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Evaluation of Curing Process for Kevlar 49-Epoxy Composites by Mechanical Characterization Designed for Brake Liners

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Abstract: ***In this present work, Kevlar 49/epoxy composites are routed with different curing processes to fabricate brake liners. The curing processes are commenced with pressure, with pressure and vacuum and with vacuum only. The Kevlar 49/epoxy composites are tested for compressive strength, tensile strength, flexural strength, hardness, compressive modulus, tensile modulus, flexural modulus and inter laminar shear strength. The reduction of volume fraction is due to pressure compactness of epoxy coated bi-directional Kevlar 49 woven in the composite. Pressure included curing processes are resulted in the interfacial microscopic cracks, which can transform to macroscopic level by coalesce, and debonding phenomena to discharge the developed residual stresses on account of the pressure applied during the curing process. The compactness is high with curing process of vacuum and applied pressure on the composite. The curing cycle (pressure and vacuum) has imparted fewer voids in the composites as compared the other two curing cycles.***

Keywords: Kevlar 49, epoxy, tensile strength, compressive strength, flexural strength, inter laminar shear strength, voids, brake liners

1. Introduction

Kevlar is the registered trademark for Poly-paraphenylene terephthalamide synthetic fiber, related to other aramids such as Nomex and Technora [1]. Kevlar is strong and also very light. The tensile strength of the Kevlar fiber is over eight times stronger than of a steel wire. It also handles heat very well and can withstand temperatures well above 455ºC. Currently, Kevlar is being used for many applications, ranging from bicycle tires to body armor because of its high tensile strength-to-weight ratio. It is also used to make modern drumheads that withstand high impact. Several grades of Kevlar are available such K29, K49, K100, K119, K129, Kevlar AP, Kevlar XP. K29 is being used in industrial applications, such as cables, asbestos replacement, brake linings, and body/vehicle armor.

Fiber composites are attractive alternatives to the metals because of their high stiffness or their excellent fatigue behavior. The disadvantage of fiber composites arises from the weak polymeric matrix and results in low interlaminar shear strength and low transverse fatigue strength. Kevlar is often combined with a variety of other materials to produce an array of composite materials. The adhesion between aramid fibers and most matrices is poor due to their chemical inertness and smooth surface that prevent chemical inertness in addition to mechanical bonding. The direction of fiber strands decides the stiffness and strength of the laminate in particular directions. The weave type determines how often the transverse (0/90°) strands of fibers in a 2-directional fabric are mutually interleaved. It mainly affects the deformability of the fabric [2]. He and Li [3] have used to study the consequences of different novolac resin loadings on mechanical characterization of carbon fiber/epoxy composite. The composites are prepared by solution blending and casting in a vacuum oven and the mechanical properties are investigated by means of shear and impact tests. Carbon fiber reinforced composites are usually processed using thermoset polymers especially epoxy resins [4 - 6]. Polymeric laminated composites present high strength-to-weight and stiffness-to-weight ratios when compared with metallic materials. However, these laminated composites are susceptible to damage loads because they are obtained by layer stacking without strong interfaces between the plies. This characteristic explains the importance of improving the damage tolerance of these materials, for instance, by modification of the resin system using adequate modifiers. The curing of carbon/epoxy laminates under vacuum has resulted to the volume fraction of 71.35%. It has been found that at reliability 0.90 the survival tensile strength and flexural strength of carbon/epoxy laminates are 721.753 MPa and 557.380 MPa respectively [7].

Kevlar 49 is 20% higher tensile strength than K29. The aim of this study is to determine mechanical properties for Kevlar 49/epoxy (LY556 + HT972) bi-directional composites with different curing process parameters to improve fiber volume fraction for brake liners (figure 1).

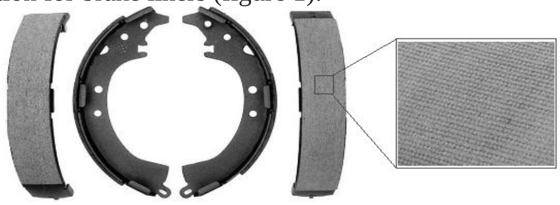

Figure 1: Goal of the present work to fabricate Kevlar 49 (Woven type)/epoxy composite for brake liners.

2. Materials and Methods

All the testing procedures were as per ASTM standards. For every test six samples were used and the average value was reported for the results and discussion.

2.1 Materials

In the present study, epoxy resin (AIRSTONE 780E) was used as a matrix material. The hardener was AIRSTONE 782H. The Kevlar 49 (woven type) bi-directional fiber was used as reinforcing material. The structure of Kevlar 49 woven is shown in figure 2.

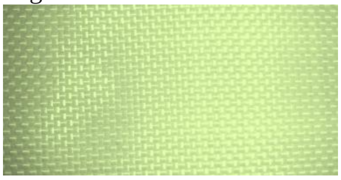

Figure 2: Kevlar 49 woven

2.2 Composite preparation

The vacuum infusion process (VIP) was employed to fabricate the composites. Kevlar 49 fiber of 320mm x 320mm was taken from the fabric role. Epoxy resin (780E) and hardener (782H) were mixed in the 100:31 (parts by weight) ratio in a beaker and the solution was applied on the bi-directional Kevlar 49. The moulds were cleaned with acetone and the wax was applied to the moulds for easy removal of the cured composite. Resin impregnated Kevlar 49 layers were placed in the mould by hand layup technique. The resin coated Kevlar 49 fibers were stacked to get 3mm thickness of the composite in the mould. The composites were prepared by different process parameters such as:
No vacuum and pressure
With vacuum
With vacuum and pressure.
The corresponding cure cycles, vacuum levels and pressure application steps were assigned as cure cycle-1, cure cycle-2 and cure cycle-3.
Cure cycle-1:
Component temperature at 140^{o}C for 4 hrs
Vacuum is -960 mbar
Pressure at 140^{o}C, 1.0 bar up to 2 hrs and 2.0 bar up to 4 hrs.
Cure cycle-2:
Component temperature at 140^{o}C for 4 hours
Vacuum is -960 mbar
Pressure at 140^{o}C, 0.5 bar up to 1 hr, 1.0 bar up to 2 hrs, 1.5 bar up to 3 hrs and 2.0 bar up to 4 hrs.
Cure cycle-3:
Component temperature at 140^{o}C for 4 hrs
Vacuum is -960 mbar
Pressure is nil.

2.3 Testing procedures

Fiber volume fraction was determined by acid digestion method. In this testing method, the digestion of resin matrix was carried out in a hot digestion medium like nitric acid which did not attack the fibers extremely. The specimens were cut in the required dimensions as per the ASTM standards using a diamond wheel cutting machine. The tensile and compression were carried out on a universal testing machine (UTM) of Instron make, 1185 model, and 100KN load capacity. The tensile specimens were prepared as per ASTM D3039 standard. The three-point flexural test was conducted on the flexural specimens prepared as per ASTM D790 standard.

A bar of rectangular cross-section was used for interlaminar shear strength (ILSS) test specimen as shown in figure 3a. As shown in figure 3b three-point loading system, with center loading in a simply supported beam, was used. The specimen was rest on two supports and was loaded by means of loading nose between the supports as shown in figure 3c. The ILSS test was conducted as per ASTM D2344. The tested specimen is shown in figure 3d.

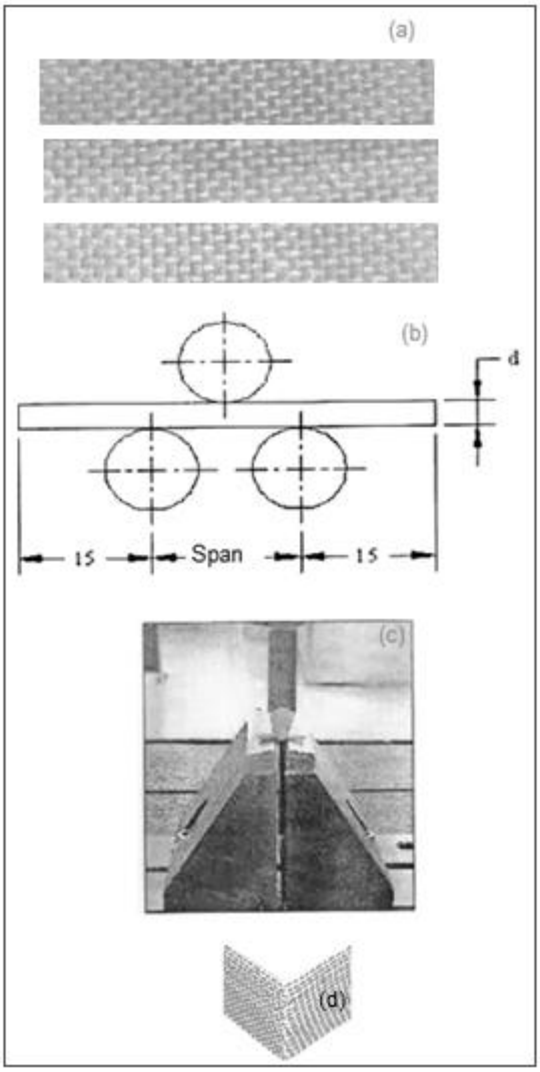

Figure 3: Interlaminar shear strength test

Longitudinal tensile strength, $\sigma_s = \mathrm{P/A}$ (1)
where P is the maximum load at failure, N and A is the minimum cross-sectional area, mm^2.
Tensile modulus, $E_t = \Delta P/Ae$ (2)
where ΔP is the load with in elastic limit, N and e is the strain.
Flexural strength, $E = 3PL/2bd^2$ (3)
where P is the maximum load at failure, N and L is the support span, mm, b is the width of specimen, mm, d is the thickness of specimen, mm.
Flexural modulus, $(L^3/4bd^3) \times (\Delta P/\Delta l)$ (4)
where ΔP is the change in load at failure, N and Δl is the deflection, mm.

The stresses acting on the interface of two adjacent lamina are called interlaminar stresses. The interlaminar stresses are illustrated in figure 4. σt is the interlaminar normal stress on plane ABCD; τtl and τtt are the interlaminar shear stresses. These cause relative deformations between the lamina 1 and 2. If these stresses are sufficiently high, they may cause failure along the plane ABCD. It is of considerable interest to evaluate interlaminar shear strength through tests in which failure of composites initiates in a shear (delamination) mode.

Interlaminar shear strength, $ILSS = 3P_r/4bd$ (5)
where P_r is the rupture load, N and L is the support span, mm, b is the width of specimen, mm, d is the thickness of specimen, mm.

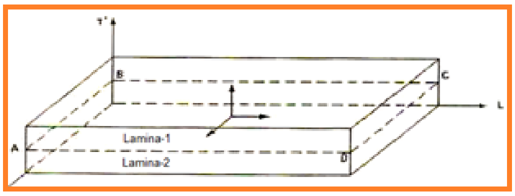

Figure 4: Interlaminar shear stresses

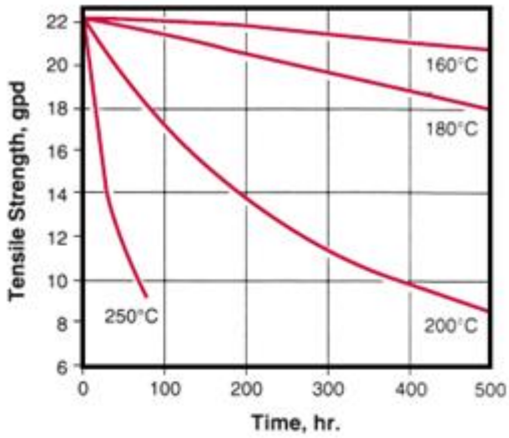

Figure 5: Tensile strength of Kevlar 49

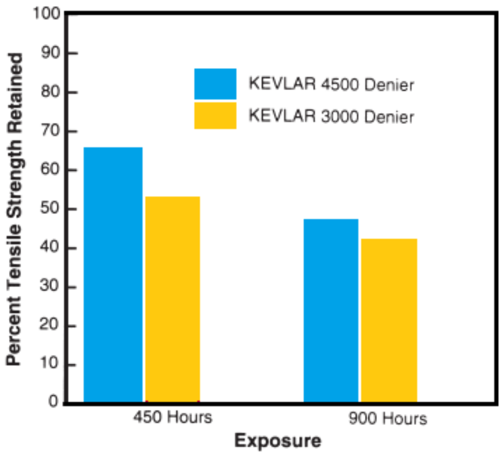

Figure 6: Ultraviolet stability of Kevlar yarns

3. Results and Discussion

The purpose of determination of mechanical properties like tensile, flexural and interlaminar shear strength for bi-directional Kevlar 49/epoxy (780E+782H) composites with different curing process parameters was to improve fiber volume fraction for the brake liners. The reaction between epoxy resins and amine hardeners is exothermic. The temperature dependent tensile strength (grams per denier, gpd, a unit of textile strength measurement) of Kevlar is shown in figure 5. The tensile strength Kevlar 49 fabric decreases with increasing temperature. The blend, 780E/782H which has high viscosity was chosen for the present work to fabricate the brake liners. The ultraviolet stability increases with the thickness of fabric (the denier of a yarn) and it decreases with time of exposure as shown in figure 6.

3.1 Physical properties of composites

The physical properties of bi-directional/epoxy composites are shown in figure 7. The curing cycle-1 results in very high volume fraction (figure 7a) of fiber in the composite and superior composite density (figure 7b) as compared to two other two cycles. The curing cycle-3 results in very low volume fraction of fiber in the composite and density. This is because of lack of compactness on account of vacuum only.

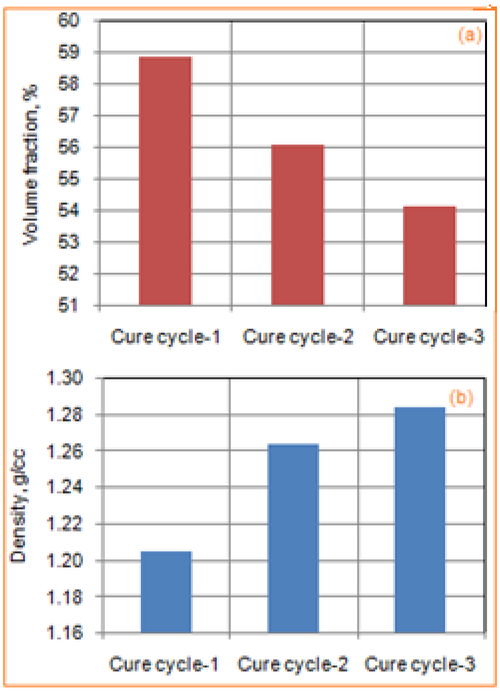

Figure 7: Physical properties of Kevlar 49/epoxy composites.

3.2 Tensile, flexural and compressive strengths of composites

The influence of fiber content in the composite on tensile strength is shown in figure 8a. The tensile strength decreases with an increase in the volume fraction of fiber in the composite. The reduction of volume fraction is due to pressure compactness of epoxy coated bi-directional Kevlar 49 woven in the composite. The pressure compaction results in the residual stresses in the composite. During tensile testing the kevlar-49 epoxy composites which were compressed during the curing process might have exhibited either elastic non-linear or plastic behavior after a certain elongation. The composites, which were cured under vacuum only without external compacting pressure, have high tensile strength. The layers in the composites were formed by strong covalent bonds and weak bonding due to Van der Waals forces. Further, the compression of composites by the external pressure effects wave shaped misalignment and the transverse compression exerted by fill and warp. The latter is especially of influence for transverse brittle Kevlar fibers. The reliability of all the composites is almost the same under tension as shown in figure 8b. From figure 8b, it is observed that at reliability 0.90 the survival tensile strength of Kevlar

49/epoxy composites for curing cycle-1 is 157.56 MPa, for curing cycle-2 is 161.09 MPa, and for curing cycle-3 is 167.16 MPa.

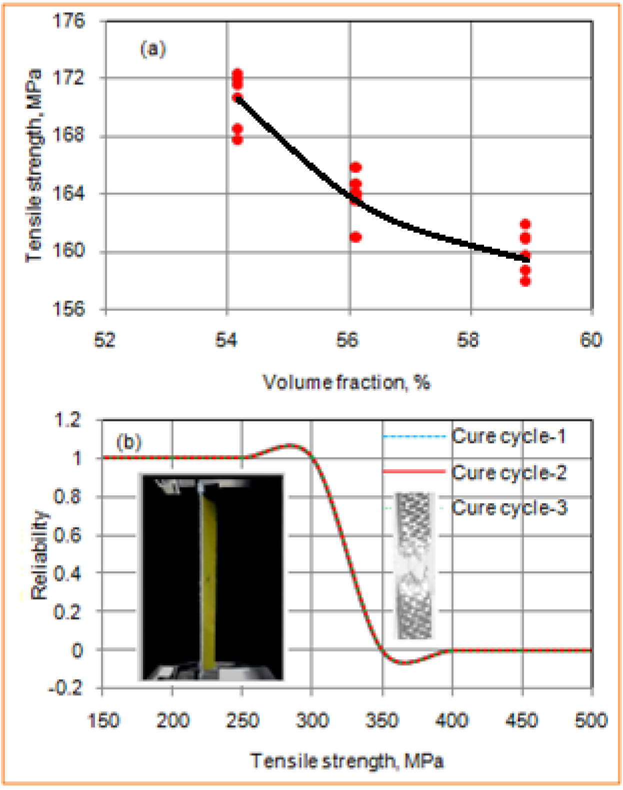

Figure 8: Tensile strength of Kevlar 49/epoxy composites.

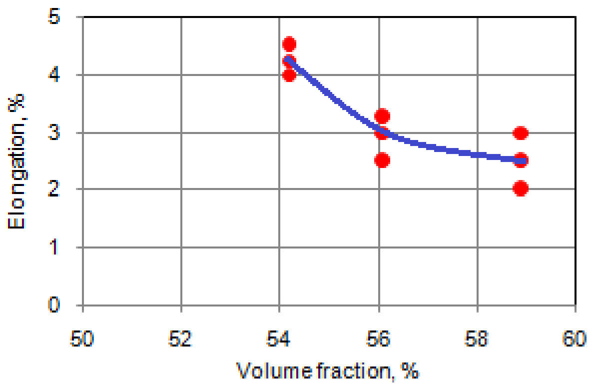

Figure 9: Tensile elongation of Kevlar 49/epoxy composites.

The tensile elongation of Kevlar 49/epoxy composites is shown in figure 9. The trend is same as that of tensile strength. The elongation is low due to brittle nature of Kevlar fabric.

The flexural strength of the Kevlar 49/epoxy composites is shown in figure 10. The composites produced through curing cycle-1 have low flexural strengths. The sheet-like aggregations readily allow the propagation of cracks. Improved flexural strengths of composites may be also due to contribution of increased stiffness for both Kevlar 49 woven and epoxy matrix after vacuum conditioning (curing cycle-3). For composites of curing cycle-1 and -2 at applied pressure result in low flexural strengths owing to the presence of more interfaces leading to the generation of large amount of residual stresses which are not easy to accommodate in the strong interface. It is resulted in the interfacial microscopic cracks, which can transform to macroscopic level by coalesce, and debonding phenomena to discharge the developed residual stresses on account of the pressure applied during the curing process. From figure 10b, it is observed that at reliability 0.90 the survival flexural strength of Kevlar 49/epoxy composites for curing cycle-1 was 1331.85 MPa, for curing cycle-2 is 133.98 MPa, and for curing cycle-3 is 139.93 MPa.

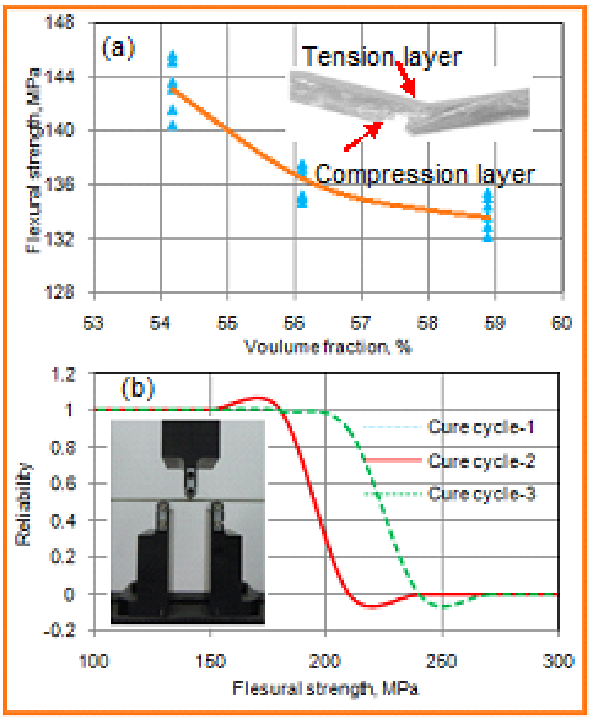

Figure 10: Flexural strength of Kevlar 49/epoxy composites.

The compressive strength of the Kevlar 49/epoxy composites is shown in figure 11. The composites produced through curing cycle-3 have higher compressive strengths than those treated with curing cycle-1 and curing cycle-2. The ultimate compressive strength and strain are always smaller than tensile properties because buckling occurs. This effect is especially serious transversally weak fibers, such as Kevlar. The composite breaks at a strain lower by a factor of (l-V_f) than the fracture strain of the matrix if the transverse fiber strain is negligible. V_f is the volume fraction of the fiber in the composite. When fracturing cross-plies the matrix in the transverse strain layers cracks earlier than the matrix and fibers in the longitudinal load-bearing layers. From figure 11b, it is observed that at reliability 0.90 the survival compressive strength of Kevlar 49/epoxy composites for curing cycle-1 was 81.72 MPa, for curing cycle-2 was 84.46 MPa, and for curing cycle-3 was 85.79 MPa.

The hardness of Kevlar 49/composites is shown in figure 12. The composites, which were cured with both vacuum and external pressure, are possessive of high hardness on account of high compaction.

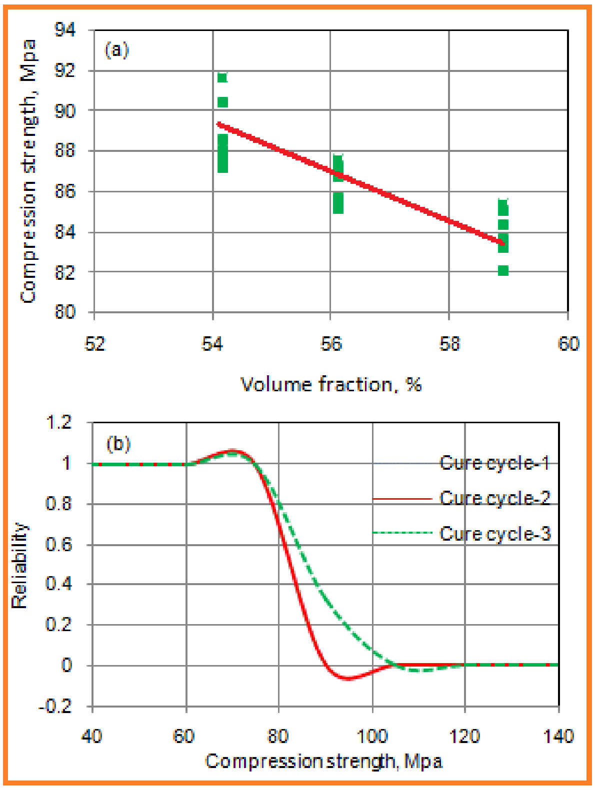

Figure 11: Compressive strength of Kevlar 49/epoxy composites.

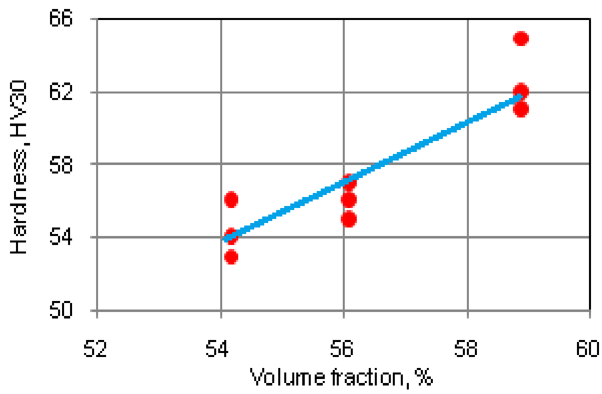

Figure 12: Hardness of Kevlar 49/epoxy composites.

3.2 Tensile, flexural and compressive moduli of composites

The influence of fiber content in the composite on tensile modulus is shown in figure 13a. The tensile modulus increases with an increase in the volume fraction of Kevlar 49 woven. The ability of a specimen to store energy, i.e. its elasticity is enhanced with curing cycle-1 and 2. Energy storage may occur as molecules are distorted from their equilibrium position by application of a pressure. From figure 13b, it is viewed that at reliability 0.90 the reliable tensile modulus of Kevlar 49/epoxy composites for curing cycle-1 is 8.94 GPa, for curing cycle-2 is 8.72 GPa, and for curing cycle-3 is 8.59 GPa.

The influence of fiber content in the composite on flexural modulus is shown in figure 14a. The occurrence of drop in the flexural modulus is probably attributed to the fracture of the 0/90° fibers of the surface lamina. From figure 10a, it is noticed that the layers on the compression side are fractured. The adhesion of Kevlar 49 woven to epoxy is not only the factor which causes the cohesive failure Kevlar 49 woven but also due to the stress concentration at the interface between Kevlar and epoxy and Kevlar to Kevlar ($0/90^0$ orientation of woven) causes the cohesive failure of the Kevlar 49 woven. From figure 14b it is also noticed that at reliability 0.90 the reliable flexural stiffness of Kevlar 49/epoxy composites for curing cycle-1 is 2.98 GPa, for curing cycle-2 is 3.34 GPa, and for curing cycle-3 is 3.54 GPa. The value of coefficient of non-linear elasticity is lower in fibers of higher modulus and it decreases with decreasing interlayer spacing of the fiber crystallite structure.

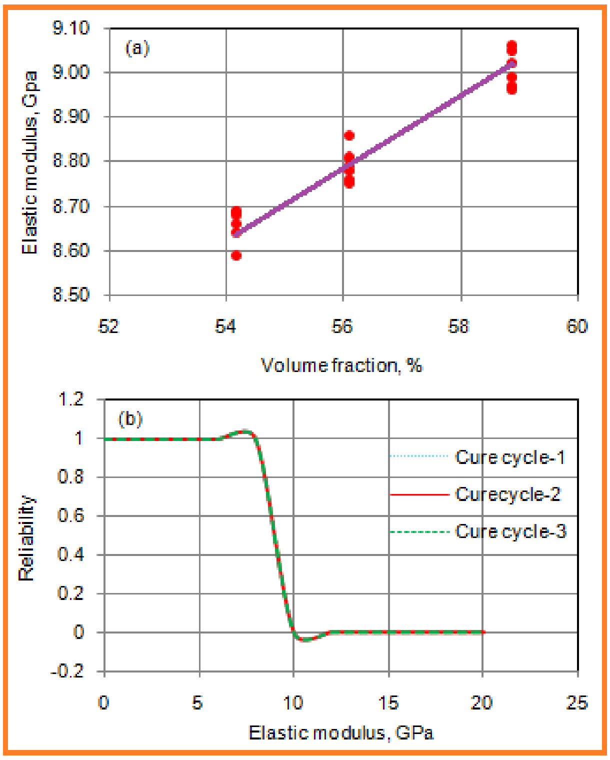

Figure 13: Tension modulus of Kevlar 49/epoxy composites.

The influence of fiber content in the composite on the compressive modulus is shown in figure 15a. The compressive stiffness increases with the degree of compactness in the composites. The compactness is high with curing process of vacuum and applied pressure on the composite. The cause of compressive stiffness deterioration and increase in deformability of the Kevlar 49/epoxy composite cured with vacuum only may be on account of local buckling in the in-plane direction and the presence of more matrix content in the composite. From figure 15b it is noticed that there is no difference between the reliability of composites cured with different curing cycles.

3.3 Inter laminar shear strength of composites

The effect of volume fraction of the epoxy resin on the inter laminar shear strength is shown in figure 16a. The effect of curing cycle on interlaminar shear strength is influential because it is resin dependent property. The interlaminar shear strength depends on the interfacial strength among the fiber layers only. The linter laminar shear strength is higher for the composites cured under vacuum only because the matrix content is more in these composites. From figure 16b, it is observed that at reliability 0.90 the reliable interlaminar shear strength tensile strength of S-glass/epoxy composites for curing cycle-1 is 35.66 MPa, for curing cycle-2 is 41.68 MPa, and for curing cycle-3 is 46.40 MPa.

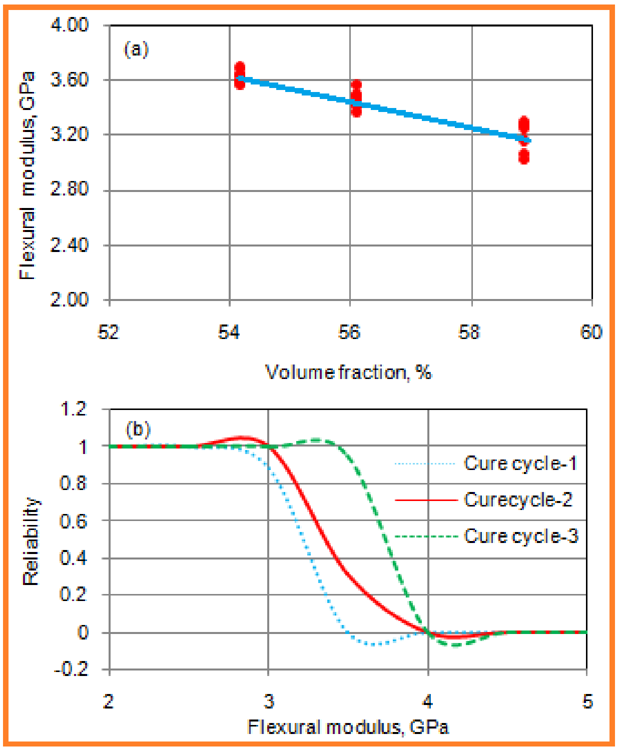

Figure 14: Flexural modulus of Kevlar 49/epoxy composites.

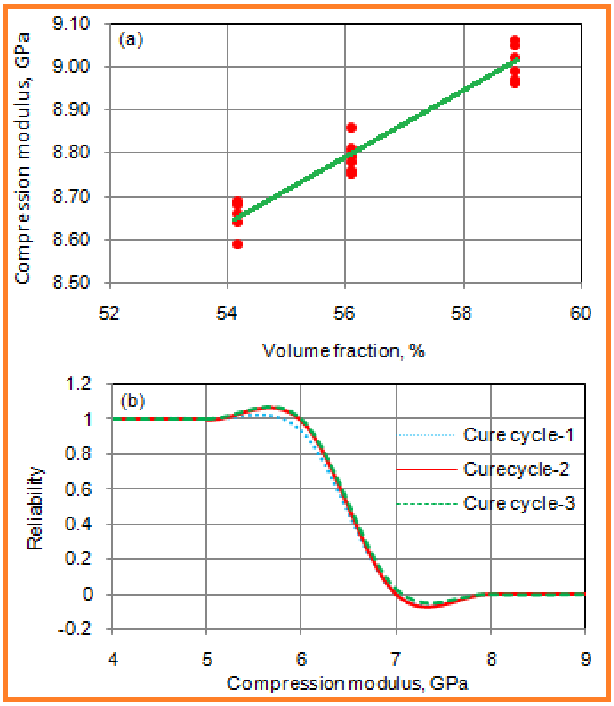

Figure 15: Compressive modulus of Kevlar 49/epoxy composites.

3.4 Influence of voids in the composites

Voids are one of the most common types of manufacturing process induced defects in composite materials that have detrimental effect on the material properties. The void content can be reduced by carefully chosen process parameters, such as pressure and temperature. The formation of voids/micro porosity in the composite prepared by the curing cycles is shown in figure 17. The curing cycle-2 has imparted fewer voids in the composites as compared the other two curing cycles. Macro porosities are mainly present during low viscosity impregnation of the reinforcement as opposed to micro pores which are the majority when the flow is governed by capillarity (high viscosity). In fact, the interlaminar shear strength (ILSS) is very responsive to the presence of these voids. The average reduction in ILSS is estimated to average 6% per unit volume of porosity for carbon / epoxy composites (Chennakesava and Vidya Sagar, 2010) (Sreenivasulu and Chennakesava, 2014) (Liu, et al., 2006) (Wisnom, et al., 1996).

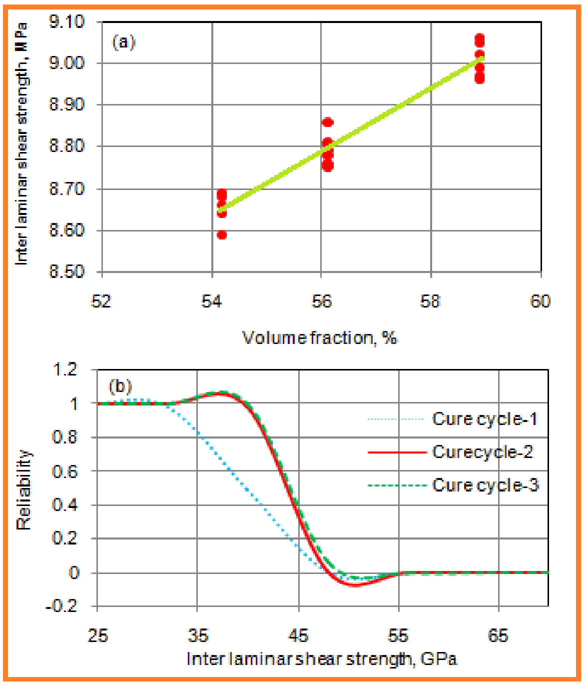

Figure 16: Inter laminar shear strength of Kevlar 49/epoxy composites.

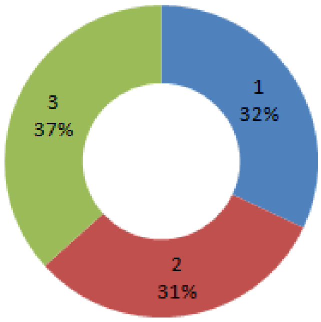

Figure 17: Void content in the Kevlar 49/epoxy composites.

3.5 Fracture of Composites

At high volume fractions of fibers, the reinforcement constitutes the major load bearing section and the addition of matrix gradually decreases the strength as the applied load is partitioned between the fibers and the matrix. The tensile strengths of Kevlar 49 fiber and epoxy are 3900 MPa and 85 MPa respectively. When the strain in the composite reaches the fracture strain of the matrix, the matrix fails first. All of the load will then transfer instantly to the fibers, which occupying a small fraction of the sample area experience a large jump in stress and they too fail subsequently. After the matrix breaks only the fibers remain to carry the load and the stress in the fiber jumps by. If this increase takes the stress in the fiber above its fracture strength then the fibers too crack. This is most likely to happen when the volume fraction of fibers is small and when the strength of the matrix is large. This is called matrix controlled fracture. However, if the jump in stress is not sufficient to break the fibers then the load can be increased until the fibers break. This is the fiber controlled fracture. The fractures specimens are shown in figure 18a during tensile testing. The fractured surface (figure 18b) indicates the fiber controlled fracture. The SEM image (figure 19b) depicts the tear bands (A) on the Kevlar 49 woven, the delamination (B), fracture of the matrix (C) and interfacial debonding (D) between matrix and fibers.

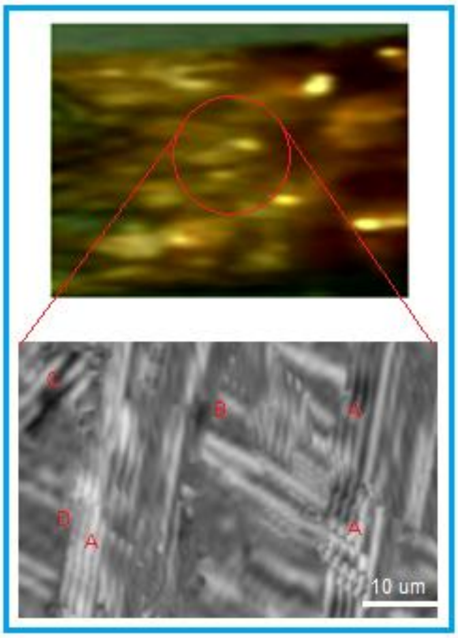

Figure 18: Fractured tensile specimen (a) and scanning electron microscopy (SEM) image (b)

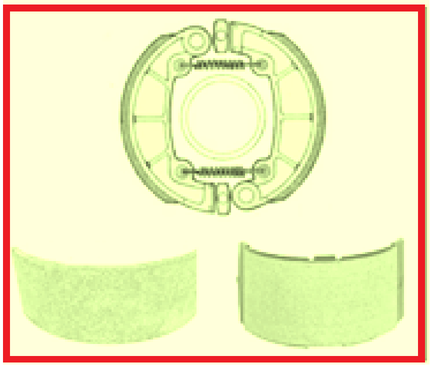

Figure 19: Brake liners fabricated from Kevlar 49/epoxy composite.

In the present work the brake liners (figure 19) are fabricated from the Kevlar 49. Epoxy using curing cycl-2 to have good compaction, hardness, compressive strength and inter laminar shear strength.

4. Conclusions

The Kevlar 49/epoxy composites were fabricated with choice of different curing cycles. The reduction of volume fraction is due to pressure compactness of epoxy coated bi-directional Kevlar 49 woven in the composite. The composites produced through curing cycle-1 (with pressure only) have low flexural strengths. The sheet-like aggregations readily allow the propagation of cracks. The composites produced through curing cycle-3 (vacuum only) have higher compressive strengths. The ability of a specimen to store energy, i.e. its elasticity is enhanced with curing cycle-1 (pressure only) and 2 (pressure and vacuum). The occurrence of drop in the flexural modulus is probably attributed to the fracture of the 0/90° fibers of the surface lamina. The effect of curing cycle on interlaminar shear strength is influential because it is resin dependent property. The linter laminar shear strength is higher for the composites cured under vacuum only because the matrix content is more in these composites.

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