Influence of nanoclay and incident energy on impact resistance of S2-glass/epoxy composite laminates subjected to low velocity impact

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Abstract

S2-glass/epoxy composite laminates were made by varying the nanoclay content from 0-12% by weight and were subjected to low velocity impact at 50 J, 110 J and 150 J incident energy respectively. It is observed that at 50 J impact energy, which is below penetration limit of laminate the presence of nanoclay could not add any advantage in total energy absorption. As the impact energy increased to 110 J (near penetration limit), nano composite laminates have shown 37% improvement in energy absorption compared to pristine laminate. Composite with 9% nanoclay has shown optimum performance in terms of energy absorption, penetration limit velocity and decrease in maximum displacement. Further increase of impact energy upto 150 J (above penetration limit) has not resulted in any improvement in energy absorption. Post impact analysis reveals that the total damage area of laminates increased with increase in impact energy and nanoclay content. Fractured area of impacted laminates calculated and observed that the fractured area of laminate decreased with increase of nanoclay content. Present study highlights that besides optimum nanoclay content, optimum impact conditions also play a vital role in deriving benefits of nanocomposites. Copyright © 2016 VBRI Press.

Keywords: S2glass, nanoclay, low velocity, composite laminate, energy absorption.

Introduction

One of the challenging tasks to improve the maneuverability of fighting vehicles is to reduce the weight of the vehicle. To achieve this objective, various advanced polymer composites were explored to replace heavy steel structures. These polymer composite structures are intended to perform on par with their steel counterparts by playing a dual role of not only protecting the vehicle against different impact loads encountered during its operation but also serve as protection against various munitions [**1**]. Advanced fibers like glass, aramid and high molecular weight polyethylene are reinforced in thermoset or thermoplastic polymer matrices and tested to weigh up their performance either as structural armour or as a part of add-on ceramic composite armour for light weight combat vehicles [**2-3**]. Among these polymer composites, glass fibre reinforced composites are preferred by armour fraternity for various application due to their abundant availability, low cost and favourable wetting characteristics against different resin systems.

The important aspect in design of composite structure is the magnitude of damage tolerance of the structure which is influenced by its toughness. The toughness of the composite plays a key role in energy absorption under dynamic loads and is highly dependent on strain rate. There are many ways to improve the toughness of thermoset matrix such as by incorporating rubber toughners into the matrix. However, problem with rubber toughners is that their addition leads to inferior mechanical properties which is an unfavourable factor in accepting the material from structural point of view for armoured fighting vehicles. On the other hand, many nanoscale fillers like carbon nanotubes, carbon nanofibers, graphite platelets, nanoclay are found to be promising candidates for making composites with increased impact performance [**4-7**]. Few studies examined on the use of nanoparticles to improve the impact response of composites [**8-9**]. Aymerich *et al.* studied the impact response of standard and modified clay with glass/epoxy laminates. The studies showed that the modified laminates exhibit improvement in energy absorption over standard laminates [**10**]. Studies have been reported on effect of nano clay on Izod impact and other properties of E-glass/epoxy composite laminates and found that 3% and 5% by weight nanoclay gives maximum improvement in impact resistance [**11-13**]. Antonia *et al.* studied the effect of montmorillonite (MMT) silicate layers on performance of glass/epoxy composites under low-velocity impact. Their study suggested that the addition of clay has decreased delamination and increased damping capacity during the rebounds and also reported shifting in failure mode of laminate from interlaminar to intralaminar [**14**]. A comprehensive review presented by lingyu sun et al on-energy absorption capability of nanocomposites has covered the effect of particle stiffness, particle geometry, particle size, energy absorption mechanisms and simulation of energy absorption of nanocomposites [**15**].

Though some reports are available on performance of S2-glassfiber/nanoclay/epoxy composites under low velocity impact loadings, effect of clay addition on laminate penetration limit velocity, displacement, bending stiffness, energy absorption, total damage area and fracture area when subjected to above and below the penetration limit energy was not studied in detail. Since S2 glass fabric is an important material for structural as well as for add-on composite armour applications for different combat vehicles, present study is aimed to understand the behaviour of these composites under low velocity impact loads and their failure analysis.

Experimental

Materials and methods

Nano composite laminates were manufactured from S2 glass and nanoclay filled epoxy resin system. The reinforcement fabric in these laminates was S2 glass plain woven roving of 830-840 gsm supplied by M/s. BGF Ltd, USA. Epoxy resin system was made of diglycidyl ether of bisphenol (LY556) and hardener (HY5200) was supplied by M/s. Huntsman chemicals. Organo modified montimorillonite (MMT) nanoclay (nanomer1.30E) was supplied by M/s. Aldrich chemicals pvt Ltd, Mumbai. Initially nanoclay powder was dispersed in the resin system with 0% 5%, 9% and 12% by weight through ball milling followed by mechanical mixing. Later, hardener was added to the resin/clay mix as per given ratio and applied uniformly on glass fabric to obtain a prepreg. Laminates were manufactured through hand layup technique followed by hydraulic pressing at 120° C for 3 h followed by 160° C for 3h under 40 bar pressure. Thickness of laminates was controlled at 4±0.2 mm. Specimens were cut in to the dimensions of 125 x125 mm for impact tests. Fiber volume fraction was maintained at 54±1% for all the combinations. Before carrying out impact tests dispersion of nanoclay in the laminate was observed through environmental scanning electron microscopy (ESEM, Quanta 400) at a voltage 15-20 kV. For ESEM studies specimens of size 10 x 10 mm were cut by using diamond wheel cutting machine followed by ultrasonic cleaning.

Low velocity impact tests

Low velocity impact tests were carried by using instrumented drop weight impact tester of Ceast-Instron make (CEAST- 9350). Hemi spherical steel impactor having 12.7 mm diameter was used to carry out tests. The striker impactor is fitted with a force transducer of 45kN capacity which measures the resistance offered by the specimen to the projectile during the impact. Data acquisition system with a sampling rate of 500 kHz was used to record the force–time history. Required impact energy was obtained by dropping the impactor tup of specific mass from a predetermined height. Using the force-time data, parameters like absorbed energy, displacement, velocity were calculated through the application software integrated with the equipment [**16**]. Prior to actual impact tests, pristine specimen was subjected to different impact energies ranging from 50 J - 200 J and generated an energy profile diagram. Based on the distinct behaviour of the laminate three different incident energies i.e. 50 J, 110 J, & 150 J were selected for low velocity impact tests. The response of laminates in terms of energy-time, force-displacement and velocity-time is compared between the afore mentioned impact energies. A minimum of five samples were tested for each type of laminate at each energy level.

Failure analysis

Post impact damage characterization of the laminates was done through visual observations and backlit reflection photography to estimate the damage area where the delaminated portions will lose translucence which gives identification of delaminated area [**17**]. Damage area and fractured area of the laminates were measured and correlated with respect to the impact energy and nanoclay content.

Results and discussion

Dispersion of nanoclay in laminate

Fig. 1 shows ESEM images of nanoclay/S2glass/epxoy laminates. It is observed that distribution of clay in the laminate is uniform upto 9% **(Fig. 2 (c))** whereas at 12% addition (**Fig. 2(d)**) agglomeration of clay particles are seen.

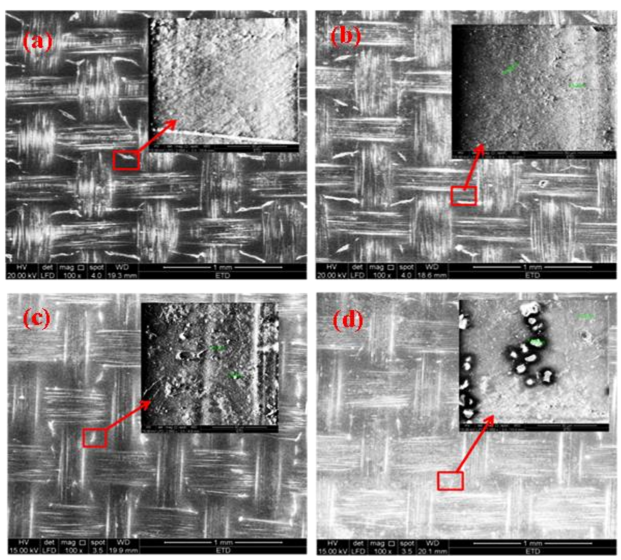

Fig. 1. SEM images of different nanoclay content composite laminates (a) 0% (b) 5% (c) 9% (d) 12%.

Energy – time response

Energy-time curve indicates how the energy is absorbed during the impact event as a function of time. Energy absorbed by the specimen can be calculated as follows. In case of non-perforated samples, the total absorbed energy (E_a) is the sum of energy dissipated (E_d) due to damage in the specimen and the rebound energy (E_r) [**19-20**]. In case of perforated samples part of impact energy is absorbed for complete perforation of the target and rest is absorbed as frictional energy (E_f) between lateral surface of the impactor and target. **Fig. 2** shows energy profile diagram for the pristine laminate. This diagrams is useful in identifying the penetration and perforation threshold of the laminate. From **Fig. 3** it can be seen that the penetration and perforation energies of pristine laminate are 80J and 90J respectively.

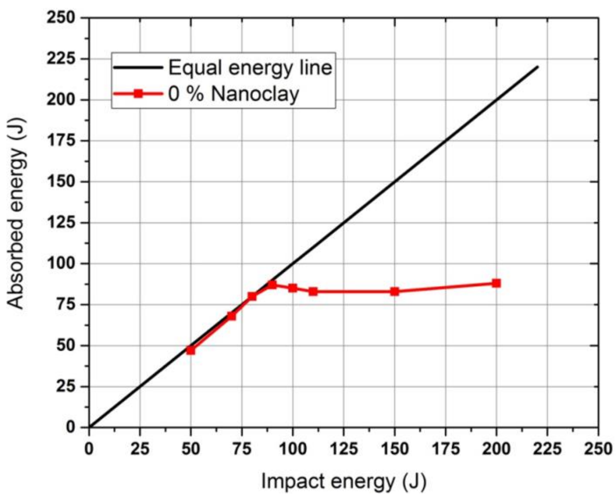

Fig. 2. Energy profile diagram for pristine laminate.

Fig. 3(a) - 3(c) show energy-time curve for the laminates impacted at 50 J, 110 J and 150 J respectively. It is observed that at 50J impact energy **(Fig. 3(a))** which is below the laminate penetration limit energy the impactor got rebounded. Therefore, at this energy all the laminates have shown similar performance with complete energy absorption. At 110 J impact energy **(Fig. 3(b))** the laminates have behaved entirely different. For instance, pristine laminate and 5% nano composite have shown two stages in energy-time curve which is due to complete penetration of impactor. The first stage is related to the energy absorbed by the laminate through delamination, fiber failure and the second stage corresponds to the frictional energy between the impactor and broken fiber layers. Absorbed energy for pristine and 5% nanoclay composite laminates is found to be 80 J and 90 J respectively. Further addition of nanoclay (9%) has shown improvement in energy absorption upto 110 J and also observed rebounding of impactor. This indicates that the laminate has got further energy absorption capability. It may be due to effective transfer of load in transverse direction with increased resistance and stiffness of the laminate. However, at 12% addition of nanoclay the laminate absorbed 110 J and neither rebound nor perforation was observed hence energy-time curve has become flat. It may be due to agglomeration effect of nanoclay. The study has shown that the addition of 9% nanoclay gives optimum (37%) improvement in energy absorption with rebound of impactor. However, at 150J impact energy **(Fig. 3(c))** all the laminates were perforated and have shown two stages in energy-time curve. Pristine laminate has shown 80 J and 135 J for absorbed energy and frictional energy respectively whereas nano composite laminates (5% and 9%) have shown 110 J and 150 J for absorbed and frictional energy respectively and 12% nanoclay addition to the laminate has shown decrease in frictional energy. Increase in absorbed energy with respect to nanoclay content at different impact energies is shown at **Fig. 3(d).** It is observed that absorbed energy increased with increase of impact energy upto 110 J and also with clay content upto 9%.

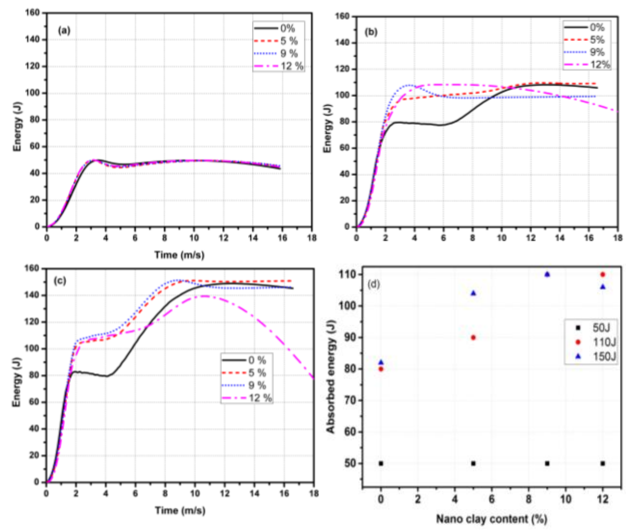

Fig. 3. Energy–time response at (a) 50 J (b) 110 J (c) 150 J and (d) absorbed energy.

Force – displacement response

Displacement of impactor in the sample gives an idea about materials resistance to impact and structural degradation history of composite. It also gives an indication of whether mode of failure is brittle or ductile. Force-displacement curve and penetration details of the laminates subjected to different impact energies are given in **Fig. 4 & Table 1**.

Table 1. Effect of nanoclay on rebound and penetration behaviour of laminate at different impact energies.

Nanoclay content	50 J	110 J	150 J	Remarks
0%	R	P	P	Penetration limit: 80J
5%	R	P	P	Penetration limit: < 110 J
9%	R	R	P	Penetration limit: > 110 J
12%	R	PP	P	Penetration limit:110 J

Final displacement is taken at a point where force will come back to zero kN after reaching its maximum value in force-displacement curve. If the impactor is rebounded, then a closed loop type of force-displacement curve is observed otherwise the curve will be open. At 50 J impact energy **(Fig. 4(a))** all the laminates have shown closed loop curve due to rebound of impactor (**Table 1**). It may be attributed that at this impact energy laminates have undergone only elastic deformation with complete recovery of impactor and there is no plastic deformation. At 110 J impact energy **(Fig. 4(b))** pristine laminate and 5% wt nanoclay laminate have shown open curve due to complete penetration of impactor and their penetration energies are below the incident energy **(Table 1)**. Further addition of nanoclay upto 9% wt has shown closed loop curve since the rebound of impactor was occurred and penetration energy would be higher than the incident energy. However, 12% nanoclay addition has shown just open curve which indicates partial penetration. At 150 J impact energy **(Fig. 4(c))** all the laminates have shown open curves due to perforation of impactor.

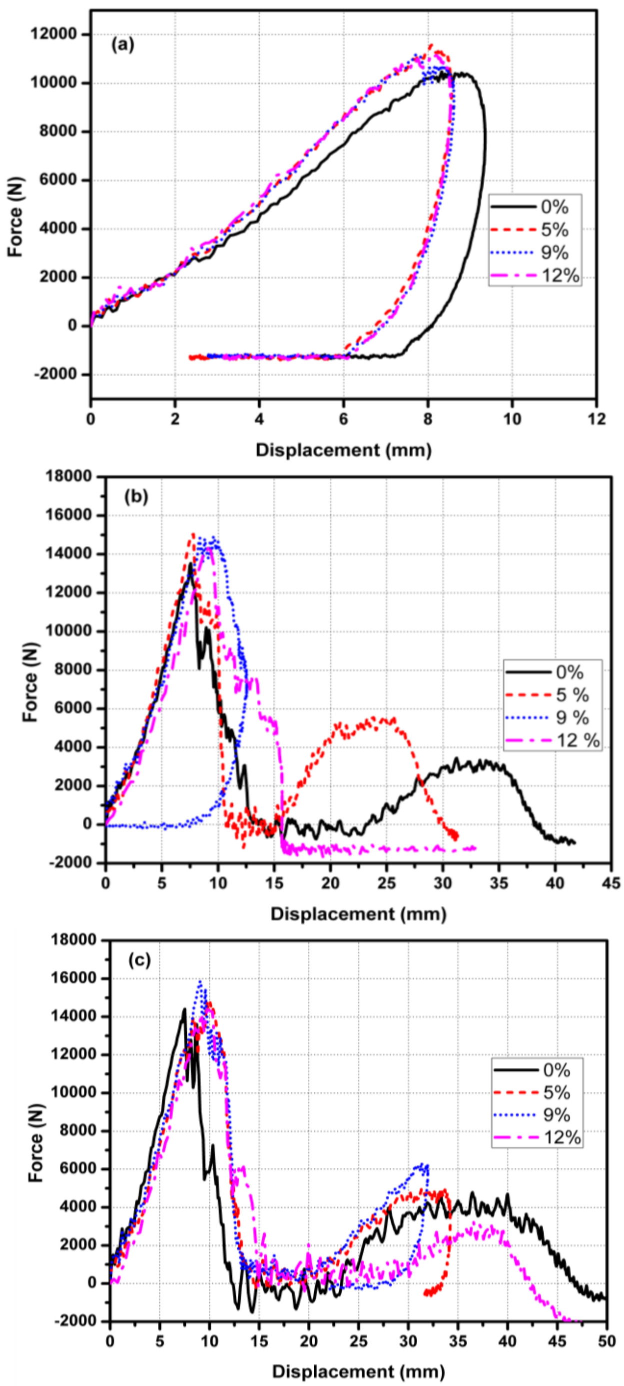

Fig. 4. Force Vs displacement for laminates impacted at (a) 50J (b) 110J (c) 150J.

At 50 J impact energy, pristine laminate has shown about 9mm maximum displacement and addition of nanoclay has not shown any significant change in displacement **(Fig. 5)**. At 110 J impact energy, addition of nanoclay has increased the penetration displacement except at 9% where rebound of impactor was observed. Further increase of impact energy to 150 J penetration displacement increased with increase of nanoclay content for all the combinations. The penetration displacement is an indicator for deformation capacity of laminate. Therefore, addition of nanoclay increased the strain capacity of the laminates prior to perforation [**15**].

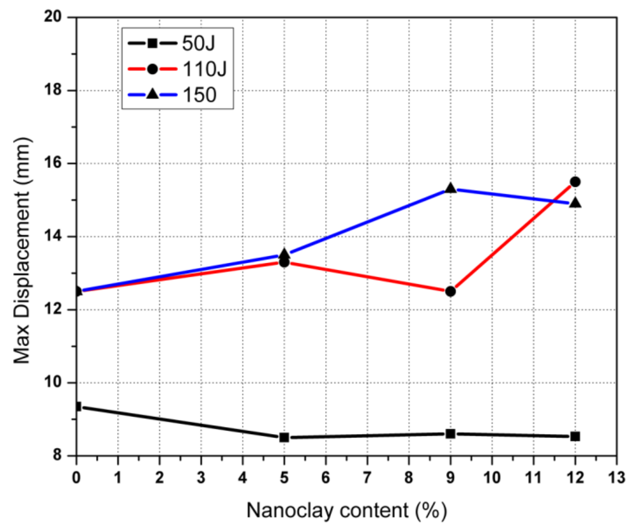

Fig. 5. Maximum displacement - nanoclay content under different impact energies.

Velocity –time response

Velocity-time curve indicates the deceleration of impactor during penetration into the specimen. The positive values for the velocity represent downward motion of the striker while the negative values represent upward motion due to striker rebound. **Fig. 6** show typical velocity-time response of laminates subjected to 110 J impact energy.

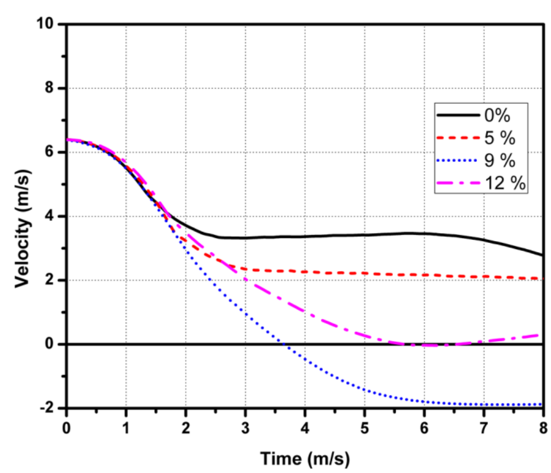

Fig. 6. Velocity-time response of nanocomposites subjected to 110 J.

The positive values for the velocity represents downward motion for the impactor while the negative values represent upward motion due to striker rebound. Penetration limit velocity of different laminates subjected to various impact energies were calculated and given in **Table 2,** [**15**]. **Table 2** shows the change in penetration limit velocity of laminates with increase of impact energy and clay content. Penetration limit velocity of laminates could not be determined at 50 J impact energy since it is below the laminate penetration limit energy. At 110 J impact energy, laminates have shown increase of penetration limit velocity from 3.08 m/s to 6.5 m/s with addition of nanoclay however, for 9% nano clay addition penetration limit velocity could not be calculated as the impactor got rebounded. Similar trend is observed at 150 J impact energy also where penetration limit velocity increased from 2.39 m/s to to 3.5 m/s with increase of nanoclay content [**16**]. Laminates shown lower penetration limit velocities at 150 J as compared to 110 J this may be due to increase of rate of loading.

Table 2. Parameters of nano composites under different low velocity impact energies.

Impact energy (J)	% Nanoclay	Peak force (N)	Absorbed energy (J)	Penetration limit (m/s)
50	0	10402	50	*
	5	11403	50	*
	9	11184	50	*
	12	10950	50	*
110	0	14138	80	3.08
	5	15012	90	3.30
	9	14927	110	*
	12	14502	110	6.5
150	0	13759	82	2.39
	5	14749	104	2.5
	9	15863	110	3.5
	12	14939	106	3.5

** No complete penetration*

Post impact analysis

Visual inspection of impacted laminate revealed various damage modes like matrix cracking, fibre damage, indentation and radial delamination. It can be assumed that energy is dissipated by the sample through plastic and elastic deformation. Back lit photographs of impacted laminates subjected to different impact energies are given in **Fig. 7.** From the images, it is observed that failure behaviour of the laminates varied with increase of clay content. For all the impacted energies, two regions are observed on back side of the laminate and marked as inner and outer circles. Inner circle represents the fractured area (A_f) of the laminate which is directly underneath of impactor and outer circle represents the total damage area of laminates. **Fig. 8** represents the change in fractured area and total damage area with addition of nanoclay respectively.

It can be observed that, as the percentage of nanoclay content increased *i.e.*, upto 9% the damage diameter of fractured area decreased **(Fig. 8(a))** this may be due to increased stiffness and effective transfer of load in transverse direction to the surrounding fibers. Hence the fibers beneath the impactor have survived and thus fractured area has decreased. Further increase of clay (12%) has not given any improvement in reduction in fractured area.

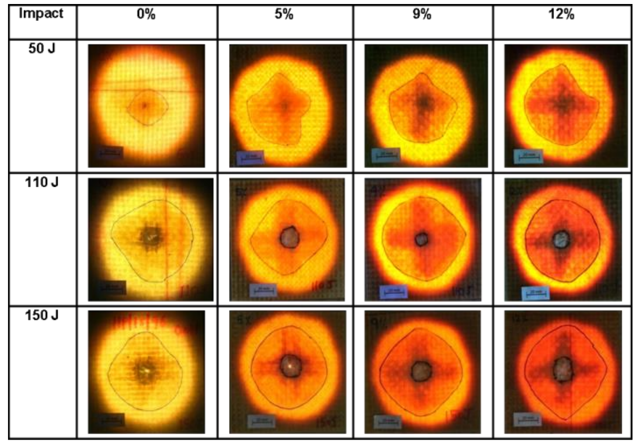

Fig. 7. Backlit images of different nanocomposite laminates subjected to different impact energy.

This effect is seen to be similar for 110 & 150 J impact energies. The second region (outer circle) which is in transverse direction to the impact spot is mainly due to delamination (A_{del}). It is calculated by subtracting fractured area from total damage area (A_d). From Fig.8b it is seen that total damage area (A_d) increased with increase of clay content. This shows that the presence of clay in laminate supports for more energy absorption by undergoing more delamination through quick dissipation of energy in transverse direction. Therefore, it protects the failure of fibres below the penetrator by spreading the energy on a larger area.

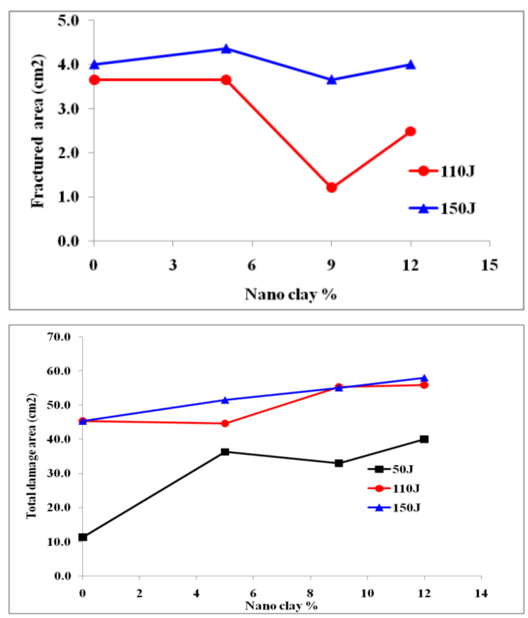

Fig. 8. Effect of Nano clay on fractured area and damage area of the laminates.

However, as the clay content increased to 12% this effect has reached a saturation stage since total matrix content in the laminate is only 20% (wt/wt) which may not be sufficient to wet the entire surface area of reinforcement. Hence further addition of clay has not yielded any increase in damage area.

Conclusion

Low velocity impact response of S2-glass/epoxy/nanoclay composites at three different impact energies were studied by varying the nanoclay content from 0 to 12% by weight. It is observed that below penetration energy (50 J) addition of nanoclay contributes for reduction in laminate displacement due to increased laminate stiffness. Whereas the above penetration limit (150 J) the presence of nanoclay supported for increased laminate displacement due to high failure strain of the laminate with increased elastic-plastic nature. At threshold penetration energy (110 J) laminates have shown improvement in performance in terms of energy absorption and penetration limit velocity, 9% wt nanoclay is found to be optimum. The effect of nanoclay is more significant at 110J energy than the other two impact energies since it is close to the laminate penetration energy. Failure analysis of laminates has shown that fractured area of the laminate decreased with increase of nanoclay content whereas total damage area has increased with increase of nanoclay content and impact energy. Hence it can be concluded that not only optimum nanoclay content but optimum impact conditions also play an important role to get maximum advantages of nano composites.

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