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Comparative Study of Shape Memory Alloy Reinforced Kevlar Polymer Composite in Sheet and Wire Form with Plain Kevlar Polymer Composite

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Abstract: The main objective of this work is to investigate the effect of shape memory alloy reinforcement in Kevlar polymer composites on mechanical and low-velocity impact properties. The sheet and wire forms of shape memory alloy (SMA-nickel-titanium alloy) are used as potential reinforcements in Kevlar-reinforced polymer composite. The developed composites were analyzed for tensile and flexural behavior. The effective bonding area, referred to as core density, contributes to incremental flexural strength in the SMA sheet reinforced composites. The developed composites exhibited better impact resistance during low-velocity impact tests at different velocities, 2.80, 3.96, and 4.85 m/sec, and simulated using a CEAST drop hammer testing machine. The impact surface of the specimen was studied on a micro-level using SEM analysis and macro-level using Image J software. The impact force, the energy absorbed, and the deformation of the specimen during impact were recorded and analyzed. The experimental results reveal that the SMA sheet reinforced Kevlar composites exhibited appreciable impact resistance with maximum energy absorbing capacity comparatively with plain Kevlar and SMA wire reinforced composites.

Keywords: low-velocity impact, shape memory alloy, Kevlar, better adhesion, fiber cracking, inter crystalline fracture.

Introduction

Kevlar¹⁻³ technically called Poly-para phenylene terephthalamide presented in Figure 1 is a heat-resistant lightweight strong fiber mainly used for ballistic armor applications in epoxy polymer composites. It is also used in various applications such as safety gloves for industries, ropes for handling heavy-weight applications, and low-velocity impact applications. The research on strengthening Kevlar composites to enhance impact resistance using metallic particulate rein-

forcements, sheet metal compounds, and different processing routes is extensively carried out. There is limited research on Kevlar composites reinforced with shape memory alloys (nickel-titanium alloy), and the effect of SMA (shape memory alloy) reinforcement on the low-velocity impact resistance of the composite materials. The high deformation resistance and shape-retaining property post removal of loading structure, which is the unique property of shape memory alloys, can be integrated with plain Kevlar composites. Also, SMAs withstand high energy deformation, thus potentially suitable for ballistic armor applications. The other applications of SMA include fire alarm, smart structures, cryo bolts used for rocket launching applications, and many more. The current research focuses on improving mechanical properties⁴⁻¹⁰ with less num-

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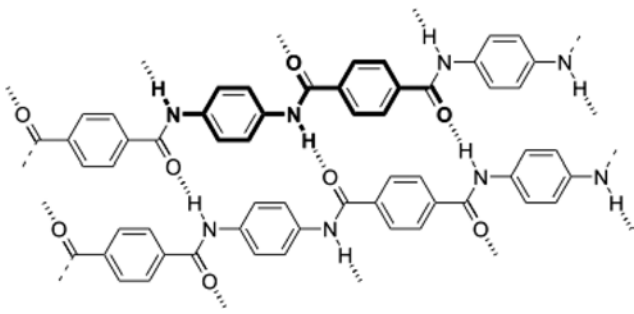


Figure 1. Chemical structure of Kevlar.

ber of reinforcement layers. Although Kevlar is a tough material that suits armor applications the current research focuses on improving the tensile,¹¹ flexural,¹² impact¹³⁻²² resistance by reinforcing Kevlar epoxy polymer composites with Ni-Ti SMA in the form of wire and sheet.

Prasad *et al.*²³ reported that employing epoxy resin as a matrix has shown good adhesion behavior to the embedded Kevlar and basalt fabric. Ramadhan *et al.*²⁴ reported that during ballistic impact the increase in thickness of aluminum laminated panels has increased the energy absorption capacity. Shi *et al.*²⁵ have reported that in nanocomposites, metal laminates, in the form of sheets can be used as reinforcement to improve the impact resistance and reported modes of failure observed during high-velocity impacts such as fractures and pullout, matrix cracking, and delamination. Kang *et al.*²⁶ investigated the impact strength of Kevlar-reinforced polymer composites based on the fabric knitting method and found that multi-axial warp knit composites have better impact resistance than woven laminates. Rajan *et al.*²⁷ have stated that carbon fiber-reinforced aluminium laminates [carbon₄/aluminium₃] manufactured by hand lay-up method using epoxy resin could withstand low-velocity impact at 10 J without complete penetration.

Rahman *et al.*²⁸ reported that the addition of graphene to the Kevlar epoxy matrix as reinforcement decreases the impact resistance of the composite, but the addition of nano clay with graphene as reinforcement reduces the damaged area and increases the resistance to UV degradation and wettability. Sharma *et al.*²⁹ have stated that the amount of energy absorbed during impact is directly proportional to the bending stiffness of the material and the value can be obtained from the peak value of the impact energy vs deflection graph. Carrillo *et al.*³⁰ stated that aramid fiber reinforced polypropylene and aluminium alloy Al 5052-H32 with the stacking sequence [Al/Kevlar₂/Al]_s has tensile strength between aluminium and Kev-

lar-reinforced polymer composites and impact resistance was found as 34.9 J without penetration. Hu *et al.*³¹ have investigated the specimens after low-velocity impact using an ultrasonic C scan and industrial computed tomography to reveal the damaged area and damage distribution. From the literature review, we can infer that most of the Kevlar-reinforced polymer composites employ epoxy resin as the matrix as it offers superior properties compared to other resins. And also reinforced Kevlar composites in the form of nano additives, metal laminates have gained commendable interest among the researchers. The present work objectively focuses on employing nickel-titanium SMA in the form of sheet and wire reinforced in plain Kevlar composites, following the hand layup technique. The developed composites are tested for tensile strength, flexural strength, core density, and low-velocity impact.

Experimental

Specimen Preparation. The Kevlar 49 fiber, a bi-directional oriented (0° and 90°) 400GSM, and epoxy resin CT/E-120 and CT/AH-60 were used for preparing plain Kevlar composites using the hand lay-up technique. SMA in the form of wire and sheet is used for developing SMA reinforced Kevlar composites. Four specimens were prepared in the size 300 mm×300 mm by hand lay-up method and the rule of the mixture with the ratio of 50:50 by the percentage of resin to that of reinforcement by weight. The stacking sequence of the specimens is shown in Figure 2. The specimens with different configurations like Kevlar/Kevlar/Kevlar; Kevlar/SMA wire/Kevlar, and Kevlar/SMA sheet/Kevlar were formed by stacking Kevlar fabric of thickness 1 mm as three layers for plain Kevlar composite; and adding SMA in wire form of diameter 1 mm as additional reinforcement between the two Kevlar fabrics at an interval of 9 mm for SMA wire reinforced Kevlar

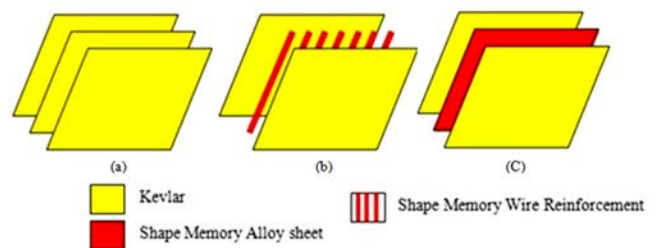


Figure 2. Stacking sequence of different forms of reinforcement (a) [Kevlar/Kevlar/Kevlar]; (b) [Kevlar/SMA wire/Kevlar]; (c) [Kevlar/SMA sheet/Kevlar].

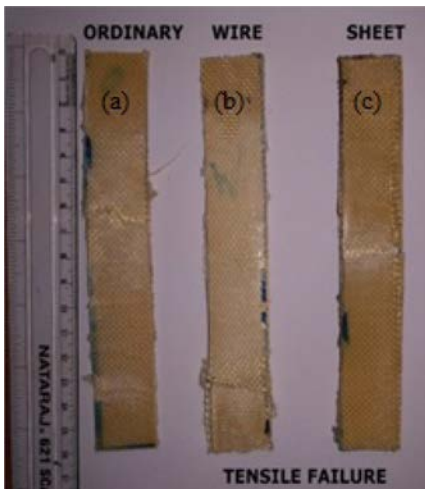


Figure 3. Tensile test specimens after testing (a) [Kevlar/Kevlar/Kevlar]; (b) [Kevlar/SMA wire/Kevlar]; (c) [Kevlar/SMA sheet/Kevlar].

composites, and by adding SMA in sheet form, placed in between the two Kevlar fabric for SMA sheets reinforced Kevlar composites. The samples were fabricated using the hand lay-up method by stacking composites in sequence with epoxy resin and hardener mixed in the ration 10:1 to form the composites.

Tensile Test. The tensile test was carried out in the Instron 3382 testing machine as per ASTM D-3039 standard. During the tensile test, the specimen was clamped at the ends by a specimen holder and the test was carried out at a speed of 5 mm/min. The different reinforcement for the tensile test is shown in Figure 3. The results of the tensile test are shown in Table 1.

Flexural Test. The flexural strength of the sandwiched composite samples was evaluated using the Instron 3382 testing machine using a three-point bend test setup as per ASTM D-790 Standard. Five specimens were tested for each sample and the average value was tabulated. The different reinforcement for the flexural test is shown in Figure 4. To get a better surface finish at the edges abrasive water jet machine was employed to cut the specimens. The results of the flexural test are shown in Table 1.

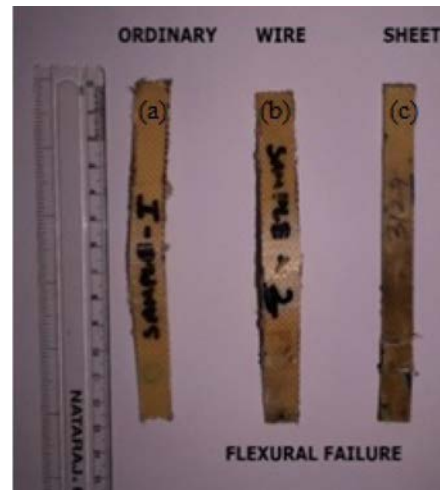


Figure 4. Flexural test specimens after impact (a) [Kevlar/Kevlar/Kevlar]; (b) [Kevlar/SMA wire/Kevlar]; (c) [Kevlar/SMA sheet/Kevlar].

The flexural strength is calculated using the formula³²

$$\sigma = \frac{3fl}{2bd^2} \tag{1}$$

σ : flexural strength, f : force, l : length between the supports, b : specimen width, d : specimen thickness

Low-Velocity Impact Test. The impact test was carried out in the CEAST Fractovis drop weight impact tower. It employs a hemispherical striker of size 25 mm diameters and weight 1.926 kg. The specimen was held in a circular enclosure of diameter 79 mm clamped with a 50 N force to avoid lateral movement of the specimen. The impact test was conducted on different Kevlar specimens at different velocities 2.8, 3.96, and 4.85 m/sec. The impact force, impact energy, deformation, the time during the impact, and rebounding were recorded using a data acquisition system. For this purpose, an inbuilt piezoelectric sensor inside the striker was used for recording the energy absorbed and the force generated during impact. A standard ASTM D5628-D standard was used for testing the specimens. The top and bottom surfaces of the specimen post-impact tests are shown in Figure 5.

Table 1. Tensile and Flexural Test Values for Different Specimens

Specimen	Tensile strength (MPa)	Flexural strength (MPa)	Density (gm/cm ³)
Plain Kevlar-reinforced polymer composites	196.09	130.97	1.40
SMA wire reinforced Kevlar polymer composites	135.53	116.49	1.84
SMA sheet reinforced Kevlar polymer composites	136.25	285.30	2.90

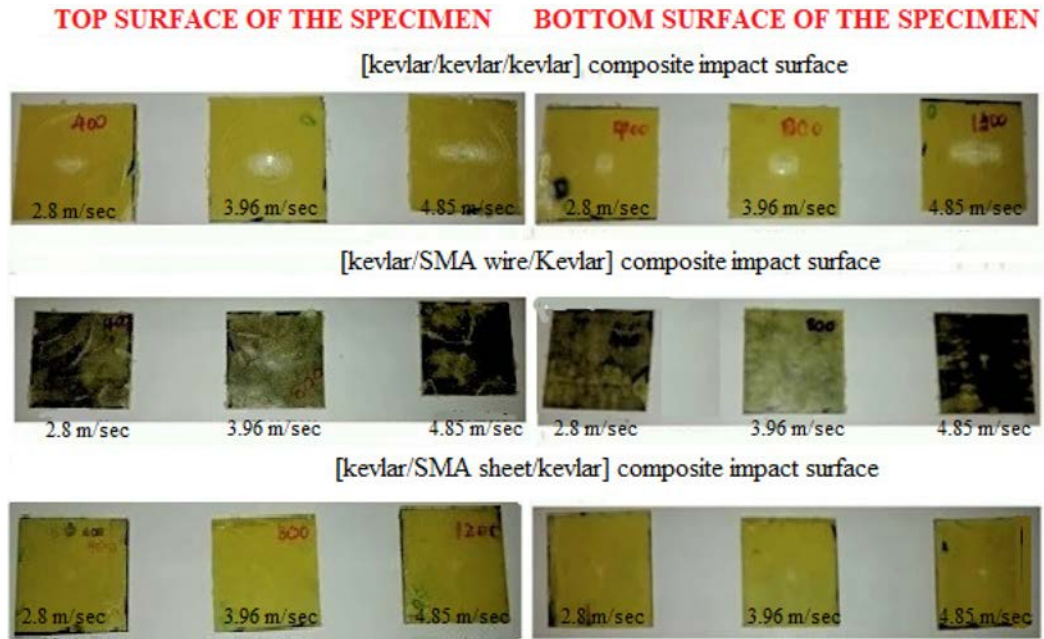


Figure 5. Low-velocity impact at bottom and top surface of the reinforced composites.

Results and Discussion

Tensile Test. The tensile and flexural test was carried out and the following readings obtained during testing are discussed below. The density of the composite is calculated using the formula below.

$$\text{Density, } \rho = \frac{m}{v} \tag{2}$$

$$\rho_{\text{composite}} = \rho_a \times V_a + \rho_b \times V_b \tag{3}$$

Where, ρ_a : density of the matrix a, ρ_b : density of the reinforcement b, V_a : volume of the matrix a, V_b : volume of the reinforcement b

From Table 1, we can observe that [Kevlar/Kevlar/Kevlar] composite stacking sequence has better tensile strength 196.10 MPa compared to [Kevlar/SMA wire/Kevlar] and [Kevlar/SMA sheet/Kevlar] composite. The high tensile strength in the composite is due to the uniform stacking sequence of Kevlar fabric and increased adhesion observed between epoxy resin matrix and Kevlar fabric as reinforcement. The [Kevlar/SMA sheet/Kevlar] and [Kevlar/SMA wire/Kevlar] composite specimens have lower tensile strength compared to [Kevlar/Kevlar/Kevlar] composite specimen because of poor adhesion between the epoxy resin matrix and SMA sheet & wire reinforcement. Also, the deformation behavior of the specimen

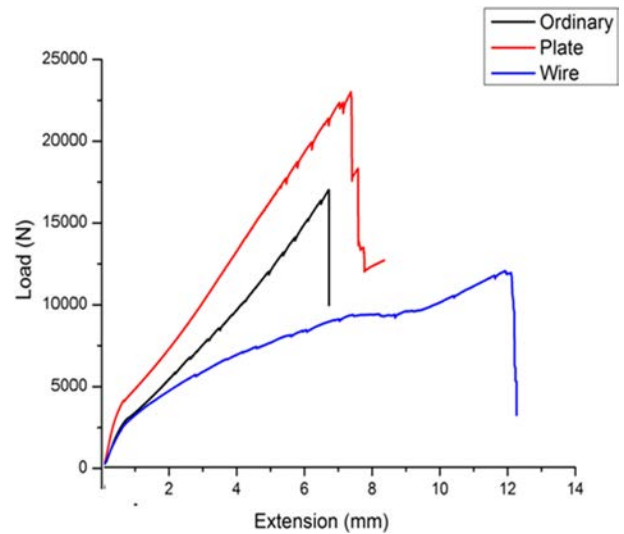


Figure 6. Tensile strength vs deformation of the reinforced composites.

during testing is shown in Figure 6. The [Kevlar/SMA sheet/Kevlar] and [Kevlar/SMA wire/Kevlar] failure mode observed during the tensile test was delamination across the cross-section of impact. In [Kevlar/Kevlar/Kevlar] composite failure is observed as matrix cracking along with fiber cracking.

Flexural Test. Flexural strength is considered an important mechanical property of any composite, as, it is related to the bending strength of the material. During the flexural test, a combination of tensile stress acts on the specimen's outermost

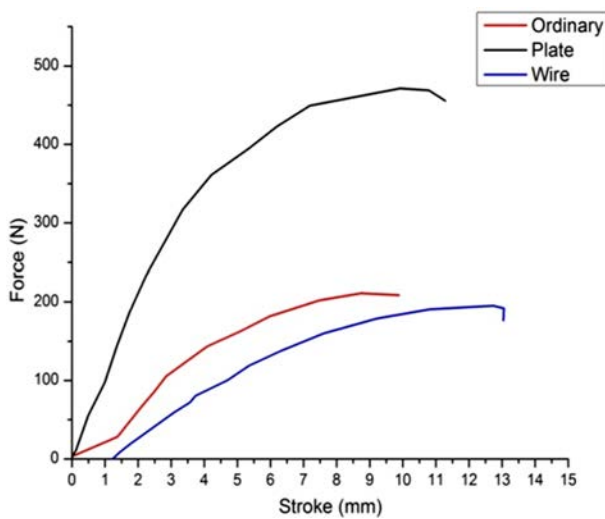


Figure 7. Flexural strength vs. deformation of the reinforced composites.

top surface of the composite, and compressive stress will act on the bottom surface of the composite specimen. The minimum flexural strength was observed for [Kevlar/SMA wire/Kevlar] composite specimen 116.49 N. The replacement of the middle Kevlar layer with the SMA sheet layer as reinforcement increased the flexural strength from 130.97 to 285.30 N, which is higher than [Kevlar/Kevlar/foam], as stated by Samlal *et al.*³² The increase in flexural strength of [Kevlar/SMA sheet/Kevlar] as the fracture toughness of nickel-titanium alloy [SMA] is high³³ around 6.45 gm/cm³. The failure mode observed in [Kevlar/Kevlar/Kevlar] and [Kevlar/SMA wire/Kevlar] composite was indentation, micro buckling at the top surface of the epoxy matrix. Also, core shear was observed at the bottom surface of the [Kevlar/Kevlar/Kevlar] composite,

similarly observed.³² The failure mode observed in [Kevlar/SMA sheet/Kevlar] composite was buckling at the center of the specimen and matrix cracking. The deformation behavior post flexural test is depicted in Figure 7.

Low-Velocity Impact Test. Impact Force vs. Time: The impact force or impact resistance offered by the material during the drop weight impact during different velocities is presented in Table 3. The tests were carried out on [Kevlar/Kevlar/Kevlar], [Kevlar/SMA wire/Kevlar], [Kevlar/SMA sheet/Kevlar] and the force was recorded using a data acquisition system. From Figure 8, it is very clear that an SMA sheet reinforced Kevlar polymer composites generated a huge amount of force compared to [Kevlar/Kevlar/Kevlar] and [Kevlar/SMA wire/Kevlar]. Also, a single peak force around 3361, 5951, 7850 N was generated for SMA sheet reinforced polymer composite at different impact speeds, and the impact force was absorbed within a short period compared to other specimens.

Impact Force vs Deformation: The graph depicts the relation obtained between impact forces generated during the impact of the drop hammer weight when it comes in contact with the specimen. It is very clear from Figure 9 that in all the three impact velocities 2.80, 3.96 and 4.85 m/sec the [Kevlar/SMA sheet/Kevlar] composite has generated high force compared to [Kevlar/Kevlar/Kevlar] and [Kevlar/SMA wire/Kevlar] composites. Also, we can observe that the [Kevlar/SMA sheet/Kevlar] composite has a very narrow area below the peak force, which shows that the deformation of the material was very less or negligible. Also, for all the [Kevlar/Kevlar/Kevlar], [Kevlar/SMA wire/Kevlar] and [Kevlar/SMA sheet/Kevlar] composites the indenter penetration was not visible. The closed hysteresis curve also depicts that the amount of

Table 2. Details of the Outputs Obtained During the Impact Test of the Specimens

Specimens at different Impact velocities (m/sec)	Peak impact force (kN)	Peak impact energy joules	Maximum deformation (mm)
Plain Kevlar-reinforced polymer composites			
2.80	2.521	07.64	04.46
3.96	2.662	15.91	07.34
4.85	2.740	22.56	11.25
SMA wire reinforced Kevlar polymer composites			
2.80	2.282	07.42	04.35
3.96	3.249	14.48	06.78
4.85	3.019	22.85	10.13
SMA sheet reinforced Kevlar polymer composites			
2.80	3.414	07.04	03.45
3.96	5.976	14.60	04.92
4.85	7.842	22.59	06.29

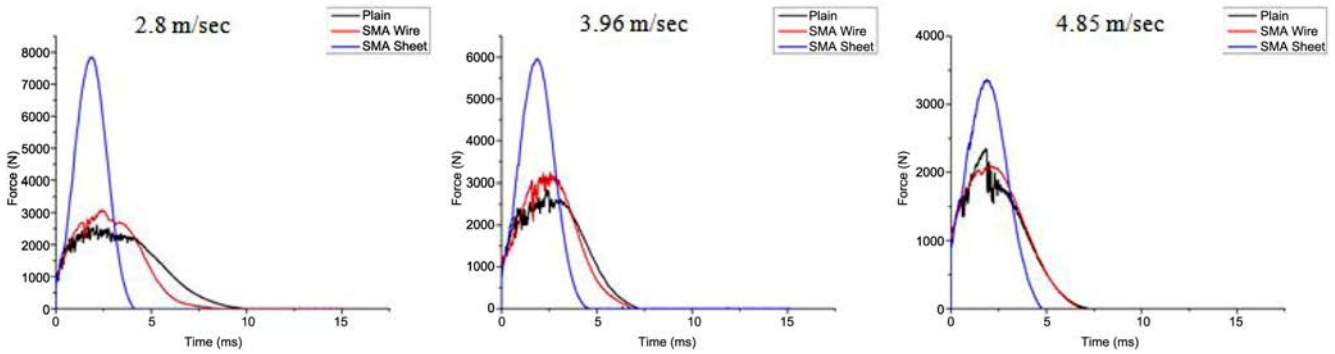


Figure 8. Impact force vs time interaction of the reinforced composites.

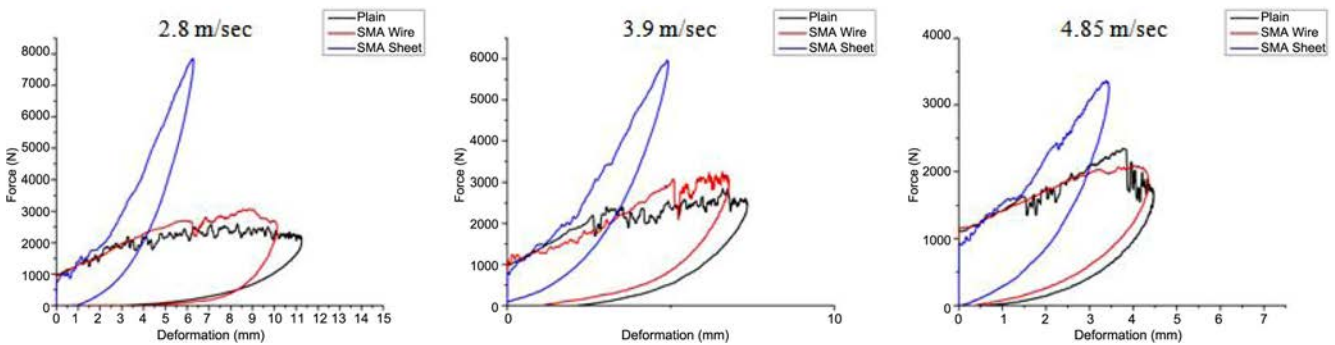


Figure 9. Impact force vs. deformation interaction of the reinforced composites.

Table 3. Impact Force Analysis of the Reinforced Composites

Reinforcement type	Force at 2.80 m/sec (kN)	Increase / Decrease in %	Force at 3.96 m/sec (kN)	Increase / Decrease in %	Force at 4.85 m/sec (kN)	Increase / Decrease in %
Plain	2.52	-	2.66	-	2.74	-
Wire	2.28	-9.48%	3.25	+28.81%	3.01	+11.02%
Sheet	3.41	+35.42%	5.98	+124.44%	7.84	+186.20%

energy released back after impact during unloading and the deformation observed in the [Kevlar/SMA sheet/Kevlar] composite was 20.69, 27.43, 37.90% less than [Kevlar/SMA wire/Kevlar] composite and 22.64, 32.97, 44.09% less than [Kevlar/Kevlar/Kevlar] composite for 2.80, 3.96, and 4.85 m/sec impact velocities respectively inferred from Table 4.

Absorbed Energy vs. Deformation: The relation between the energy and deformation rates between different specimens is depicted in Figure 10. The plain Kevlar polymer composite has the highest energy peak 7.65, 15.12, 22.97 J, and SMA sheet reinforced polymer composite has the lowest energy 7.04, 14.66, 22.69 J. It is observed that [Kevlar/SMA sheet/Kevlar] composite has maximum energy absorption 102.56, 147.04, 324.31% higher than [Kevlar/Kevlar/Kevlar] com-

posite and 22.65, 32.97, 44.09% less deformation compared to [Kevlar/Kevlar/Kevlar] composite for 2.80, 3.96, and 4.85 m/sec impact velocities respectively. Also, a steep energy peak is observed for [Kevlar/SMA sheet/Kevlar] could be observed from Figure 10, which depicts better impact resistance compared to [Kevlar/SMA wire/Kevlar] and [Kevlar/SMA sheet/Kevlar] composites.

Impact Area Analysis: The impact surface area analyzed using Image J software is shown in Figure 11. The impact areas of the composite specimens after the drop hammer impact test were calculated and the average reading is tabulated in Table 5.

The impact area was analyzed using Image J Software, developed by the National Institute of Health, University of

Table 4. Absorbed Energy and Energy Peak for the Reinforced Composites

Type	Impact velocity (m/sec)	Energy peak (J)	Minimum absorbed energy (J)	Absorbed energy (J)
Plain	2.80	7.65	6.09	1.56
Sheet	2.80	7.43	5.44	1.99
Wire	2.80	7.036	3.88	3.16
Plain	3.96	15.19	11.64	3.55
Sheet	3.96	14.57	10.41	4.17
Wire	3.96	14.66	5.89	8.77
Plain	4.85	22.97	20.08	2.88
Sheet	4.85	22.97	18.93	4.04
Wire	4.85	22.69	10.48	12.22

Wisconsin. The obtained impact area of the composite specimens was grouped for each impact velocity and the different forms of Kevlar reinforcement were ranked from the lowest impact area to the highest impact area as shown in Table 5. For all the impact velocities the [Kevlar/SMA sheet/Kevlar] has shown less impact area compared to the [Kevlar/Kevlar/Kevlar] composite. The decrease in impact area in [Kevlar/SMA sheet/Kevlar] composite is due to an increase in core density, 107.14% compared to [Kevlar/Kevlar/Kevlar] composite as depicted in Table 5.

Surface Morphology: After the impact tests, the Kevlar specimen surface was analyzed and the following observations were made. For all the specimens tested under different impinging velocity, perforation and zero penetration were observed. For [Kevlar/SMA wire/Kevlar] composite matrix cracking was observed and the damaged area was 35% high compared to [Kevlar/Kevlar/Kevlar] composite. For the [Kevlar/SMA sheet/Kevlar] composite, the damaged area was almost negligible, and very few matrix cracks were observed at

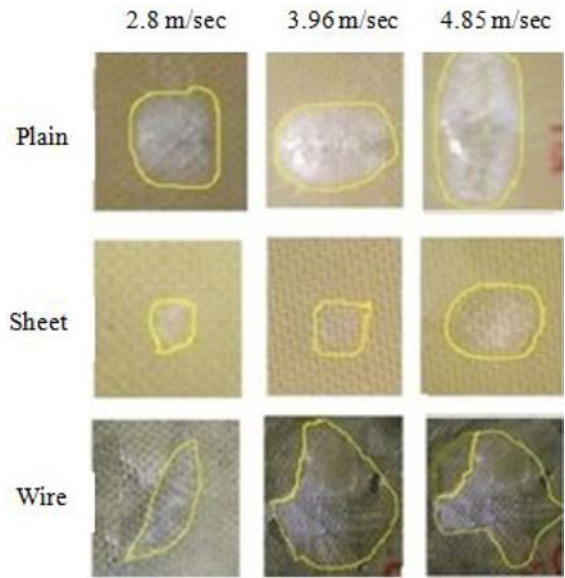


Figure 11. Impact area analysis using image J software of the reinforced composites.

Table 5. Impact Velocity Ranking for Different Specimens

Type	Impact velocity (m/sec)	Area (mm ²)	Increase in (+ %)/Decrease in (- %)	Ranking
Plain	2.80	223.42	-	2
Sheet	2.80	45.44	-79.66	1
Wire	2.80	303.18	35.70	3
Plain	3.96	437.56	-	2
Sheet	3.96	72.48	-83.43	1
Wire	3.96	594.45	35.86	3
Plain	4.85	909.02	-	2
Sheet	4.85	138.77	-84.77	1
Wire	4.85	1229.93	35.30	3

the top surface. At the bottom surface, no crack was observed for the SMA sheet reinforced Kevlar specimen. For [Kevlar/

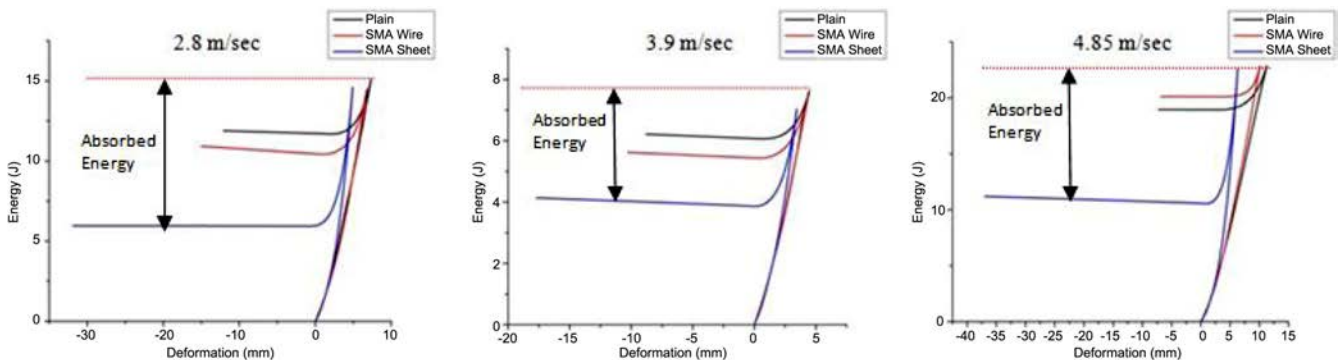


Figure 10. Absorbed energy vs. deformation of the reinforced composites.

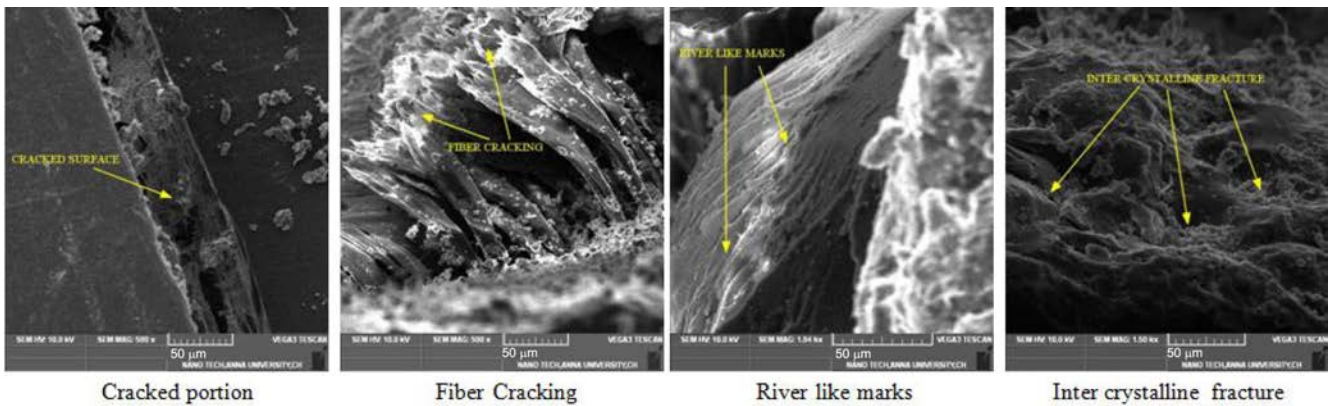


Figure 12. Mechanisms of failure in specimens of the reinforced composites.

Kevlar/Kevlar] composite matrix cracking and fiber cracking were observed in Figure 12. The matrix reinforcement composite fracture was studied using a scanning electron microscope and from Figure 12, we can infer that resin has undergone inter crystalline fracture which represents the brittle nature of epoxy resin also observed by Luz *et al.*³⁴ Also, from Figure 12 we can see a river-like stretched mark, which reveals the direction in which the failure occurred in the matrix, and also represents the brittle fracture in epoxy resin similarly observed by Filho *et al.*³⁵

Conclusions

The following observations which were observed during the current research are discussed below.

- The addition of SMA in the form of sheet has reduced the deformation by 20.69, 27.43, 37.90% and increased the absorbed energy by 102.56, 147.04, 324.31% in comparison to plain Kevlar epoxy polymer composites at impact velocities 2.80, 3.96, and 4.85 m/sec for low velocity impact test.
- Also, the decrease in the impact area and high absorbed energy peak force indicates increased impact resistance of the [Kevlar/SMA sheet/Kevlar] composite.
- The tensile strength is reduced in SMA Sheet reinforced Kevlar epoxy composite by 30.52% compared to the plain Kevlar epoxy composite due to improper adhesion between the SMA sheet and the Kevlar fabric.
- The SMA sheet reinforced Kevlar epoxy composite has flexural strength 117.84% higher than the plain Kevlar epoxy composite.
- The SMA wire reinforced Kevlar polymer composite has low tensile, flexural strength in comparison to SMA sheet reinforced Kevlar polymer composite and plain Kevlar reinforced

polymer composite.

- The reinforcement in SMA wire form reduced the deformation by 2.47, 7.63, 9.96% and increased the impact area by 35% in comparison to [Kevlar/Kevlar/Kevlar] composite at impact velocities 2.80, 3.96, and 4.85 m/sec.
- The SMA sheet reinforced Kevlar epoxy polymer composite has shown superior impact resistance properties with less deformation, and high energy absorption compared to SMA wire reinforced Kevlar epoxy polymer composite and plain Kevlar reinforced epoxy polymer composites.
- The hysteresis curve obtained from the low-velocity impact test revealed that there is little or no penetration in the for all the composite specimens [Kevlar/Kevlar/Kevlar], [Kevlar/SMA wire/Kevlar], and [Kevlar/SMA sheet/Kevlar] composite.
- The failure mode observed during the tensile test, flexural test, and impact test for Kevlar epoxy polymer composite was dominated by fiber cracking and matrix cracking.
- The failure mode observed during the tensile test, flexural test, and impact test for SMA wire and sheet reinforced Kevlar epoxy polymer composites was delamination and matrix cracking on the surface.
- The mechanism of failure majorly observed in the matrix was river-like flow failure stretch marks and intercrystalline fracture.

From the results obtained we can conclude that [Kevlar/SMA sheet/Kevlar] composite has better flexural and superior impact resistance property suitable for automobile structural applications. The [Kevlar/Kevlar/Kevlar] composite has better tensile properties in comparison to SMA wire and Sheet reinforced composites. Further, the research could be carried out on analyzing the bonding strength of matrix and reinforcement to improve the mechanical property of the SMA wire and sheet

reinforced Kevlar epoxy polymer composites.

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