Steel and Composite Structures, *Vol. 24, No. 2 (2017) 191-200*
DOI: https://doi.org/10.12989/scs.2017.24.2.191

Ballistic impact response of Kevlar Composites with filled epoxy matrix

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(Received July 01, 2016, Revised March 17, 2016, Accepted March 20, 2017)

Abstract. Impact resistance and weight are important features for ballistic materials. Kevlar fibres are the most widely reinforcement for military and civil systems due to its excellent impact resistance and high strength-to-weight ratio. Kevlar fibres or spectra fiber composites are used for designing personal body armour to avoid perforation. In this study, the ballistic impact behaviour of Kevlar/filled epoxy matrix is investigated. Three different fillers, nanoclay, nanocalcite and nanocarbon, were used in order to increase the ballistic impact performance of Kevlar-epoxy composite at lower weight. The filler, nanoclay and nanocalcite, content employed was 1 wt.% and 2 of the epoxy resin–hardener mixture while the nanocarbon were dispersed into the epoxy system in a 0.5%, 1% and 2% ratio in weight relating to the epoxy matrix. Specimens were produced by a hand lay-up process. The results obtained from ballistic impact experiments were discussed in terms of damage and perforation. The experimental tests revealed a number of damage mechanisms for composite laminated plates. In the ballistic impact test, it was observed whether the target was perforated completely penetrated at the back or not. The presence of small amounts of nanoclay and nanocalcite dispersed into the epoxy system improved the impact properties of the Kevlar/epoxy composites. The laminates manufactured with epoxy resin filled by 1 wt.% of nanoclay and 2 wt% nanocalcite showed the best performance in terms of ballistic performance. The addition of nanocarbon reduced ballistic performance of Kevlar-epoxy composites when compared the results obtained for laminates with 0% nanoparticles concentration.

Keywords: ballistic impact performance; nanoclay; nanocalcite; nanocarbon; Kevlar; lightweight armour

1. Introduction

Polymer composites have been used in many fields such as aerospace, defence, marine, automotive, civil infra-structure, sporting goods due to stiffness-to-weight and strength-to-weight, tailor-ability and thermal properties. In last two decades, properties and performances of fiber reinforced polymer matrix materials have been improved by incorporated nano and micro-scale particles. The thermal and mechanical, properties of thermosetting and thermo-plastic polymer systems have been improved with the appearance and application of nanotechnology. Most of the works have been carried out in the polymer nanotechnology research field. Nanoparticle reinforced materials have been widely utilized in engineering and commercial areas because of unique surface effects and particular physical properties. The use of nanocomposite is increasing day by day because of it is applicability in high technology.

It has been carried out several investigations with regard to the increase of the mechanical and thermal properties of composites by adding low concentrations of nanoparticles into polymers without jeopardizing density, toughness or the manufacturing process (Wang *et al*. 2001, Ho *et al*. 2006, Chowdhury *et al*. 2006, Grujicic *et al*. 2007, Liu *et al*. 2010). Investigations on the mechanical properties of nano-composites demonstrated that addition of nanoparticles has some influence on the tensile strength and modulus, elongation at break and fracture toughness. Several examples can be found in the literature regarding to the effect of nanoclay used in epoxy systems. Fabricated laminates structures with epoxy resin filled by nanoclay show outstanding improvement in mechanical properties. Park and Jana (2003) were among those researchers who worked on the effect of nanoparticles into epoxy systems. In their study, they claim that the degree of exfoliation of the nanoclay material in the epoxy matrix is thought to be responsible for the increase in the properties of the materials. The hypothesis of exfoliation of nanoclay suggests that the elastic forces developed in the clay galleries during epoxy curing are responsible for exfoliation of the clay structures. Haque *et al*. (2003) showed that by dispersing 1wt.% nanosilicates, S2-glass/epoxy-clay nano-composites exhibited an improvement of 44%, 24% and 23% in interlaminar shear strength, flexural strength and fracture toughness, respectively. As stated by Haque *et al*. (2003), thermo-mechanical properties mostly increase by adding ~1-2% in weight nanoclay but decrease at higher clay loadings (≥ % 5 in weight). They also observed a degradation of properties at higher clay loadings because of phase-separated structures and defects in crosslinked structures.

Promising results are being obtained with regard to matrices filled with nanoclays or carbon nanotubes (CNTs). Mahfuz *et al*. (2004) investigated the tensile response of carbon nanoparticle/whiskers reinforced composites. They

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http://www.techno-press.org/?journal=scs&subpage=6
ISSN: 1229-9367 (Print), 1598-6233 (Online)

observed that both stiffness and toughness were improved by the use of nanoparticles. Mahfuz *et al*. (2004) highlights the idea of an improvement of 15-17% in the tensile strength and modulus, respectively. Another set of experiment on carbon/SiC-epoxy nanocomposites was conducted by Chisholm *et al*. (2005). They showed 20-30% improvement in mechanical properties. A noteworthy amount of study has focused on the improvement of properties of epoxies using nanoclays. The mechanical properties of composite materials were improved at a loading of little wt.% clay. Chowdhury *et al*. (2006) showed that the flexural strength of the epoxy over the control samples meaningfully increased by adding 2 wt.% nanoclay.

In the literature, there are a significant number of examples explaining the effect of clay addition on the strength-stiffness, thermal properties and low velocity impact response of resin systems (Hou *et al*. 2010, Ferreira *et al*. 2011a, 2013, Ávila *et al*. 2011). On the other hand, there is a few of studies about high velocity ballistic impact properties of composite filled nanoparticles.

Ballistic materials have been studied for many years especially for military applications. Impact resistance and weight is important for ballistic/impact resistant materials. Kevlar fibers or spectra fiber composites are used in designing personal body armour due to its excellent impact resistance and high strength-to-weight ratio. In the literature, several studies have carried out improving the impact strength of composites at lower weight (Pol *et al*. 2013, O'Masta *et al*. 2014). Both defence safety and mobility of the user are considered selection of suitable armour materials for defence applications. The clothes ensuring the ballistic protection have to be designed USA NIJ 01.01.04 standard for ensuring the necessary protection level.

Impact resistance of composite materials depends on the fiber type, the matrix material, the layer thickness, the alignment of layers and the boundary conditions. In literature, many polymer matrix composites (PMC) studies have been conducted on reinforced target materials, target material thickness, understanding damage modes and improving the mechanical properties of the material after impact (Mohagheghian *et al*. 2011, Pol *et al*. 2012). Bandaru *et al*. (2015) produced hybrid composites using Kevlar, carbon and glass fibers of different combinations, and the results of their study indicated that the ballistic strength of composites increased as a result of hybridization; ballistic strength changed depending on the alignment of layers and residual velocity was determined by comparing energy absorption and ballistic limit values. In another study, it was produced hybrid composites using E-Glass and 8H Satin weave T300 Carbon woven fabric by Pandya *et al*. (2013), and then they applied V_{50} ballistic tests to these composites. The highest ballistic strength was achieved when E-Glass was used as a back layer and carbon woven fabric was used as an intermediate layer in the composite. Randjbaran *et al*. (2014) used Kevlar, glass fiber and carbon fiber as reinforcement to produce hybrid composites and observed that the use of glass fiber in the front layer of the composite absorbed much higher impact energy compared to that of Kevlar. They also found out that the use of carbon and glass fiber as intermediate layers improved the ballistic strength of composites, but that carbon fibers used as back layers decreased ballistic strength.

Based on these investigations, it was observed that the ballistic strength of hybrid composites changed depending on layer alignment and fiber type. It is also noted in literature that, in addition to the effects of reinforcement material, matrix material has a significant effect on a material's ballistic strength. In several studies, addition of nano reinforcements—nano-calcite, nano-clay and CNT—into the matrix material increased the mechanical strength and ballistic resistance of the material. In the study conducted by Qian *et al*. (2004), polyamide/nano-clay composites produced by a 5% volume ratio increased tensile strength, elastic modulus, compressive strength and compressive modulus by 40, 68, 60 and 126%, respectively. In another study using nano-clay as reinforcement, composite plates with 0, 1, 2, 3, 5, 6 and 7 wt.% nano-clay were produced, and the elastic modulus of composites with 3 wt.% nano-clay increased by 16%. Moreover, the highest energy absorption was obtained in composites with 5 wt.% nano-clay (Pol *et al*. 2013).

One of the most important key points to be noticed in the design and applications of composite materials is the damage resistance of each component, i.e., fibers and matrix resulting from impact. If the kinetic energy of an impactor is greater than the ballistic range, perforation will occur. Perforation depends on the fiber type and volume fraction, the matrix, the stacking sequence, the size, and initial kinetic energy of the impactor. The impactor the ability for full penetration without any remaining energy is defined as impact or ballistic velocity. The penetration process consists of punching, fiber breaking and delamination (Mohagheghian *et al*. 2011, Ferreira *et al*. 2011a, Reis *et al*. 2012, Talib *et al*. 2012, Frontán *et al*. 2012). Penetration behavior of polymer composites under ballistic impact has been investigated by many authors through experimental and theoretical studies (Rama *et al*. 2015, Vargas-Gonzalez and Gurganus *et al*. 2015, Liu *et al*. 2015, Sorrentinoa *et al*. 2015). Various researchers have proposed numerical and analytical models to predict the ballistic limit of polymer composites subjected to high velocity impact.

The present study has focused on the ballistic performance of laminated Kevlar composite plates with nanoparticles, commonly used in protective body armour due to its excellent impact resistance, high strength-to-weight ratio. The aim of this study is to determine the ballistic impact performance Kevlar composites with nano enhanced resin at lower weight. The results of the present paper are discussed in terms of damage and perforation.

2. Material and method

The objective of this study is to determine the effect of adding nanoparticle on the ballistic impact response of composite plate. The composite plates were fabricated from Kevlar fiber and different nanoparticle concentrations in epoxy and to use them as a target in the ballistic impact tests.

The composite preparation and the target geometry constitute the target preparation processes. The target area was 300×300 mm, and totally number of 20 Kevlar prepreg with different nanoparticles concentrations in epoxy was used to construct the composite plate. The composite plate with 2 mm thickness and placed back to back to each other has symmetrical lay–ups.

The concentration of nanoclay and nanocalcite dispersed into the epoxy is given by the following sequence: 0%, 1% and 2% ratios in weight with respect to the epoxy matrix. Notice that 0% nanoparticles concentration is used as a benchmark for comparison purposes. This filler content was used by the authors according to the literature Haque *et al*. (2003) is the value most likely to promote optimum strength and stiffness as a balanced enhancement. Three specimens are prepared and tested for controlling the sample (no nanoparticle addition).

A pre–measured unsaturated matrix was mixed with a nanoclay, nanocalcite and nanocarbon of different particle concentrations in epoxy; it was then mixed properly together for providing whole air and moisture removal. The epoxy filled by nanoparticle (nanoclay + epoxy; nanocalcite + epoxy, nanocarbon+ epoxy) were mixed in the Kevlar fiber layer by using brushes and rollers. And then another Kevlar fiber sheet was laid down and the mixing process was repeated until the composite plate was reached the desired thickness.

Experimental works has been completed in three steps: (1) Matrix preparation (Ultrasonic mixing); (2) fabrication of nanocomposite samples; (3) ballistic impact test. The details of the fabrication steps, materials preparation and ballistic tests have been clarified in the following sections.

2.1 Matrix preparation

In this study, three types of nanoparticles were prepared. In the first category, a desired amount epoxy resin was mixed with various amounts of nanoclay and nanocalcite particles. The epoxy resin filled by 1 wt.% and 2 wt.% of nanoclay and nanocalcite was chosen due to the excessive increase in the mechanical behaviour of composites in prior work Haque *et al*. (2003).

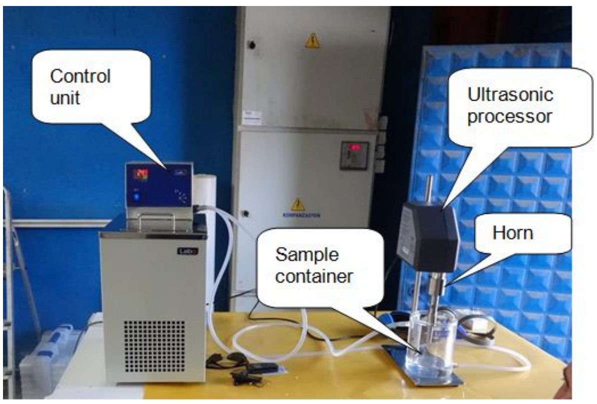


Fig. 1 Ultrasonic processor (Hielscher UP-400S) mechanical mixing of part nanoparticle of epoxy

In the production stage of nanocomposites, it is difficult to get effective dispersion of the nanoparticles in the polymer matrix. Ultrasonic cavitation technique is one of the most efficient means to disperse nanoparticles into a polymer. Hielscher UP400S ultrasonic processor (Ultrasonic Device UP400S 400 watts, frequency 24hHz amplitude adjustable 20-100%) as shown in Fig. 1 was used to obtain a homogeneous mixture of epoxy resin and Eczacıbaşı Product nanoclay. The mixture of epoxy resin and nanoclay was stirred at 25°C for an hour with an ultrasonic device to carry out clay dispersion into polymer matrix.

It was used as a high speed shear mixer at a shear rate of 2500 rpm for 1 h for homogeneous mixture of epoxy resin. Then, sonication for 2 h was performed by using an ultrasonicator to further disperse the nanoparticles (clay, calcite and carbon). Attention was taken to prevent from formation of bubbles. During the mixing process, the resin temperature was ensured at a certain value. After sonication, the epoxy/clay mixture displayed a uniform distribution of particles. The process of dispersing nanocalcite and nanocarbon into epoxy resin and the mixing ratios of nanocalcite-nanocarbon, epoxy and hardener were similar as described earlier.

The epoxy resin and hardener used in this study was provided by Fibermak, Turkey. The nanoclay and nanocalcite particles used in this study were organically modified montmorillonite minerals of type supplied by Eczacıbaşı Product and Afyon Adaçal Product, Turkey, respectively. Short length multi-walled carbon nanotubes – DWCNTs was supplied with Ege Nanotek Inc., İzmir, Turkey. Table 1 summarizes properties of short length multi-walled carbon nanotubes used in this study.

The samples of both epoxy–nanoparticles and pure epoxy composites were prepared for identifying ballistic impact performance. Totally 10 compositions were prepared in order to display a gradual trend of changes upon ballistic performance, they were pure epoxy, that is 0 wt% nanocarbon, 0.5 wt%, 1 wt%, 2 wt% nanocarbon and 1 wt%, 2 wt% nanoclay and nanocalcite. Notice that 0% nano-particles concentration is used as a benchmark for compari-son purposes.

2.2 Fabrication of nanocomposite laminates

The laminated samples had been fabricated using hand lay-up method. The structure was composed of 20 layers

Table 1 Properties of short length multi-walled carbon nanotubes

Purity	%98
-OH Content	Wt %1.76
Outer diameter	10-20 nm
Inner diameter	5-10 nm
Length	0.5-2.0 μm
Surface area	> 200 m^2/g
Colour	Black
Density	0.22 g/cm^3
Electrical conductivity	> 100 S/cm

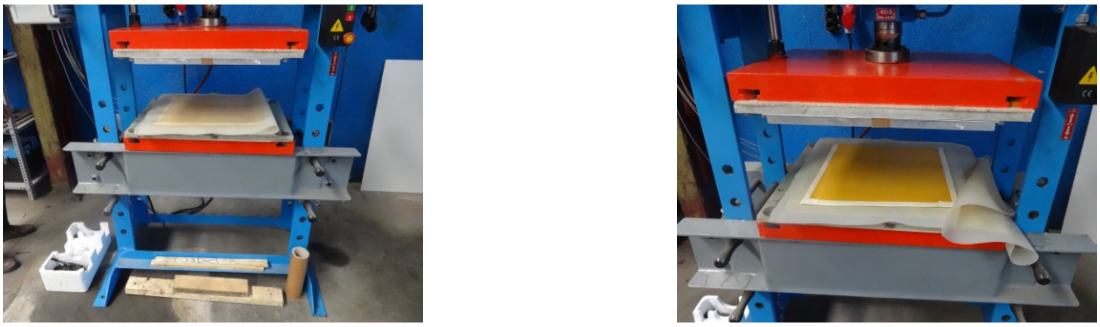


Fig. 2 Curing of nanocomposite laminates

Table 2 Properties of Twaron CT 736-1680 dtex

Linear density [dtexnom] Warp & Weft	1680×1640
Weave type	Plain
Thickness	0.25 mm
Breaking strength	385 N

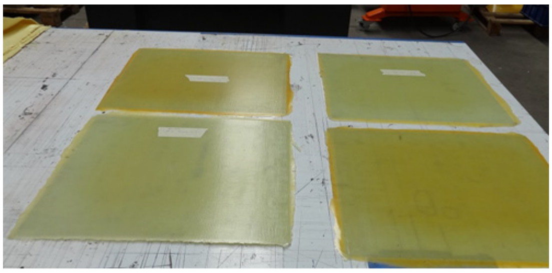


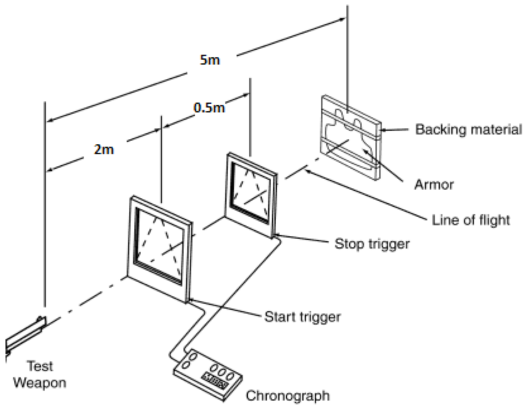
Fig. 3 Pictures of the fabricated laminates with epoxy resin and epoxy filled with nanoparticle

of Kevlar fibers. Then, Kevlar prepregs were wetted by a thin layer of the epoxy/clay, epoxy/calcite and epoxy/carbon, separately. The Kevlar used in this study was supplied by Fibermak, Turkey. Fiber volume fraction of the structure was approximately 60%. In Table 2 properties of Twaron CT 736-1680dtex is showed.

Weight ratio of 1% and 2% of nanoclay and nanocalcite; had been added to the base epoxy resin while nanocarbon with percentage of weight (0.5-1-2%) was added to the epoxy. Curing of the Kevlar/epoxy nanoclay and nanocalcite and nanocarbon plate was carried out for 150 minutes at 80°C followed by 150 minutes at 120°C. Kevlar prepregs was stacked until a desired thickness of composite (Fig. 2).

After curing process, a plate with average thickness of 2 mm ready to be cut into plates. Finally, the fabricated nanocomposite laminated plate had been cut into 300 mm long and 300 mm width plates. Fig. 3 shows the fabricated nanocomposite laminated plate.

(a)



(b)

(c)

(d)

Fig. 4 (a) Photograph of a typical ballistic impact test facility; (b) schematic view of ballistic test setup; (c) test weapon; (d) fragment projectiles

2.3 Ballistic tests

The ballistic impact tests were performed at the 8. Main Maintenance Center Command in Afyon, Turkey. The National Institute of Justice Standard NIJ 01.01.04 was used for the experimental set-up.

A single stage gas gun operated ballistic impact test apparatus was used for experimental ballistic studies. Fig. 4 indicates a photograph of the ballistic impact test apparatus used in this study. Projectile propelling mechanism, chronograph for velocity measurement, support stand for holding the specimen are test apparatus. The high-speed gas gun which is used for ballistic impact tests is shown in Fig. 4.

The target was impacted by a full metal jacket projectile (FMJ). The FMJs are defined by MKE (Mechanical and Chemical Industry) and manufactured according to 9×19 mm MP-5. The target was impacted by a full metal jacket projectile (FMJ). The mass of the bullet was 3.8 g. Technical properties of 9 mm FMJ are given in Table 3. A full metal jacket projectile (FMJ) is shown in Fig. 4.

2.4 Test procedure

The specimen dimension was controlled by specimen holder device which was a part of the ballistic impact test apparatus. Ten plates were constructed for each configuration and each plate was impacted with six projectiles, as shown in Fig. 5. The locations for projectile impact were chosen so as to see the effect of previous impact damage and of boundary conditions.

Table 3 Technical Properties of 9 mm FMJ

	9 mm FMJ
Bullets core diameter (mm)	9.08
Projectile weight (gr)	7.43
Projectile barrel weight (gr)	3.8
Projectile length (mm)	15
The amount of gunpowder (gr)	0.41±0.005

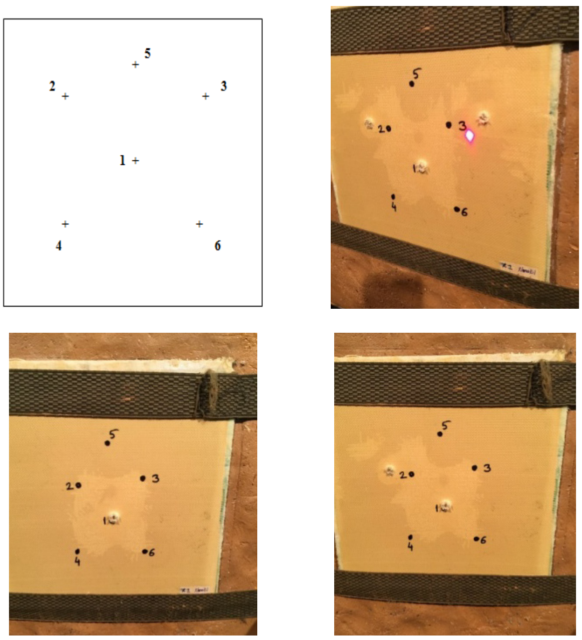


Fig. 5 Sketch of impact locations and firing order for specimen testing

Table 4 Target characteristics

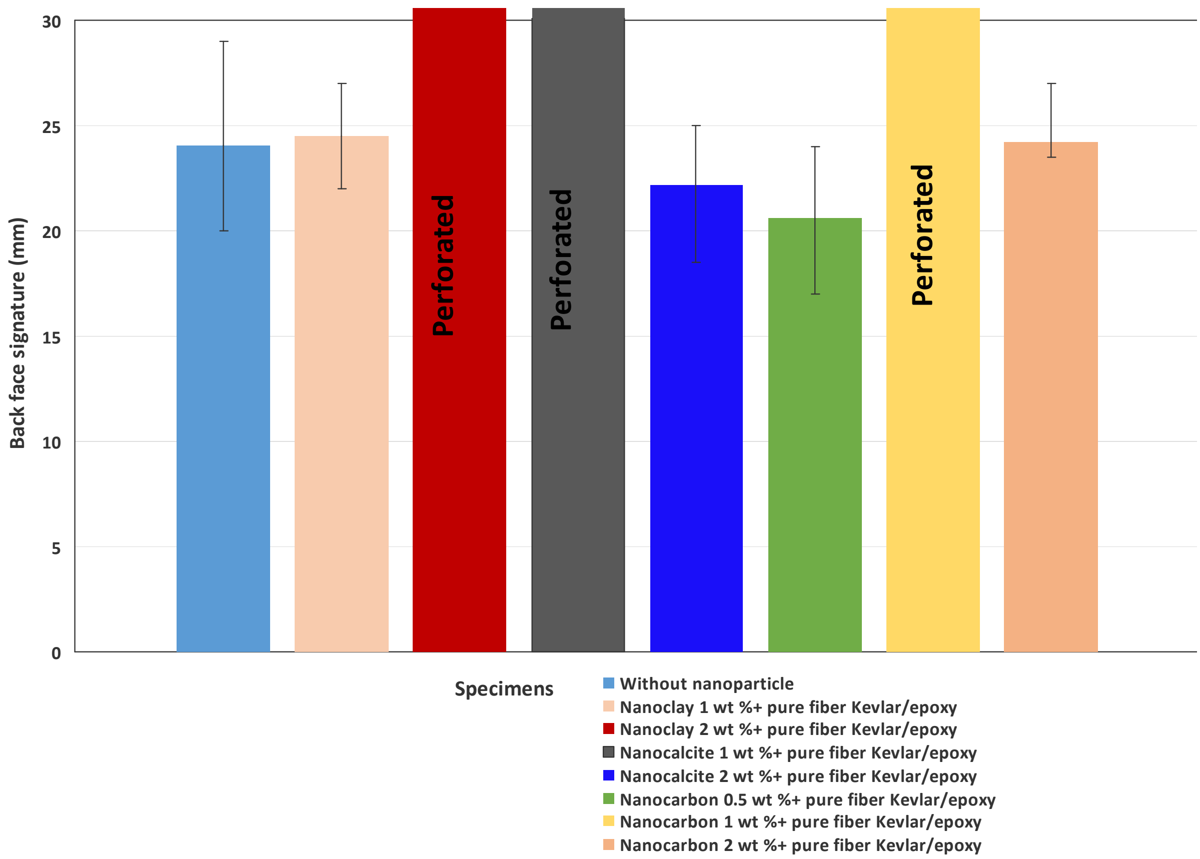
Target ID	Target characteristics	Weight [g]	Total thickness (*t*) [mm]
1	No nanoparticles (pure fiber Kevlar/epoxy) (no nanoparticle addition, Control sample)	988.3 999 1012.4	2 2 2
2	Nanoclay 1 wt %+ pure fiber Kevlar/epoxy	991.4	2
3	Nanoclay 2 wt %+ pure fiber Kevlar/epoxy	1009.5	2
4	Nanocalcite 1 wt %+ pure fiber Kevlar/epoxy	997	2
5	Nanocalcite 2 wt %+ pure fiber Kevlar/epoxy	1021.7	2
6	Nanocarbon 0.5 wt %+ pure fiber Kevlar/epoxy	1020.9	2
7	Nanocarbon 1 wt %+ pure fiber Kevlar/epoxy	1026.3	2
8	Nanocarbon 2 wt %+ pure fiber Kevlar/epoxy	1024.9	2

The tests can be grouped under two categories. The first set of ballistic tests was composite laminates with epoxy resin. At the first, Kevlar fiber epoxy composite plates with 0% nanoparticles concentration were tested in order to set the basis for comparison when testing subsequent configurations. The second set of ballistic tests was conducted on laminates with epoxy filled by three different nanoclay, nanocalcite and nanocarbon. The ballistic tests were also carried out to show how the performance of Kevlar composites can be increased by nanoclay, nanocalcite and nanocarbon. Table 4 shows eight different types of targets for investigating the nanoparticle effect on target protection. Implications of the results of the composite plate configurations, ballistic impact performance comparisons were made.

The ballistic test begins with firing a projectile at an estimated velocity. If any fragment of the projectile forms a hole, then it constitutes a complete penetration. Otherwise, a partial penetration is considered. If the previous projectile is to be concluded a partial/complete penetration the next projectile is fired with a higher/lower velocity, respectively. This procedure is repeated to acquire progressively smaller differences between partial and complete penetrations. Projectile speed that would scarcely penetrate the specimen was varied between 411-441 m/s. The average impact velocity was 426 m/s.

The caused damage has to be quantified since the high-velocity impact is accomplished. The projectile's radial deformation was evaluated to characterize the effect of the projectile on energy absorption and the penetration region. Perforation, fiber breakage, and matrix cracking are impact damage.

Table 5 Ballistic test results



3. Results and discussion

In the ballistic tests, the aim was to find out the best ratio of the additive nanoparticle added into the epoxy resin to prevent the perforation. The results were presented as complete penetration or partial penetration. It is considered whether the target is perforated completely penetrated at the back or not. A number of damage mechanisms were displayed for composite plates added with nanoparticles obtained from experimental tests. Failure modes changed with the addition of nanoparticles. After ballistic impact test, it was cared damage areas on the front and back surface. An increase in the delamination process is affected by impact energy. Damage takes place in the form of delamination or matrix crazing at a lower velocity. Later, at higher velocity, it occurs in the fibre–matrix separation, matrix–fiber debonding, fibre failure and combined delamination and fibre failure. The delaminated area can be utilized to evaluate impact energy absorption on composite plate. The mechanism of failure and energy-absorbing capability of Kevlar/epoxy/nanoparticle nanocomposites in ballistic impact tests is affected many parameters such as projectile geometry, projectile velocity, the properties of the matrix and fiber and the fiber-matrix adhesion. Intense delamination area in the back side and front side and central fiber breakage which is the main failure modes occurs under ballistic test. During ballistic impact, energy transfer occurred from the projectile to the target relies on density, tensile strength, hardness, toughness, failure strain, strain–stress relationship and fracture toughness of Kevlar/epoxy/nanoparticles nanocomposites. Delamination, friction, cone formation on the face of the target tension failure primary yarns and the elastic deformation are probable energy absorbing mechanisms. During ballistic impact, tension loading developed through the composite thickness created fiber breakage. At the same time, delamination is occurred by shear stress generated between the layers.

Table 5 summarizes the specimen of ten ballistic impact tests conducted in this study. As can be seen in Table 5, it is possible to conclude that specimens with 1% nanoclay and 2% nanocalcite content are the ones with best performance with respect to ballistic impact. The only specimens where no perforation is noticed are the ones with 1% nanoclay, 2% nanocalcite and with 0% nanoparticles content.

For 2 wt% nanocalcite samples impacted, energy absorption capacity was higher than the 1 wt% nanocalcite samples. Another interesting observation was the 9 mm FMJ impact for control samples. The energy absorption for the control sample (no nanoparticle addition) was higher than the 2 wt% nanoclay and 1 wt% nanocalcite samples. The nanocomposite becomes brittle by adding of an extra amount of nanoclay and nanocalcite (2 wt% nanoclay and 1 wt% nanocalcite). The energy absorption is lower bound for the 2 wt% nanoclay and 1 wt% nanocalcite samples. A little nanoparticle-epoxy nanocomposite was much better in resisting ballistic impact comparing with the control sample (no nanoparticle addition). The presence of small amounts of nanoparticle, such as nanoclay and nanocalcite, epoxy matrix can improve the impact properties of the nanocomposite. Addition of 1 wt% clay and 2 wt% calcite

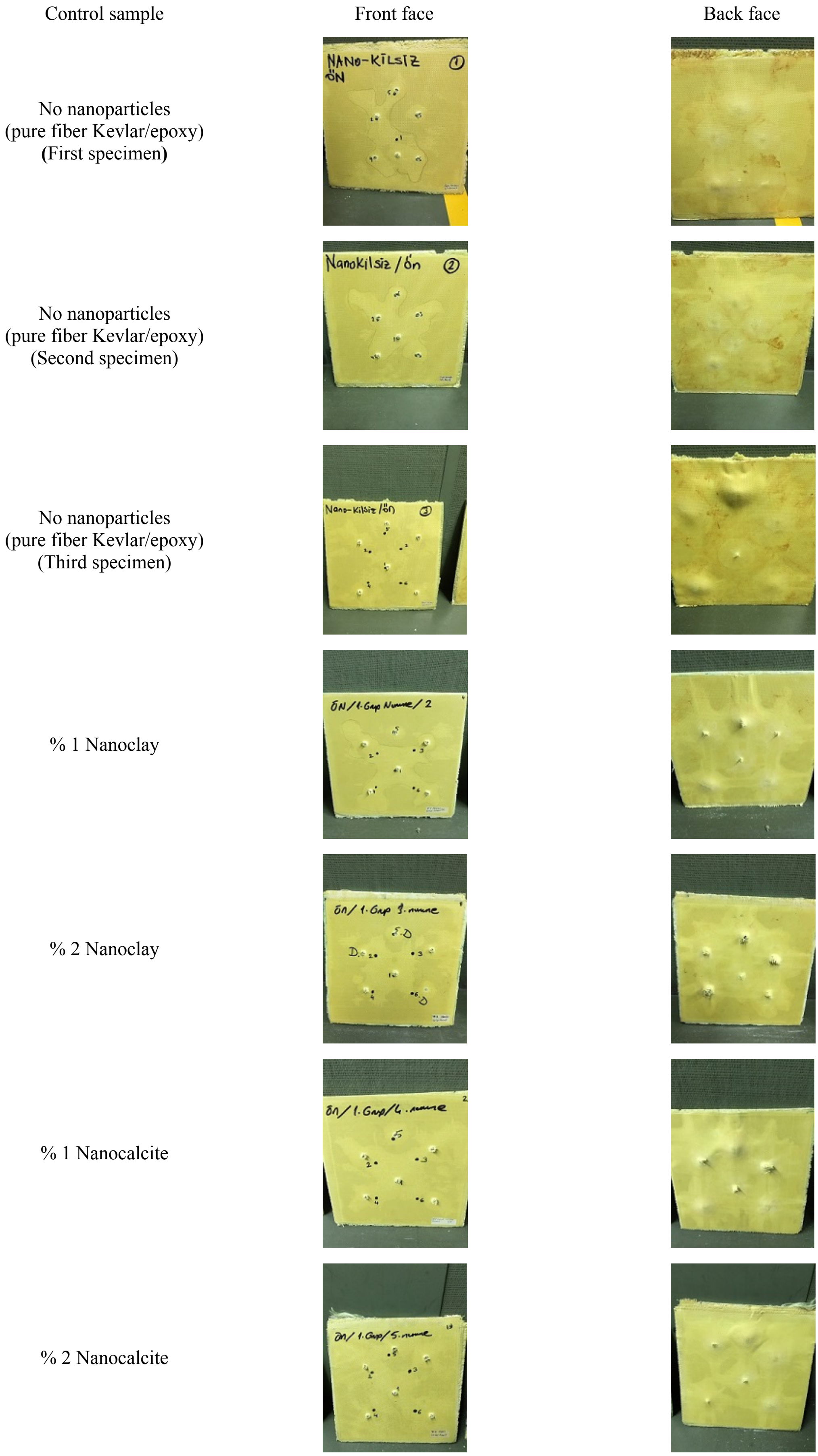


Fig. 6 Post impact photos of damaged specimens' profiles: front view and back view

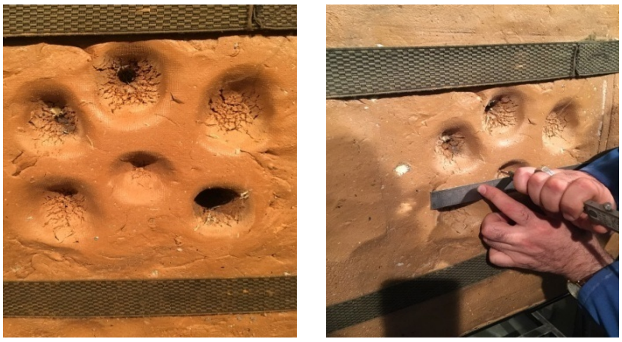


Fig. 7 Measurement of the amount of collapse after ballistic test

were shown to be an optimal content for the highest damage resistance. The Kevlar fibre reinforced plastic laminates containing nanoclay and nanocalcite cause considerable improvement in impact damage resistance and damage tolerance in the form of smaller damage area.

The damage is localized and can be easily noticed by the naked eye in ballistic impacts. The presence of nanocarbon in the epoxy matrix induced the transition of failure mechanisms of Kevlar fibre reinforced plastic laminates during the ballistic test, from the ductile mode to more brittle mode.

Failure mechanism, damage area and the deformation area of nanocomposites are being different according to amount of nanoparticle dispersion into the epoxy matrix and quality of nanoparticle dispersion. Fig. 6 shows photos of damage in laminated plates: front view and back view of samples. When the projectile initially impacted that plate, a compressive wave occurred through the thickness of the laminate and reflected off the rear surface as a tensile wave, which may produce delamination. It was observed delamination between plies through the thickness of the nanocomposite plate. The delaminations were large near the front face and the back face whereas the delaminations were reduced in the mid region. Also, damage was most strong the back face. This is indicated in the photo shown in Fig. 6. Because the initial shock wave created upon impact, the delamination occurred near the front face of the composite. The dimension of delamination area was reduced because of creation of the shear plug. As the velocity of the projectile decreased as it penetrated the composite, the Kevlar fibers have increasingly more time to fail. The delamination area outwards propagated with depth in the composite. These results are convenient with comment accomplished by literature.

For 0.5 wt%, 1 wt% and 2 wt% nanocarbon samples impacted, the projectile penetrated through and exited from the back side of the composite. There was serious damage to the composite. Increasing the percentage of nanocarbon don't improve the ballistic performance of the plates for all impact velocity, the rate of improvement of the ballistic characteristics of the plates began to decline, when the weight ratio of nanocarbon reaches to 2%. Perforation occurred for 0.5 wt%, 1 wt% and 2 wt% nanocarbon samples. The extra nanocarbon layer split up from the fiber Kevlar/epoxy/nanocarbon part. The extra nanocarbon layer produces stress discontinuity at the interface nanocarbon layer/laminate. Notice that, some cracks were also noticed because of brittle behaviour of the carbon. Furthermore, an extensive damage can also be considered for nanocarbon samples.

The back face signature criteria must be determined and less than 44 mm according to NIJ standard (Reis *et al*. 2012) (Fig. 7). The back face signature is the depth of depression in backing material. When the back surface signature criteria were analyzed, there were no perforation for 1 wt% nanoclay and 2 wt% nanocalcite samples.

In stopping a bullet, a change of penetration mode, and the deformation of the bullet have to be regarded. Penetrations occurred for the first layers without significant deformation of the projectile, whereas the last layers are penetrated partially or not penetrated at all, and experience a high degree of deflection. There was no perforation the composition with pure epoxy sample. For the case when the filler nanoclay content employed was 2 wt.% of the epoxy resin–hardener mixture, it was observed that complete perforation of the bullet occurred. The perforation was occurred with the increasing amount of nanoclay. The nanoparticle agglomerate in nanoclay content 2 wt% the epoxy/nanoclay surface interactions were reduced. In addition, the clay agglomerates become brittle under ballistic impact loading. Also, the clay agglomerates treats as stress concentrators or crack initiation sites in the matrix. As a result the ballistic impact performance of nano-composite was decreased by adding nanoclay. By adding nanoclay, the largest damage area of nanocomposite was in clay content 2 wt%, which was responsible for the lower energy-absorbing capability and the cone area results in increase. Experimental studies demonstrated that, with the nanoclay with percentage of weight 2% complete perforation of the bullet became with near zero exit velocity. Only partial penetration occurred for the case of the targets with thicknesses of 1 wt% nanocalcite.

The 2 wt% nanoclay samples was impacted at 425 m/s, 428 m/s and 430 m/s, the 9 mm FMJ projectile penetrated into the composite. Similarly, 1 wt% nanocalcite impacted at 435 m/s the 9 mm FMJ projectile penetrated into the composite. Also, delamination was observed for the 2 wt% nanoclay and 1 wt% nanocalcite specimens.

At a velocity of 430 m/s, 428 m/s and 425 m/s, specimens dispersed into the epoxy system in 2% ratio clay failed and perforated. Similarly, specimens and filling with 1% calcite and 1% carbon perforated at a velocities of 435 m/s, 443 m/s, respectively. Nanocarbon -epoxy nanocom-posites were the materials that had failure through the thickness at low and intermediate velocities. For example, nanocarbon-epoxy nanocomposites 2% ratio perforated at velocities of 424 m/s, 427 m/s. All of the composites with nanocarbon perforated in comparison with non-nanoparticle composites. The perforated areas for nanocomposites were considerable different than those observed for composites with non-nanoparticle composites.

As a result, the ballistic impact performance can be improved with the addition of nanoclay content up to 1 wt.% and then decreases for 2 wt.%. However the ballistic impact performance decreases with the addition of nanocalcite content up to 1 wt.% and then again increases for 2 wt.%. The presence of nanoclay or nanocalcite resulted in distinct failure modes. Also, the ballistic performance of control sample (no nanoparticle addition) cannot be improved by the addition of nanocarbon.

4. Conclusions

In this study the effect of the nanoclay, nanocalcite and nanocarbon on the ballistic performance of Kevlar/ composite plates were investigated experimentally. It can be seen that there is a major effect of nanoparticles on ballistic impact performance of the target. Notice that, the addition of nanoclay and nanocalcite to ballistic materials was a widespread strategy utilized to increase energy dissipation by projectile split. The strength and capability of energy absorbing for composites can be increase with adding the nanoclay particles. However, the dispersion quality of the nanoparticle in composite is affected ballistic impact performance of composite.

Dispersed little nanoclay and nanocalcite particles caused significant improvements in ballistic performance. However, as the amount of clay is increased, the ballistic performance of epoxy–clay nanocomposites decreased. The ballistic performance of epoxy–calcite nanocomposites increased with calcite quantity all the way up to 2%. Clay layers were ineffective as nanocomposite fillers since the clay layers was broken the higher speeds. The ballistic performance showed best results at lower clay and higher calcite causing specimen brittleness and disruption of its properties. The laminates manufactured with epoxy resin filled by 1 wt.% of nanoclay shown the best performance in terms of ballistic performance. Also, the addition of nanocarbon reduced ballistic performance in comparison with 0% nanoparticles concentration. The addition of nanocarbon to fiber Kevlar/epoxy laminates not only decreased the ballistic impact resistance of these composites, but it also had major influence on their failure mechanism. Therefore, it is not suggested the use of nanocarbon in composites for ballistic impact test. It is recommended the use of nanoclay or nanocalcite as nanocarbon replacement.

Acknowledgments

The authors gratefully acknowledge The Scientific and Technological Research Council of Turkey (TÜBİTAK) for the financial support 114M762 project for carrying out this work.

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