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VOLUME FRACTION ANALYSIS AND STATIC COMPRESSION TEST OF THERMOPLASTIC COMPOSITES FOR LIGHT WEIGHT BODY ARMOR

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Abstract- In the present study material characterization of thermoplastic composite is performed. Two types of fibers i.e. Kevlar fiber and Basalt fiber are considered and matrix is maleic- anhydride grafted polypropylene (PP). Kevlar/PP and Basalt/PP composite laminates with 8 layers are fabricated using vacuum based compression molding technique. Since these composites have extremely tough surface and are very difficult to cut, hence, these composites are cut by laser cutting and the samples for the static compression, shear and dynamic compression tests are prepared. Volume fraction analysis is carried out by using burn off test. Static compression is performed on UTM. Compression test has been carried for getting the properties in in-plane compression.

1. INTRODUCTION

In present time, composites are extensively used for the body armor application due to high strength to light weight ratio in comparison to conventional materials. Fiber reinforced composite mainly consist of fibers of high strength and modulus bonded with matrix. In present study, two types of fibers are used- Kevlar and Basalt. Kevlar or aramid fiber, chemical name poly-paraphenylene terephthalamide exhibits a combination of high strength, high modulus, and is widely accepted as a better option for impact related applications due to its high strain to failure. It is lightweight, strong and exhibits desired combination of high strength, high toughness and thermal stability. The various Kevlar fibers used in industry are Kevlar29, Kevlar 49 and Kevlar 129. In the present study high-performance Kevlar 29 (Kevlar) fiber tows of 1000 Denier have been considered, shown in figure 1. Fabric architectures, used is 2D-Plane, weaved using CCI sample weaving machine. The beams required feeding this loom are prepared on the CCI sample warping machine. The weaving pattern is shown in figure 3.

Figure 1. Kevlar Fiber

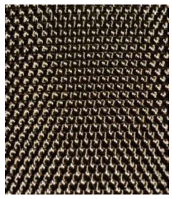

Figure 2. Basalt Fiber

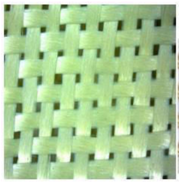

Figure 3. Weaving Pattern

Basalt fiber (BFs), obtained from the fusion of volcanic rocks, is a good alternative to reinforce polymeric materials. It has better mechanical properties than vegetable fibers and slightly higher than conventional glass fiber. The Basalt fiber matrix is shown in figure2. Cost of the basalt fibers is less as compared to Kevlar and other fibers. Basalt fiber tows of 2700 Denier has been considered.

The matrix used in present study is polypropylene. Polypropylene (PP) is a thermoplastic polymer used in a wide variety of applications. Polypropylene is chosen because it is one of the lightest polymers with density of 0.855 g/cm3. It has certain advantages in improved specific strength and specific stiffness owing to low density, good impact strength, surface hardness and excellent abrasion resistance.

Polypropylene presents poor interfacial adhesion with practically any material. Kevlar fibers suffer from weak interfacial adhesion with most matrix resins. Henceforth, to use it as an alternative for body armor a method is needed for improving the interfacial adhesion of Kevlar with Polypropylene. The solution suggested in the literature to solve problem of low adhesion between Kevlar and Polypropylene is the use of compatibilizer or coupling agent, to reinforcement. Maleic Anhydride grafted Polypropylene was suggested. (Bandaru et al. 2016)

1.1 KEVLAR

Tensile tests on single Kevlar-29 filaments was conducted by Cisneros et al.(2012), to characterize their intrinsic behavior under quasi-static loading, and nano-indentation tests, to investigate their cross-sectional mechanical properties. The results reveal that the elastic modulus measured in the fiber cross-section (i.e. 20GPa) is lower than that obtained in the longitudinal direction (i.e. 80GPa) due to the high anisotropy of the fibers.

The numerical simulation on two ballistics test standards for KEVLARs helmets was performed by Tham et al. (2008). They are namely the NIJ-STD-0106.01 Type II and the V50 requirement of the US military specification for Personal Armor System Ground Troops (PASGT) Helmet, MIL-H-44099A. For the simulation on MIL-H-44099A, a fragment-simulating projectile (FSP) strikes the helmet with an impact velocity of 610 m/s. The simulation revealed that an impact velocity above 610 m/s is required to perforate the KEVLARs helmet.
Ballistic behavior of multi-layer Kevlar fabric/polypropylene (PP) composite laminate (CL) and plain layered aramid fabric (AF) impact specimens were investigated by Carrillo et al. (2012). They found that the thermoplastic PP matrix increases the ballistic performance. The ballistic limit and penetration threshold energy of the CL configurations, which were predicted using an empirical model, were found to be higher than those of the AF targets. They also found that use of PP reduces the cost and weight of the composite, but the interfacial property between Kevlar and PP was not good.

Ballistic impact response of Kevlar/PP composites was investigated by Bandaru et al. (2016). Three different kinds of laminates of 2D plain woven, 3D orthogonal and 3D angle interlock were produced. Interfacial property between PP and Kevlar was improved by adding a coupling agent called maleic anhydride. They found, that the density of Kevlar thermoplastic based composites was lower as compared to that of the thermoset-based laminates. 3D composite armors with less layers were able to confront the 9 mm FMJ projectile as compared to the 2D plain woven armor.

Experimental and numerical simulation of ballistic impact on Kevlar 29/vyniliester composite was performed by Silva et al. (2005). The size of the laminate of 400X400X2.4 mm^3 corresponds to seven layers. Young's modulus in compression is found to be 239.2MPa.

1.2 BASALT

Basalt fiber (BFs), obtained from the fusion of volcanic rocks, is a good alternative to reinforce polymeric materials. It has better mechanical properties than vegetable fibers and slightly higher than conventional glass fiber. Cost of the basalt fibers is less as compared to Kevlar and other fibers.

The mechanical properties of Basalt and its adhesion to PP matrices was studied by Greco et al. (2014). They compared the properties of Basalt with PP and with maleic anhydride grafted PP. Single fiber fragmentation test was carried out and it was found that Basalt with anhydride grafted PP show better properties.

Tensile, flexural and impact properties of Basalt/polybutylene succinate was investigated by Zhang et al.(2012) It was found that the basalt fiber enhances the properties of the composite. Tensile strength increased from 31MPa to 46MPa as the basalt fiber loading increased from 3 vol% to 15 vol%.

Composites with the fabric of basalt and the matrices of epoxidized linseed oil (ELO) and epoxidized soybean oil (ESBO) were manufactured by Samper et al.(2015) The basalt fabrics were modified with amino-silane and glycidyl-silane to increase fiber-matrix interactions. The evaluation of mechanical properties was made by tensile, flexural and Charpy tests. The extent of the fiber-matrix interactions among interface was evaluated by scanning electron microscopy (SEM). The obtained results revealed that surface modification of basalt fibers with glycidyl-silane clearly improves the mechanical properties of the composites. The use of the ELO resin as matrix for composite laminates improved substantially the mechanical performance compared to composites made with ESBO.

Basalt reinforced epoxy composites evidenced higher mechanical properties with respect to vinyl-ester, both in the tensile and compressive behavior, and the failure mode is more compact, since fibers do not tend to explode.

2. MATERIAL SELECTION

Polypropylene (PP) is a thermoplastic polymer used in a wide variety of applications. Polypropylene is chosen because it is one of the lightest polymers with density of 0.855 g/cm^3. It has certain advantages in improved specific strength and specific stiffness owing to low density, good impact strength, surface hardness and excellent abrasion resistance. Polypropylene is the most versatile and cost effective plastic. Polypropylene presents poor interfacial adhesion with practically any material. Kevlar fibers suffer from weak interfacial adhesion with most matrix resins. Henceforth, to use it as an alternative for body armor a method is needed for improving the interfacial adhesion of Kevlar with Polypropylene. The solution suggested in the literature to solve problem of low adhesion between Kevlar and Polypropylene is the use of compatibilizer or coupling agent, to reinforcement. Maleic Anhydride grafted Polypropylene was suggested. (Bandaru et al. 2016)

FOR KEVLAR/PP

The 8 layer laminate refers to 8 layers of fiber (Kevlar 29) and 9 layers of matrix (PP) stacked together in alternating sequence. The measured thickness of 8 layer laminate is 1.5-1.6 mm.

FOR BASALT/PP

The 8 layer laminate refers to 8 layers of fiber (Basalt) and 9 layers of matrix (PP) stacked together in alternating sequence. The measured thickness of 8 layer laminate is 1.9 - 2.1 mm.

3. Volume Fraction Analysis

The volume fraction of the laminate was calculated by burn off test in accordance with ASTM standard D3171. The specimen contained in a crucible is ignited and allowed to burn till all the matrix vaporizes. The residue obtained by heating in a muffle furnace at 308°C, cooled and weighed. The melting temperature of the matrix (Maleic Anhydride grafted Polypropylene) is around 170°C while that of Kevlar 29 fibers is around 550°C and Basalt fibers is around 1020°C beyond which it starts decomposing. The sample is allowed to burn at desired temperature (308°C) and then maintained that temperature for around 3-4 hours and then it is cooled in a furnace by switching off to room temperature and weighed.

The calculation for V_f is done based on the following relation :-

$$V_f = (W_2/\rho_f)/(W_1/\rho)*100 \quad \ldots\ldots(1)$$

where, W_1= Weight of Specimen in grams, W_2= Weight of Residue in grams,

ρ_f= density of fibers in grams per centimeter cube,

ρ = density of composite in grams per centimeter cube.

4. RESULTS AND DISCUSSION

4.1 Volume Fraction Analysis

Initially the test was carried out at a temperature of 370^{0}C. However, at this temperature burning of Kevlar fiber was seen and because of that reduced volume fraction of fiber was obtained as shown in Table 1. After that, test was carried out at 308^{0}C and at this temperature no burning of Kevlar fiber was observed. So at this temperature volume fraction test was considered to be correct and weight of the specimen calculated before and after the burn off test to evaluate the volume fraction is shown in Table 2.

Table 1. Volume fraction test at 370^{0}C

Composite	Sample	Weight (mg) before test	Weight (mg) after test	Weight fraction (%)	Volume fraction (%)
Kevlar/PP	1	20	12	60	44.167
Kevlar/PP	2	18	11	61.11	44.98

Table 2. Volume fraction test at 308^{0}C

Composite	Sample	Weight (mg) before test	Weight (mg) after test	Weight fraction (%)	Volume fraction (%)
Kevlar/PP	1	20	16	80	58.89
Kevlar/PP	2	18	14	77.77	57.25
Basalt/PP	3	49	42	85.71	54.92
Basalt/PP	4	47	40	85.11	54.53

The density of Kevlar fiber is 1.44 g/cc and that of basalt fiber is 2.7g/cc. Density of Kevlar/PP laminate is 1.06g/cc and that of Basalt/PP laminate is 1.73g/cc.

By using the volume fraction formula, the calculated volume fraction for KPL is 57%-59%, while for BPL it is 54%-55%.

4.2 Compression Test

The static compression test is performed on Kevlar/PP and Basalt/PP laminate having 8 layers. The cross section of the specimen is square of 10 mm x 10 mm. The thickness of Kevlar/PP specimen is 1.5 mm and that of Basalt/PP is 2.1 mm. The test was performed on UTM. By using the experimental data Stress-Strain curve for Kevlar/PP (KPL) and Basalt/PP (BPL) plotted are shown in figure 4 and figure 5.

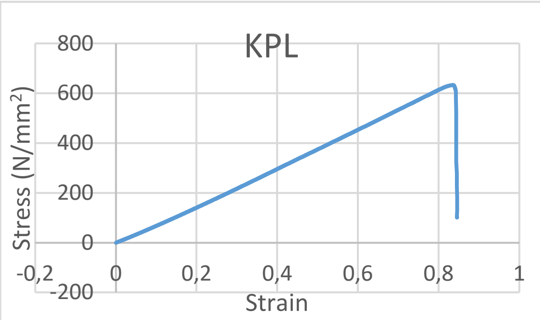

Figure 4. Stress vs. Strain Curve for KPL

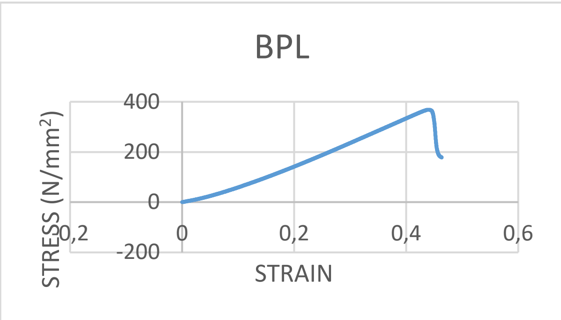

Figure 5. Stress vs. Strain Curve for BPL

The non-linearity in stress-strain behavior is seen more in Basalt/PP compared to Kevlar/PP, shows more ductility of Basalt/PP composite.

5. SUMMARY AND CONCLUSIONS

5.1 Summary

In the present study, Kevlar/PP and Basalt/PP composite laminates were fabricated using vacuum compression moulding machine. Volume fraction test is conducted to calculate volume fraction of the fibre in the composite. Specimens were prepared by laser cutting because of very tough surface. For static compression specimen of square shape is prepared.

5.2 Conclusions

Based on the results and discussion in the preceding section, following conclusions are drawn:

- Volume fraction of Kevlar fibre in Kevlar/PP composite is 57-59% and that of Basalt fibre in Basalt/PP composite is 54-55%.
- The non-linearity in stress-strain behavior is seen more in Basalt/PP compared to Kevlar/PP, shows more ductility of Basalt/PP composite.

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