Energy Absorption and Low-Velocity Impact Performance of Nanocomposites: Cones and Sandwich Structures

James Njuguna, Sophia Sachse and Francesco Silva

Abstract The increasing need for high performance structures, in the energy and transport industry, demands a continuous development of new engineering materials. Unique mechanical properties together with low specific weight can be achieved by the combination of various constituent materials into one macroscopic composite material. Coupling of the high strength reinforcement with supporting matrix creates a novel material with the improved characteristics, which could never be obtained using either of the constituents separately. These types of materials are particularly desirable in structures where a high strength to weight ratio is of great importance. In this chapter, two case studies are provided one on nanophased sandwich composites with polyurethane/layered silicate foam cores and the other on thermoplastic glass-fibre and nano-silica reinforced nanocomposites.

1 Introduction

Over the last decade increased amount of research in the field of composite materials proved that addition of nano-sized fillers, rather than micro-sized fillers, can significantly enhance mechanical properties of the polymeric materials. Composite material is usually defined as a 'nano', if one of the constituents possess at least one dimension in the range of 1–100 nm. The unique properties, of the material reinforced with nano-particles, come from the large number of interfacial effects, existing due to the high surface-area-to-volume ratio of the

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reinforcement. For the spherical nano-particles and nano-fibres this ratio is irreversibly proportional to their radius, and its value can be even up to 1,000 m^2/g. In case of light weight structures, the most widely used nano-reinforcements are silica based particles, due to their good mechanical properties and high thermal stability [1].

Up to date, research works have been conducted to study the influence of the nano-particles on the mechanical behaviour of polymer composites. Several factors influencing the enhancing capabilities of the nano-reinforcements were studied in the literature [2–4]. This includes key parameters such as shape and size of nano-fillers, matrix and reinforcement material, interfacial strength and interphase characteristics, as well as volume fraction and quality of dispersion within the matrix. Mechanical properties and energy absorption characteristics of nanocomposites have been mainly characterized by means of tensile, flexural or Izod impact testing.

2 Energy Absorption of Composite Materials

Modern vehicle structures must be able to withstand severe impact loads, at the same time providing safety of the occupants. That is why structural materials used for crashworthy applications must be characterized by the energy absorption capability. In order to ensure survivability of the accident, structure has to dissipate energy in a controlled manner. This is limited by the two factors: induced decelerations and maintaining of a survival space for occupants during a crash [5]. Energy absorbed throughout a collision is defined by the area under the load–displacement curve as shown in Fig. 1 [6].

Analyzing the above graph we can notice that the energy absorbed can be controlled by the value of the force and the deflection. The maximum peak load is limited by the occupants' tolerance and the maximum deflection is limited by the geometry of the structure. In an idealized energy absorbing system induced load should be constant and just below the human tolerance limit. In reality design of

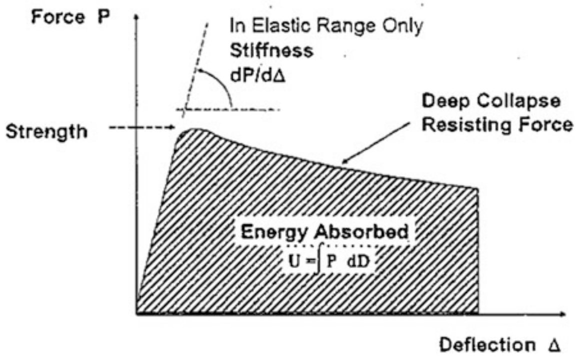

Fig. 1 General load–displacement curve [6]

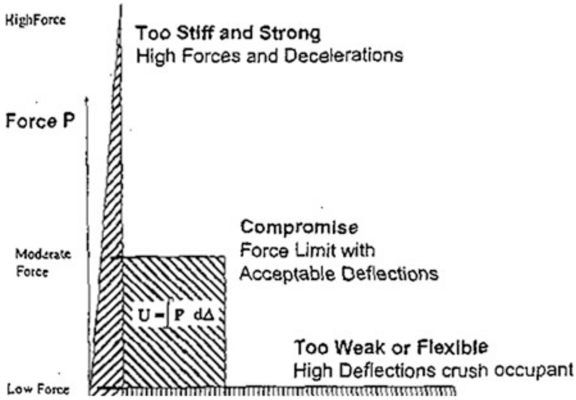

Fig. 2 Various structural responses [6]

crashworthiness structure is always a compromise and trade off. As an example three different structural responses are compared in Fig. 2. In the scenario with very stiff structure induced peak loads can highly exceed allowable limit. In such case occupants will suffer high decelerations while deformations of the structure are small. In case of the weak structure induced peak loads are strongly reduced but large deformations can crash the occupants causing serious injuries or even death. The third scenario is a compromise with the moderate value of the force and acceptable deflections not affecting occupants' space. In this scenario energy absorbed by the structure is maximized but within the limits of allowable load and deformation.

Traditionally metallic materials have been applied for the crashworthy structures due to their ability to sustain plastic deformations. In contrast, composite materials do not exhibit plastic deformations as they are usually brittle. However, if they are properly designed, they can absorb high amounts of impact energy by the progressive failure and delamination.

In order to facilitate a comparison of various crashworthiness materials, several measuring parameters are commonly used, and the most important ones are the specific energy absorption (SEA) parameter and the energy absorption efficiency. The specific energy absorption (SEA) parameter is defined by the amount of energy absorbed per unit mass of crushed material.

$$SEA = \frac{energy\_absorbed}{crashed\_mass} = \frac{\int Fdx}{m_c}$$

where F—load, x displacement.

The energy absorption efficiency (EAE) is defined by the ratio of the area under the load–displacement (true energy absorbed) curve to the rectangular area formed by the maximum load and maximum displacement (perfect energy absorbed).

$$EAE = \frac{energy\_absorbed}{\max\_load * \max\_displacement} \cdot 100$$

The most widely used method to evaluate the ability of a composite material to absorb the energy, is axial collapse of a structural elements. This technique has been applied by many researchers, on various composite materials.

The ability of a composite structure to absorb energy is highly dependent on the mode of fracture. Materials which fail in a progressive manner, with extensive delamination and fragmentation, are able to absorb much higher energies than those materials which tend to fail in a brittle manner. Farley [7–9] found that thermoset composites reinforced with glass and carbon fibres fail progressively in fragmentation and splaying modes. On the other hand, thermoset tubes reinforced with Kevlar, failed in a progressive folding mode. Mamalis et al. [5] who studied polyester cones, cylinders and tubes, reinforced with random orientated glass fibres, divided failure of the samples into four modes: progressive crushing with microfragmentation (Mode I), brittle fracture with catastrophic failure (Mode II and III, depending on the crack form), Progressive folding and hinging, similar to the metallic tubes (Mode IV). The authors observed that significant influence on fracture mode has geometry of the sample. Conical and square tubes with small semi-apical angles (5°–15°) tend to fail in a stable Mode I, whereas samples with large semi-apical angles (20°–30°) were found to fail in a brittle Mode II. They also found that wall thickness, related to number of composite layers, has direct influence on the mode of failure. The collapse mode for large semi-apical angel samples has changed from stable to unstable, with increasing wall thickness. In case of small angel samples, the collapse mode remained the same with increased thickness of the wall.

3 Energy Absorption in Nanocomposites

Modern vehicle structures must be able to withstand severe impact loads, at the same time providing safety of the occupants. For this reason, structural materials used for crashworthy applications must be characterized by the energy absorption capability. Energy absorbed throughout a collision is controlled by the value of the force and the deflection. The maximum peak load is limited by the occupants' tolerance and the maximum deflection is limited by the geometry of the structure. In the scenario with very stiff structure induced peak loads can highly exceed allowable limit and occupants will suffer high decelerations while deformations of the structure are small. In case of the weak structure induced peak loads are strongly reduced but large deformations can crash the occupants causing serious injuries or even death. The third scenario is a compromise with the moderate value of the force and acceptable deflections not affecting occupants' space. In this scenario energy absorbed by the structure is maximized but within the limits of allowable load and deformation.

The most widely used method to evaluate the ability of a composite material to absorb the energy, is axial collapse of a structural elements. The experiments presented in the literature vary in geometry and material of the specimen, as well as parameters of the impact such as: velocity and energy. The most often used geometries of crash-samples are: cylinders, cones and square tubes [5, 7–11]. The materials which have been investigated extensively include: carbon, Kevlar and glass as fibre materials; and epoxy [7–9], PEEK [12], polyester [5] and vinylester [10] as matrix materials.

Low cost thermoplastic polymers, such as polypropylene (PP) and polyamide (PA), are widely used in the aerospace industry because of their good mechanical performances, processing properties and low cost. However, their application as structural materials is limited due to their low impact resistance [13]. Incorporation of various nano-sized filers like; nano-particles (SiO_2, TiO_2, WS_2, $CaSiO_3$, Al_2O_3), carbon nanotubes, and clay nano-plates; can be an appropriate solution to this problem [14]. Injection moulded, short fibre-reinforced thermoplastic composites are the most prevalent composite materials as thermoplastic nano-reinforced structures. Several important factors influencing energy absorption capability of nanocomposites are summarized in the followings:

- *Particles stiffness:* The particles stiffness influences the mechanical properties of polymer matrix nanocomposites. For instance, the impact response of the high density polyethylene with addition of elastic rubber and rigid calcium carbonate ($CaCO_3$) particles was investigated by means of notched Izod impact testing [15, 16]. The results showed that addition of 22 vol. % of elastic rubber causes an increase in notch toughness more than 16 times. However, a decrease by 50–60 % in the Young's modulus and yield stress by 40–50 %, was observed in relation to the net polymer.
- *Particles geometry:* Addition of Al_2O_3 nano-whiskers, glass fibres and wallastonite into polymer matrix improves the fracture toughness significantly, while incorporation of the plate shaped particles of nanoclay, into the same matrix material, was found to decrease it [17]. Favourable effect on the impact toughness was also observed after the addition of amino-functionalized multi wall carbon nano tubes [18] or small amounts of single wall carbon nano tubes [19]. Moreover, it was observed by Kireitseu [20] that the composite impact toughness and stiffness are highly dependent on the modulus of nano-tubes.
- *Volume fraction and inter-particle distance:* Important influence on the impact toughness of nano-composites has the inter-particle distance τ, independently of the reinforcement geometry. Its value is closely related to the concentration φ and average size of the particles d [21]. Zhang et al. [21] found, that if inter-particle distance is smaller than average particle size d, then composite toughness increases significantly, as it are presented in Fig. 3. This phenomenon can be explained by the fact, that distance between particles is small enough to build around them, a three dimensional network of interphase region.
- *Effects of particles size*: Effect of particles size on the mechanical properties of the polyurethane foams was studied by Javni et al. [22]. Incorporation of nano-sized filler was found to increase the compression strength of the foam, and to decrease its rebound resilience. On the other hand the addition of micro-sized fillers was found to lower the hardness and compression strength, at the same time leading to an increase in rebound resilience. This indicates that foams

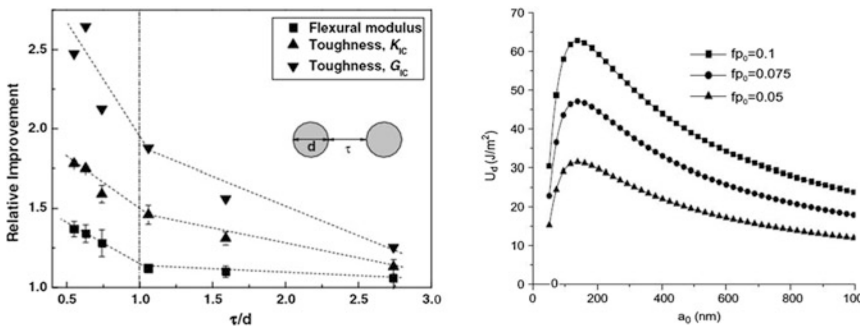

Fig. 3 Improvements in mechanical properties due to the inter-particle distance [21] and energy dissipation against average radius of the filler [23]

reinforced with nano-particles are able to absorb higher amounts of impact energy. According to the analytical studies carried out by Chen et al. [23], energy dissipation due to the interfacial debonding is highly dependent on the size of particles. The material ability to dissipate energy increases significantly with increasing size of the particles up to 140 nm, whereas particles bigger than that indicate gradual decrease in the material performances.

4 Sandwich Composites

Sandwich composites are widely used in wind turbines, automotive bumpers, aircraft engine nacelle, on wings for fuel tanks protection, tail plane panels for protection of stones and pebbles on take-off and landing, naval ships, human vests and helmets for ballistic protection, automotive for collision and heat protection. Unfortunately, any composite materials are susceptible to impact and the damage can be big and tend to increase in time- Research has shown that damage initiation thresholds and damage size on sandwich composites, primarily depend on the properties of the core materials, face sheets, and the relationship between the properties of the cores and those of the facings. Much of the earlier research on sandwich composites under impact loading focused on the honeycomb core (Nomex, glass thermoplastic or glass-phenolic) sandwich constructions. A key problem in the honeycomb sandwich constructions is the low core surface area for bonding. Consequently, expanded foams, (often thermoset) are nowadays preferred to achieve reasonably high thermal tolerance, though thermoplastic foams are also used. In turn, the response of foam core sandwich constructions to impact loading has been studied by many researchers [24–26]. Accordingly, it is now well understood that the response of the foam core sandwich composites strongly depend on the density and the modulus of the foam.

Foams are defined as materials containing gaseous voids surrounded by a denser matrix, which is usually a liquid or solid. Polymer foams can also be defined as either closed cell or open cell foams. In closed cell foams, the foam cells are isolated from each other and cavities are surrounded by complete cell walls. In open cell foams, cell walls are broken and the structure consists of mainly ribs and struts. Generally, closed cell foams have lower permeability, leading to better insulation properties. Open cell foams, on the other hand, provide better absorptive capability. One-step reactive foaming is typical for thermoset polymers. A good example is PU/clay nanocomposite foams, where a physical blowing agent such as pentane is used with monomers and clay nanoparticles. Reaction exotherm leads to a temperature jump and foaming. Most nanocomposite foams to date are synthesized via a two-step process: the nanocomposite is synthesized first and followed by foaming. Readers interested in the synthesis of PU/clay foams are referred to available literature such as Refs. [27, 28] (literature related to the reactive extrusion foaming of various nanocomposites is also covered). Polymeric foams have been widely used as packing materials because they are lightweight, have a high strength/weight ratio, have superior insulating properties and high energy absorbing performance.

A possible way of improving the properties of foam materials is through the inclusion of small amounts of nanoparticles (like carbon nanotubes and nanofibres, TiO_2, nanoclay, etc.) to improve the foam density and modulus properties. Up to now, montmorillonite nanoclays are the best candidate for foam reinforcement due to ease in processing, major thermal–mechanical properties enhancement, wide availability and are relatively cheap [2, 3]. Likewise, polyurethanes (PU) are core materials of choice due to their tailorable and versatile physical properties, ease of manufacture and their low costs. Unfortunately, the use of thermoplastic resins filled with nanoparticles to construct either laminates or foams is relatively new. Moreover, the use of nanoparticles in such laminates or foams in sandwich composite construction is in its infancy but realistic and beneficial. For instance, by using less than 5 % by weight nanoclay loadings, significant improvement on the foam properties (failure strength and energy absorption) can be realised with over 50 % increase in the impact load carrying capacity over the neat foam sandwich [29, 30]. However, since most current research concentrates on the processing and characterization of nanophased foams and evaluation of static properties only, materials data on impact behaviour, failure mechanisms due to impact and impact-structure–property relations is missing. For wide usage of nanophased foams in the sandwich constructions and reduction of weight (while maintaining the same level of protection), proper understanding of their impact behaviour at both high- and low-velocity impact is required.

4.1 Fabrication of Sandwich Panels with Nanophased Cores

Polyurethane foam with various different weight percentages (up to 10 %) of nanoclay have been prepared. The low weight percentages are targeted for infusion to avoid the agglomeration of nanoparticles common in high concentrations.

Preparation of the PU systems modified with MMT consists of three steps—first, polyol blend (polyether RF-551) and polyester (T-425R) mixture from Alfasystems, Brzeg Dolny, Poland, was stirred with powdered MMT (Optibent 987, Süd Chemie AG, Moosburg, Germany). Then catalyst (N,N-dimethyl cyclohexylamine), water and surfactant (SR-321, Union Carbide, Marietta, GA) were added in order to prepare the polyol premix (component A). In the next step n-pentane as a physical blowing agent was added to component A. Component B was polymeric 4, 4'-diphenylmethane diisocyanate (PM 200). It was added to component A and the mixture was stirred for 10 s with an overhead stirrer. Finally, the prepared mixtures were dropped into a mould. All the experiments were performed at ambient temperature of ca. 20 °C.

The sandwich beam samples are fabricated from aluminium face sheets (aluminium grade 24,139, Young's modulus of 79 GPa, 2 mm thick) and the above manufactured 20 mm thick nanophased polyurethane rigid foams. Firstly, the aluminium faceplates were pre-treated and polished. Later they are degreased using acetone for 2 min before applying the adhesive (DP-100 supplied by 3 M[@]). The surfaces are then dried and the adhesive applied evenly on the foam surface using a glue gun, and the metal skin is laid on top for each side at a time. This is repeated for the other side of the foam after allowing for 24 h of curing time. Once the adhesive is applied the sandwich samples are cured for a further period of 24 h in a press. Basically, the samples are laid on the base of the press between two thick metal plates to ensure pressure is distributed evenly all through the structure. The finished products are 5 specimens of sandwich beams of length 140 mm and width 100 mm for each.

4.2 Low Velocity Impact Tests

All the low impact tests were conducted using an instrumented falling weight impact tester, type 5. The device is equipped with impulse data acquisition system that can acquire data points. Using this machine, impact energy and velocity can be varied by changing the mass and height of the dropping weight. The velocity of the tup is measured just before it strikes the specimen. It is also fitted with pneumatic rebound brake, which prevents multiple impacts on the specimen. During the testing, the specimen is held in the fixture placed at the bottom of the drop tower which provided a clamped circular support span (Fig. 1). The weight of cross-head is maintained at a specific value and it is guided through two smooth guide columns. The impactor end of the drop mass is fitted with an instrumented tup with hemispherical end having a capacity to record the transient response of the specimens. To carry out the impact tests, sandwich composite samples (140 × 100 mm) are placed between the clamps and heights adjusted depending on the desired energy level. The projectile had a 20 mm diameter hemispherical tip. The impact force history obtained during the test was measured using a piezoelectric load cell located above the impactor tip. The amplified signals from the load cell were recorded by the computer. The height is the distance between the tip of the indenter and the top surface of the sample held between the clamps. Once the height required to attain a particular energy level is known, the indenter is moved accordingly to that height before it is dropped on the specimen for the test.

4.3 Results and Discussions

The impact response of sandwich structures with and without nanoclay core and nanophased face sheets were evaluated. Several samples of each set were tested at different energy levels. Transient data including time, load, energy, velocity and deflection were collected for each sample as functions of time. Figure 4 compares typical load and deflection versus time curves for the four specimen types at 45 J impact energy level.

The peak loads were 3,560 N for neat cored sandwich and for 2.5 % MMT loaded core sandwich composites. A slight improvement of ~300 N was observed in peak load for both 5 and 7.5 % MMT loaded samples, indicating that higher MMT loading samples performed better than the lower MMT loaded ones.

The energy absorption at failure point was recorded as 32.5, 32.5, 43.4 and 44 J for 0, 2.5, 5 and 7.5 % MMT loading respectfully. The energy absorption in any material under impact loading is mainly through the elastic deformation in the initial stage with some energy absorbed through friction. Once, the energy level is

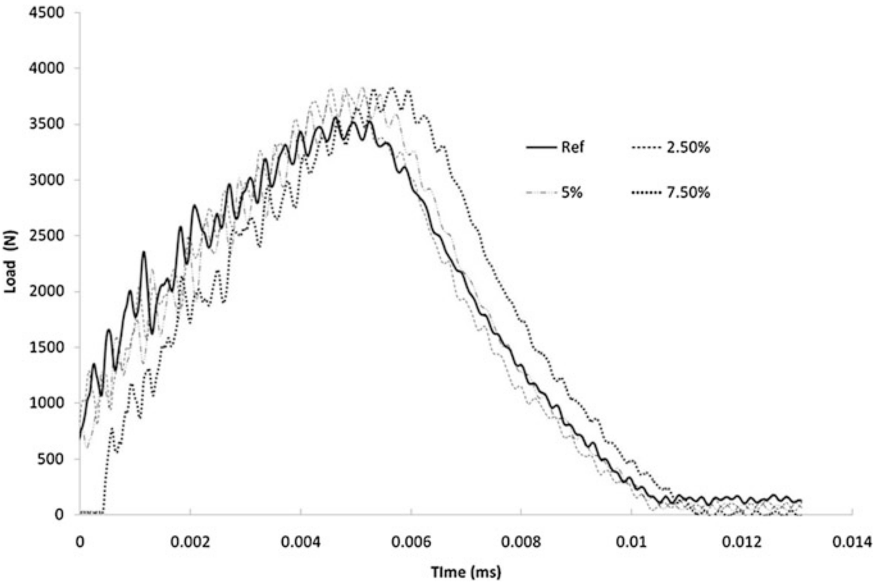

Fig. 4 Comparison of load versus time graph obtained from first impact

beyond the level required for maximum elastic deformation, the structure then dissipates the excess energy in the form of either plastic deformation in case of ductile materials or through various damage mechanisms in the case of brittle materials. As can be seen on Fig. 5, it is evident that the absorbed energy at peak load was within a close range for all samples.

The deflection at peak load is a qualitative indication of the stiffness of the material. The same applies to their maximum deflection recorded, averaging around 2.1 mm but minor diversity between the specimens was found. As expected, the peak loads and deflections were similar at low impact energy. These current results were in contrast to related published work in the literature which reported that at 45 J, the neat core sandwich structures had higher deflection at peak load on nanophased core and fibre-reinforced sandwich composites [30]. The literature further reported that the total time and the time to peak load were also higher for the neat core sandwich samples [30]. However, it should be noted that the work was based on fibre-reinforced composites as face sheets whereas aluminium face sheets have been used in the current work. In the latter case, there was no perforation on the face sheets by the indent striker. It is also apparent that we will need to undertake future tests at higher energy levels above the 45 J thresholds the current tests were conducted at.

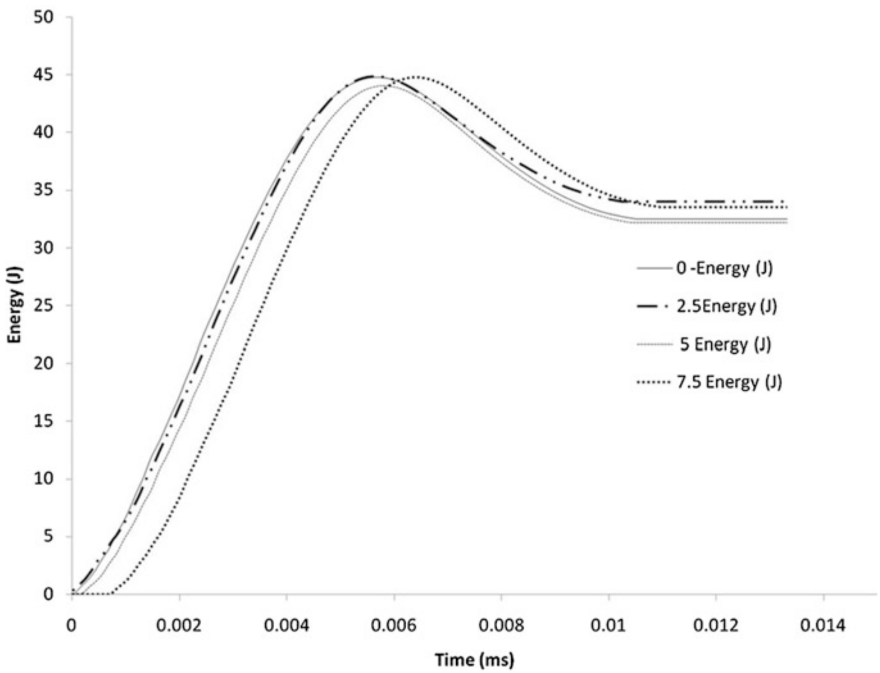

Fig. 5 Energy versus time graph obtained from first impact

A detailed examination revealed no debonding of the skin and core or crack development into the foam cross-section at the mid-plane of the structures over the range of energies considered. This demonstrated the importance of a proper selection of adhesive for particular foams. Typically, core fracture takes place when defects exist in the adhesive layer and at the skin/adhesive/core interfaces or where poor adhesion occurs between the skin and the adhesive. In our case, DP-100$^{@}$ is a thin film and highly viscous. When a one-step process is used to cure the facings to the core, localized cell wall collapse and cell coalescence occur, leading to non-uniform thickness and weaker cores near the skin/core bondline. In such cases, the problem is caused by the high pressure required to cure the facings. In the current work, therefore, a thin layer application was employed followed by compression during bonding hence minimising potential defects in the materials at fabrication stage. Nevertheless, a microscopic inspection revealed some small debonding for both 5 and 7.5 % samples along the skin/foam interface edges in the structure width after the first impact tests. This failure may be attributed parameters that are direct indications of the stiffness of the samples rather than just the adhesive failure. It follows that at impact, as the dented aluminium face sheet yielded inwards, the back face remained intact and no deformations were observed along the cores length. However, debonding occurred along the sandwich composite edges (face plate, width-wise) to make up for the bending displacements thereby forcing the edge lines to split along the skin/core interface. The core at the midsection experienced compression forces but there were no signs of cracks formation for all samples even under microscopy. This may be related to reactive foams and their microcellur cells collapsing to absorb load instead of expected cracks and fracture characteristics, as widely reported in the literature.

Since sandwich structures are often used as energy absorbing structures in damage susceptible areas, we decided to conduct a second drop weight impact recurrence on the previously impacted samples in order to closely replicate repetitive occurrences. Such scenarios are common between structural inspection periods or in incidences where the damage was missed during normal inspection routines. Interestingly, we found out that the nanophased samples recorded significantly higher peak loads than the neat PU cored ones. As can be seen from Figs. 6 and 7, a difference of over 1,000 N in peak load was observed for the 7.5 % samples as compared to that of neat PU foam samples.

It was further noted that the neat foam samples had the highest energy intake at failure point, in agreement with previous observations by Hosur et al. [24]. Still, there was no visible cracking deformation on the surface of the reactive foam cores along the length of the structures. The only visible debonding and crack formation was along the width of the structures which, as eluded to earlier on, may be associated to bending deformation on the face plate due to impact loads. Further investigations by microscopy are currently underway to investigate the level of damage on the microcellular cores' cross-sections in conjunction with in-depth morphology studies.

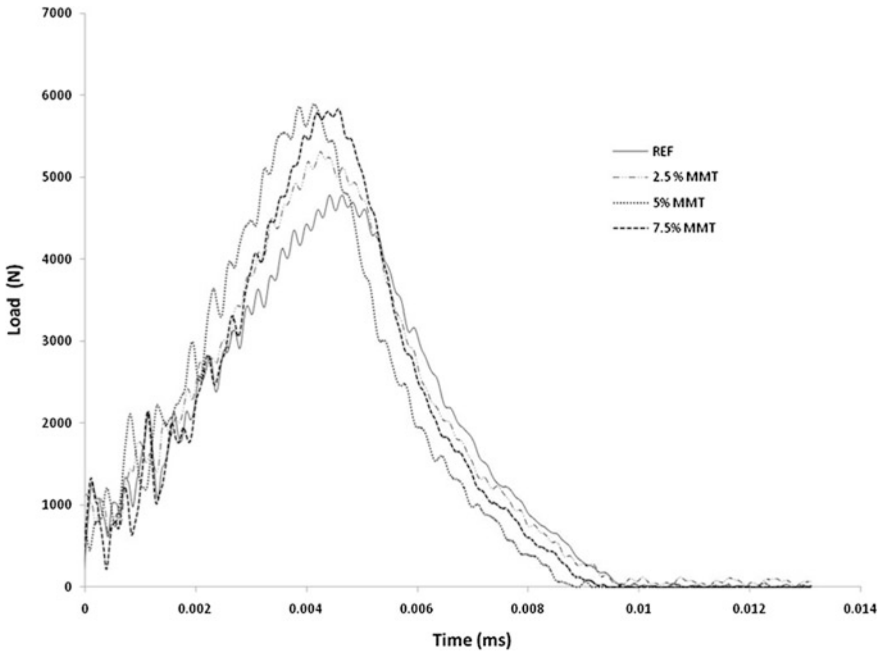

Fig. 6 Load versus time graph obtained from second impact test

5 Thermoplastic Nanocomposites

Numerous researches have been conducted to study the influence of nano-particles on the mechanical behaviour of polymer composites. Several factors influencing the enhancing capabilities of the nano-reinforcements were studied in the literature. This includes key parameters such as: shape [31] and size [32] of nano-fillers, matrix and reinforcement material [33, 34], interfacial strength and interphase characteristics [35], as well as volume fraction [21] and quality of dispersion within the matrix [36].

For the purpose of measuring the energy absorption in composite structures, tube crashing experiments are the most prevailing. The ability of a composite structure to absorb the energy was found to be highly dependent on the mode of fracture. Materials which fail in a progressive manner, with extensive delamination and fragmentation, are able to absorb much higher energies than those materials which tend to fail in a brittle manner. Farley [7–9] found that thermoset composites reinforced with glass and carbon fibres fail progressively in fragmentation and splaying modes. On the other hand, thermoset tubes reinforced with Kevlar, failed in a progressive folding mode. Mamalis et al. [5] who studied polyester cones, cylinders and tubes, reinforced with random orientated glass fibres, divided failure of the samples into four modes: progressive crashing with micro-fragmentation (Mode I), brittle fracture with catastrophic failure (Mode II and III, depending on

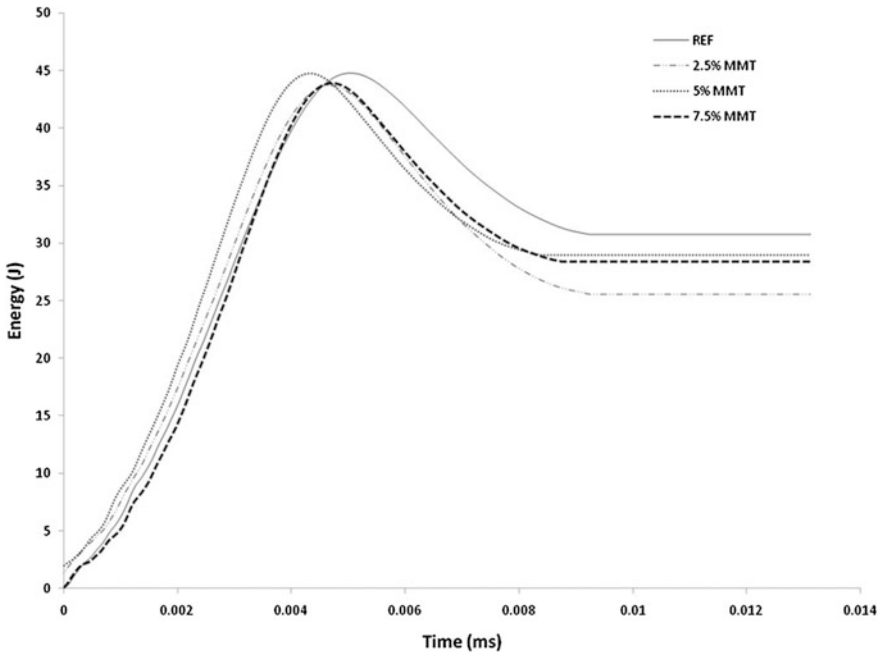

Fig. 7 Energy-time graphs after second impact test

the crack form), progressive folding and hinging, similar to the metallic tubes (Mode IV).

Regarding nanocomposite structures there is a lack of crash experiments conducted on these materials presented in the literature [14]. Energy absorption characteristics of these materials have been mainly characterized by means of compression [37], flexural [38] and Charpy or Izod impact testing [17]. The relationship between mechanical properties of nanocomposite material and energy absorption characteristics of nanocomposite structure is not fully understood. This work therefore aims to correlate changes in the mechanical properties of the material with induced fracture modes and ability of the structure to crash progressively, after the addition of secondary reinforcement.

5.1 Fabrication of Cone-Shaped Nanocomposites Structures

Preparation of the nano and glass reinforced polymer composites was conducted in three main steps: preparation of the nano-composites granulate, mixing and extrusion of the nano and glass reinforced composite granulate and injection moulding of the macro-sample. The flow chart showing the preparation process is shown in Fig. 8.

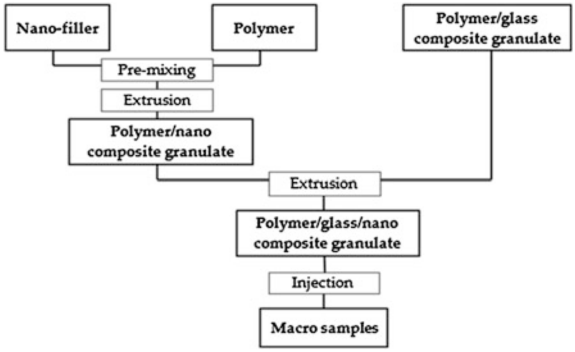

Fig. 8 Material compounding and test sample manufacturing

In order to warrant the highest homogeneity of the composition, nano-reinforcement and polymeric matrix, all in solid (powder) form, were premixed before extrusion. This activity was performed by the use of a turbomixer with rotatory blades. The pre-mixing phase consisted of two steps, the first one at lower speed (1,500 rpm) and the second one at higher speed (3,000 rpm). This choice was made in order to ensure the maximum homogeneity of the premix and, on the other hand, to subject the polymer to a small temperature stress, to improve binding between polymeric matrices and added reinforcements. Subsequently the premixed materials were fed into a twin-screw extruder at a constant predefined rate.

5.2 *Crashing Behaviour*

Crashing behaviour and energy absorption characteristic of the polymer composites were studied by means of quasi-static compression and dynamic impact tests. Figure 9 show the variation of load with increasing crashed length of the conical structure. Comparing the load–displacement curves, several important comments can be made. In all conducted experiments the initial slope of the load curve is approximately linear. This is associated with the elastic deformation of the structure [39–41]. The first extremism of the curve indicates maximum load supported by the structure, which depends on the material strength. After that point, a sudden drop in load is observed due to the formation of the cracks. Subsequently, a progressive crashing occurs, what is visible as following sharp load peaks. Analyzing the obtained results we can note, that magnitude of the load peaks depends on the crashing characteristic of the material and testing speed. It could be seen that all PA composites and neat PPGF composite, tested under the quasi-static load, had bigger secondary peaks than the initial one. On the other hand, the same materials, tested under the dynamic conditions, induced significantly lower secondary peaks. This difference is associated with the mechanism of cracks propagation. If the crack propagates along the height of the cone, as it can be seen in Figs. 9 and 10, then the load required to crash the sample can be smaller

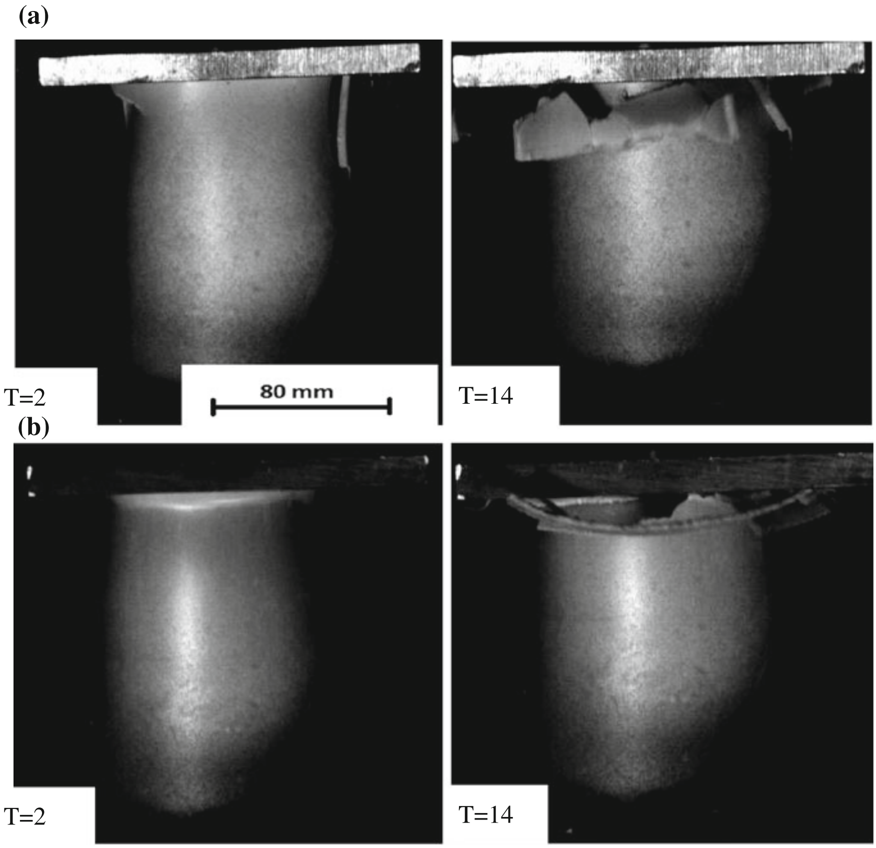

Fig. 9 Crushing characteristics of nanofilled cones. High speed camera records (**a**) PA/GF/MMT (**b**) PA/GF/SiO_2

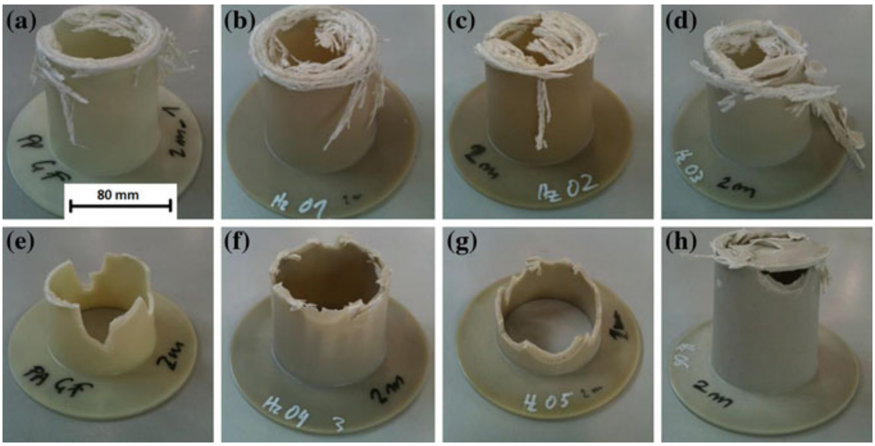

Fig. 10 Dynamic collapse mode in: (**a**) PP/GF (**b**) PP/GF/SiO_2 (**c**) PP/GF/MMT (**d**) PP/GF/GS (**e**) PA/GF (**f**) PA/GF/SiO_2 (**g**) PA/GF/MMT (**h**) PA/GF/GS

than that required to form the initial crack. The opposite situation exists if propagation of the crack stops quickly after the formation, and new cracks have to be initiated in order to crash the sample.

5.3 Energy Absorption Characteristics of Nanocomposite Structures

By relating the energy absorption characteristic with the propagation of the crack, it can be seen that materials that fail in a progressive manner, are able to absorb much higher energies than those with large continuous cracks. Furthermore, the mean crashing load in these materials is either on the same or higher level than the initial peak, what causes that the area under the load–displacement curve is significantly bigger.

Analyzing the results listed in Tables 1 and 2, we can note that crashing characteristic under dynamic load are different from those subjected to quasi-static compressive load.

All materials absorbed similar amount of impact energy, whereas energy absorbed during the quasi-static test is different in each material. This discrepancy is caused by the fact that each material failed with a different crashing length under the impact loading, while under the static loading the crashing length is constant in all experiments

Regarding the loads induced during the impact, we can note that mean crashing load was much closer to the initial peak, in case of all PP composites, what has a direct influence on the amount of energy absorbed by the structure. In case of PA materials the mean crashing load was significantly smaller than the initial peak, indicating weaker impact-energy absorption capabilities. Conclusions

Nanophased reactive polyurethane cores were manufactured and then used to fabricate sandwich structures. It has been found that the incorporation of MMT resulted in higher number of PU cells with smaller dimensions and higher anisotropy index (cross-sections RI and RII). The obtained materials exhibited

Table 1 Quasi-static crashing characteristics

Material	Crash length (mm)	Collapse mode	Initial peak (kN)	Mean crashing load (kN)	Energy absorbed (kJ)	Specific energy (SE) [kJ/kg]	Change in SE (%)
PPGF	86	III	29.74	34.75	2.993	49.4	
PPGF + SiO_2	86	III	26.59	17.86	1.489	24.4	−50.7
PPGF + MMT	86	III	24.75	15.39	1.294	21.2	−57.0
PPGF + GS	86	I	22.06	17.66	1.652	26.3	−46.9
PAGF	86	III	47.66	50.44	4.339	58.1	
PAGF + SiO_2	86	III	44.61	45.66	4.156	54.5	−6.1
PAGF + MMT	86	III	54.59	40.65	3.232	42.9	−26.2
PAGF + GS	86	III	55.10	45.74	4.117	51.7	−11.0

Table 2 Dynamic crashing characteristics

Material	Crash length (mm)	Collapse mode	Initial peak (kN)	Mean crashing load (kN)	Energy absorbed (kJ)	Specific energy (kJ/kg)	Specific energy increase (%)
PPGF	29.79	I	22.99	14.19	0.365	23.6	–
PPGF + SiO_2	31.4	I	25.72	15.41	0.376	22.6	−4.2
PPGF + MMT	36.02	I	20.02	12.86	0.401	20.5	−13.0
PPGF + GS	35.03	I	26.28	13.52	0.403	20.7	−12.3
PAGF	60.5	II	19.99	5.64	0.356	7.7	–
PAGF + SiO_2	57.56	III	26.51	8.98	0.432	9.8	27.0
PAGF + MMT	62.61	II	38.82	4.48	0.376	7.7	0.1
PAGF + GS	22.03	III	40.42	15.58	0.320	22.3	188.5

improved parameters in terms of thermal insulation properties. The investigation revealed that nanophased sandwich structures were capable of taking higher peak loads than those made of neat polyurethane cores when subject to low-velocity impact. This was especially true for multi-impact recurrences within the threshold loads and energies studied. It is proposed to investigate the threshold load that initiates delamination damage in the sandwich laminate which is a particularly important property of polymer composite components exposed to water and/or moisture and subjected to low energy impact.

Thermoplastic polymer glass-fibre and nano-silica reinforced composites were investigated as an alternative to polymer glass-fibre composites. The effect of matrix and reinforcement material on the energy absorption capabilities of composite structures was studied in details. The axial dynamic and quasi-static collapse of conical structures was conducted using high energy drop tower, as well as Instron electro-mechanical testing machine. The impact event was recorded using high-speed camera and the fracture surface was investigated with scanning electron microscopy (SEM). Attention is directed towards the relation between micro-fracture process and crack propagation mechanism, and energy absorbed by the structure.

The obtained results indicate an important influence of filler and matrix material on the energy absorption capabilities of the polymer composites. A significant increase in specific energy absorption is observed in polyamide 6 reinforced with nano-silica particles and glass-spheres, whereas addition of montmorillonite caused a decrease in that property. On the other hand, very little influence of the secondary reinforcement on the energy absorption capabilities of polypropylene composites was found.

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References

1. Njuguna, J., Pielichowski, K., Desai, S.: Nanofiller-reinforced polymer nanocomposites. Polym. Adv. Technol. **19**(8), 947–959 (2008)
2. Leszczyńska, A., Njuguna, J., Pielichowski, K., Banerjee, J.R.: Polymer/montmorillonite nanocomposites with improved thermal properties: Part II. Thermal stability of montmorillonite nanocomposites based on different polymeric matrixes. Thermochimica Acta. **454**(1), 1–22 (2007/2/15)
3. Leszczyńska, A., Njuguna, J., Pielichowski, K., Banerjee, J.R.: Polymer/montmorillonite nanocomposites with improved thermal properties: Part I. Factors influencing thermal stability and mechanisms of thermal stability improvement. Thermochimica Acta. **453**(2), 75–96 (2007/2/1)
4. Njuguna, J., Pielichowski, K., Desai, D.: Nanofiller-reinforced polymer nanocomposites. Polym. Adv. Technol. **19**(8), 947–959 (2008)
5. Mamalis, A.G.: Crashworthiness of composite thin-walled structural components. Technomic Pub. Co., Lancaster, Pa (1998)
6. Njuguna, J.: Crashworthiness of composite materials, Cranfield University, School of Applied Sciences, lecture notes (2012)
7. Farley, G.L.: Effect of fiber and matrix maximum strain on the energy absorption of composite materials. J. Compos. Mater. **20**(4), pp. 322 (1986)
8. Meressi, T., Paden, B.: Buckling control of a flexible beam using piezoelectric actuators. J. Guidance Control and Dyn. **16**(5), 977–980 (1993)
9. Farley, G. L.: The effects of crushing speed on the energy-absorption capability of composite tubes. J. Compos. Mater. **25**(10), pp. 1314 (1991)
10. Thornton, P.: The crush behavior of pultruded tubes at high strain rates. J. Compos. Mater. **24**(6), pp. 594 (1990)
11. Thornton, P.: Energy absorption in composite structures. J. Compos. Mater. **13**(3), pp. 247 (1979)
12. Hamada, H., Coppola, J., Hull, D., Maekawa, Z., Sato, H.: Comparison of energy absorption of carbon/epoxy and carbon/PEEK composite tubes. Compos. **23**(4), 245–252 (1992)
13. Yuan, Q., Misra, R.: Impact fracture behavior of clay-reinforced polypropylene nanocomposites. Polym. **47**(12), 4421–4433 (2006)
14. Sun, L., Gibson, R.F., Gordaninejad, F., Suhr, J.: Energy absorption capability of nanocomposites: A review. Compos. Sci. Technol. **69**(14), 2392–2409 (2009)
15. Bartczak, Z., Argon, A.S., Cohen, R.E., Weinberg, M.: Toughness mechanism in semi-crystalline polymer blends: I. High-density polyethylene toughened with rubbers. Polym. **40**(9), 2331–2346 (1999)
16. Bartczak, Z., Argon, A.S., Cohen, R.E., Weinberg, M.: Toughness mechanism in semi-crystalline polymer blends: II. High-density polyethylene toughened with calcium carbonate filler particles. Polym. **40**(9), 2347–2365 (1999)
17. Viana, J.: Polymeric materials for impact and energy dissipation. Plast., Rubber Compos. **35**(6–7), 260–267 (2006)
18. Wang, J., Fang, Z., Gu, A., Xu, L., Liu, F.: Effect of amino-functionalization of multi-walled carbon nanotubes on the dispersion with epoxy resin matrix. J. Appl. Polym. Sci. **100**(1), 97–104 (2006)
19. Cooper, C.A., Ravich, D., Lips, D., Mayer, J., Wagner, H.D.: Distribution and alignment of carbon nanotubes and nanofibrils in a polymer matrix. Compos. Sci. Technol. **62**(7–8), 1105–1112 (2002)
20. Kireitseu, M., Hui, D., Tomlinson, G.: Advanced shock-resistant and vibration damping of nanoparticle-reinforced composite material. Compos. B Eng. **39**(1), 128–138 (2008)
21. Zhang, H., Zhang, Z., Friedrich, K., Eger, C.: Property improvements of in situ epoxy nanocomposites with reduced interparticle distance at high nanosilica content. Acta Mater. **54**(7), 1833–1842 (2006)

22. Javni, I., Zhang, W., Karajkov, V., Petrovic, Z., Divjakovic, V.: Effect of nano-and micro-silica fillers on polyurethane foam properties. J. Cell. Plast. **38**(3), pp. 229 (2002)
23. Chen, J., Huang, Z., Zhu, J.: Size effect of particles on the damage dissipation in nanocomposites. Compos. Sci. Technol. **67**(14), 2990–2996 (2007)
24. Caprino, G., Teti, R.: Impact and post-impact behavior of foam core sandwich structures. Compos. Struct. **29**(1), 47–55 (1994)
25. Anderson, T., Madenci, E.: Experimental investigation of low-velocity impact characteristics of sandwich composites, Composite Structures. **50**(3), 239–247 (2000/11)
26. Mines, R.A.W., Worrall, C.M., Gibson, A.G.: Low velocity perforation behaviour of polymer composite sandwich panels. Int. J. Impact Eng. **21**(10), 855–879 (1998)
27. Lee, L.J., Zeng, C., Cao, X., Han, X., Shen, J., Xu, G.: Polymer nanocomposite foams. Compos. Sci. Technol. **65**(15–16), 2344–2363 (2005)
28. Cao, X., James Lee, L., Widya, T., Macosko, C.: Polyurethane/clay nanocomposites foams: Processing, structure and properties. Polymer **46**(3), 775–783 (2005)
29. Mahfuz, H., Islam, M.S., Rangari, V.K., Saha, M.C., Jeelani, S.: Response of sandwich composites with nanophased cores under flexural loading, Composites Part B: Engineering. **35**(6–8), 543–550 (2004/0)
30. Hosur, M.V., Mohammed, A.A., Zainuddin, S., Jeelani, S.: Processing of nanoclay filled sandwich composites and their response to low-velocity impact loading. Compos. Struct. **82**(1), 101–116 (2008)
31. Wetzel, B., Rosso, P., Haupert, F., Friedrich, K.: Epoxy nanocomposites-fracture and toughening mechanisms. Eng. Fract. Mech. **73**(16), 2375–2398 (2006)
32. Subramaniyan, A.K., Sun, C.: Toughening polymeric composites using nanoclay: Crack tip scale effects on fracture toughness. Compos. A Appl. Sci. Manuf. **38**(1), 34–43 (2007)
33. Njuguna, J., Michalowski, S., Pielichowski, K., Kayvantash, K., Walton, A.: Improved car crash protection. SPE Plastic Research Online (2010). 10.1002/spepro.003061
34. Hussain, F., Hojjati, M., Okamoto, M., Gorga, R.E.: Review article: Polymer-matrix nanocomposites, processing, manufacturing, and application: An overview. J. Compos. Mater. **40**(17), pp. 1511 (2006)
35. Ng, C., Schadler, L., Siegel, R.: Synthesis and mechanical properties of TiO2-epoxy nanocomposites. Nanostruct. Mater. **12**(1–4), 507–510 (1999)
36. Ma, J., Mo, M.S., Du, X.S., Rosso, P., Friedrich, K., Kuan, H.C.: Effect of inorganic nanoparticles on mechanical property, fracture toughness and toughening mechanism of two epoxy systems. Polym. **49**(16), 3510–3523 (2008)
37. Guo, Y., Li, Y.: Quasi-static/dynamic response of SiO2-epoxy nanocomposites. Mater. Sci. Eng. A. **458**(1–2), 330–335 (2007)
38. Han, J., Cho, K.: Nanoparticle-induced enhancement in fracture toughness of highly loaded epoxy composites over a wide temperature range. J. Mater. Sci. **41**(13), 4239–4245 (2006)
39. Njuguna, J., Silva, F., Sachse, S.: Nanocomposites for vehicle structural applications" in nanofibers—production, properties and functional applications, Lin, T. (ed.) In Tech Press, (ISBN: 978-953 307 420 7) (2011)
40. Silva, F., Sachse, S., Njuguna, J.: Energy absorption characteristics of nano-composite conical structures, IOP Conf. Ser.: Materials Science and Engineering **40** 012010 doi:10.1088/1757-899X/40/1/012010 (2012)
41. Silva, F., Njuguna, J., Sachse, S., Pielichowski, K., Leszczynska, A., Gianocolli, M.: The influence of multiscale fillers reinforcement into impact resistance and energy absorption properties of polyamide 6 and polypropylene nanocomposite structures. Mater. Des. **50**, 244–252 (2013)