
5. Cunniff, P.M. A design tool for the development of fragmentation protective body armor. *In* Proceedings of the 18th International Symposium on Ballistics. San Antonio, Texas, 1999. p. 1295–1302.
6. Hazzard, M.K.; Hallett, S.; Curtisa, P.T.; Iannucci, L. & Trask, R.S. Effect of fibre orientation on the low velocity impact response of thin Dyneema composite laminates. *Int. J. Impact. Eng.,* 2017, **100**, 35-45. doi:10.1016/j.ijimpeng.2016.10.007
7. O'Masta, M.R.; Russell, B.P.& Ronan, W. Inter-ply angle influence on the out-of-plane compressive response of polyethylene laminates. *Compos. Part A.,* 2018, **110**, 11-20. doi:10.1016/j.compositesa.2018.03.032
8. Zhang, T.G.; Satapathy, S.S.; Vargas-Gonzalez, L.R. & Walsh, S.M. Ballistic impact response of Ultra-High-Molecular-Weight Polyethylene (UHMWPE). *Compos. Struct.* 2015, **133**, 191–201. doi:10.1016/j.compstruct.2015.06.081
9. Nguyen, L.H.; Ryan, S.; Cimpoeru, S.J.; Mouritz, A.P. & Orifici, A.C. The effect of target thickness on the ballistic performance of ultra high molecular weight polyethylene composite. *Int. J. Impact. Eng.* 2015, **75**, 174-183. doi:10.1016/j.compstruct.2015.06.081
10. Vargas-Gonzalez, L. & Gurganus, J.C. Hybridized composite architecture for mitigation of non-penetrating ballistic trauma. *Int. J. Impact. Eng.* 2015, **86**, 295-306. doi:10.1016/j.ijimpeng.2015.08.014
11. Karthikeyan, K.; Kazemahvazi, S. & Russell, B.P. Optimal fibre architecture of soft-matrix ballistic laminates. *Int. J. Impact. Eng.* 2016, **88**, 227–237. doi:10.1016/j.ijimpeng.2015.10.012
12. Wang, H.; Hazell, P.J.; Shankar, K. Morozov, E.V. & Escobedo-Diaz, J. Impact behaviour of Dyneema® fabric-reinforced composites with different resin matrices. *Polym. Testing,* 2017, **61**, 17-26. doi:10.1016/j.polymertesting.2017.04.026
13. Wang, H.; Weerasinghe, D.; Hazell, P.J.; Mohotti, D.; Morozov, E.V. & Escobedo-Diaz, J. Ballistic impact response of flexible and rigid UHMWPE textile composites: Experiments and simulations. *Def. Technol.* 2022 In Press. doi.org/10.1016/j.dt.2022.08.009
14. Lässig, T.R; May, M.; Heisserer, U.; Riedel, W.; Bagusat, F.; Van der Werff, H. & Hiermaier, S.J. Effect of consolidation pressure on the impact behavior of UHMWPE composites. *Compos. Part B*. 2018, **147**, 47-55. doi:10.1016/j.compositesb.2018.04.030
15. Asija, N.; Chouhan, H.; Gebremeskel, S.A.; Singh, R.K. & Bhatnagar, N. High strain rate behavior of STF-treated UHMWPE composites. *Int. J. Impact. Eng.* 2017, **110**, 359-364. doi:10.1016/j.ijimpeng.2017.02.019
16. Hu, Y.; Shi, Y.; Liu, D.; Guo, J.; Zhang, J. & Chen, Z. Damage tolerance of 2-dimentional UHMWPE/CF hybrid woven laminates subjected to low-velocity impact. *Mater. Des.,* 2020, **191,** 108604. doi.org/10.1016/j.matdes.2020.108604.
17. Hu, Y.; Liu, D.; Guo, J.; Shi, Y. & Shan, C. Low-velocity impact damage research on 2-dimentional UHMWPE/CF hybrid woven laminates under preloading. *Thin Walled Struct.* 2021, **161**, 107472. doi.org/10.1016/j.tws.2021.107472
18. Hu, Y.; Shi, Y.; Liu, D.; Guo, J. & Zhang, J. Low-velocity impact damage tolerance of ultra high molecular weight polyethylene/carbon fibre laminates under pre-stress. *Polym. Compos.,* 2022, **43**, 712-729. doi.org/10.1002/pc.26404
19. Sreekantha Reddy, T.; Ramasubba Reddy, P. & Madhu, V. Low velocity impact studies of E-glass/epoxy composite laminates at different thicknesses and temperatures. *Def. Technol.* 2019, **15**, 897-904. doi:10.1016/j.dt.2019.02.003
20. ASTM. Standard test method for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop-weight impact event. D7136 / D7136M, West Conshohocken, PA. 2007. p.1-16.
21. Gowariker, V.R; Viswanathan, N.V. & Sreedhar, J. Polymer Science. New Age International, New Delhi, India, 1986. ISBN:0852663074
22. Crouch, I.G. Introduction to armour materials. *In* The Science of Armour Materials, edited by I.G. Crouch. Woodhead publishing, Cambridge, UK, 2017. pp. 1-54. doi:10.1016/B978-0-08-100704-4.00001-3
23. Hazell, P.J. Armour: Materials Theory and Design, CRC Press, Boca Raton, Finland, 2016. p. 137-175. doi:10.1557/mrs.2016.155
24. Wang, H.; Hazell, P.J.; Shankar, K.; Morozov, E.V.; Escobedo-Diaz, J. & Wang, C. Effects of fabric folding and thickness on the impact behaviour of multi-ply woven fabrics. *J. Mater. Sci.* 2017, **52**, 13977-13991. doi:10.1007/s10853-017-1482-y

CONTRIBUTORS

Mr T. Sreekantha Reddy is working as a Scientist 'D' in DRDO-DMRL. His area of research includes: Development of composite armour materials and their evaluation for high velocity and low velocity impacts.
His contribution in the current study is Planning the experiments, interpretation of results and writing of draft manuscript.

Dr P. Rama Subba Reddy is working as a Scientist 'F' at DRDO-DMRL. His area of research includes: Development of composite armour materials and its ballistic evaluation.
His contribution in the current study is: Design of experiments and reviewing the manuscript.

Dr Vemuri Madhu is a Retd. Scientist 'H' at DRDO-DMRL. His research interests are in the areas of ceramic and composite armour development, modelling and simulation of ballistic phenomena, high strain rate characterisation, blast and shock studies on armour materials.
His contribution in the current study is: Overall guidance and time to time suggestions for improving the quality of this study