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Effect of Carbon Fiber Winding Layer on Torsional Characteristics of Filament Wound Composite Shafts

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Abstract

Composite hollow shafts can be manufactured using filament winding technology employing hoop and helix winding layers. Filament winding technology offers several advantages such as continuous filaments through structure and capability for continuous manufacturing. Previous researchers have investigated composite shafts, however this research elaborates the significance of winding layer types on torsional characteristics. This paper reports the effects of carbon fiber winding layer on torsional characteristics of filament wound composite hollow shafts. Shafts were manufactured using filament winding technology with continuous carbon fiber roving and epoxy matrix material. The Finite Element (FE) simulations have been carried out with a general purpose commercial FE code, ABAQUS to demonstrate shafts in torsional loading. The results revealed that values from torsional test correlate with developed finite element model. It was concluded that helix winding layer offers high hardness and more resistance to torsional forces as compared to hoop winding layer in filament wound composite hollow shafts.

Keywords: Composite, Carbon fiber, Hollow shafts, Filament winding,

1 Introduction

Composite materials are gradually replacing many structural parts for aerospace and automotive vehicles. Parts such as shafts demand high torsional strength without compromise on weight. Shafts are mostly used to transmit rotary motion from one component to another. Conventionally, metallic shafts are used in a variety of engineering systems to account for adequate strength. These metallic shafts have many limitations such as heavy weight, low permissive speeds, and less vibration damping characteristics. To overcome limitations of metallic shafts, composite materials may be used to fabricate lightweight shafts for load transmission [1]. Composite materials especially carbon fiber offer light weight, high strength and excellent corrosion resistance for projecting long service life. [2]

Past researchers have shown that composite material shafts offer promising application in various sectors. Henry et. al. [3] utilized light weight and high strength offered by composite materials to design rotorcraft shaft for aerospace applications. Rao et. al. [4] analyzed composite propeller for automotive applications and concluded that composite materials offer better torsional properties as compared to conventional steel shafts. George Marsh [5] studied potential applications of composite shafts specifically in marine applications. The research highlighted that composite shafts not only decrease weight but also reduce the complexity of a system. The research also summarized many in-service applications of shafts made up of specifically carbon fiber used in cruise ships and lifeboats.

As shafts are mainly subjected to torsional and bending loads, torsional characteristics are prerequisites for replacing conventional metallic with composite materials. Reddy and Nagaraju [6] studied weight optimization on composite shafts. Different types of composite materials were employed in fabrication of the shafts to evaluate optimized performance. The research concluded that hollow shafts made up of carbon/epoxy composite material offer 97% weight reduction as compared to conventional steel automotive shafts. Conventional shafts are made up of solid materials, Pater [7] reported that solid shaft may be replaced with a hollow composite shaft to achieve better performance and decreased weight.

In the past several years, researchers have investigated the effect of various parameters on the torsional behavior of composite shafts. Sevkat et al. [8] inspected the effect of torsional strain-rate and lay-up sequences. The properties of the composite material are enhanced by adding additives. Some other researchers used additives such as kenaf [9] and carbon nanotubes [10] as reinforcements and concluded that these additives may be used to tailor the properties of composite shafts.

Mendonça et. al. [11] simulated composite shafts using finite element analysis. The methodology included visualization of composites using classic laminate theory in which composite was treated as a combination of various layers oriented at an angle using viscoelastic resin. The research showed that composite materials can be optimized to improve dynamic behavior of rotors. Additionally, Porter et. al. [12] investigated ZrO_2-epoxy composites developed by magnetic freeze casting with helix reinforcement. It was concluded that considerable increase in strength can be achieved with helix reinforcement. In another study Sevkat and Tumer [13] manufactured various shafts having different reinforcement combinations with helix pattern using filament winding technology. Composite shafts were impacted at various energy levels using the drop weight tester. The reduction in torsional strength due to impact-induced damage was investigated. FE simulations were used to predict torque-twisting angle relations for non-impacted composite shafts.

Previous researchers have investigated composite shafts manufactured with different combinations of reinforcements using filament winding technology. However, no reported work was found on the effect of winding pattern and its direct effect on torsional properties. For manufacturing purposes, winding layers and their orientation is a prime factor hence this study elaborated the effect of helix and hoop winding on torsional properties of shafts.

This study investigates the effect of winding layers such as hoop and helix on torsional characteristics by employing variations in the number of layers and their orientation sequence. The design of experiments was furnished as to express effect of adding a helix and hoop layer which has not been reported before. As carbon fiber exhibits high strength, it was used as the material of choice for reinforcement along with epoxy matrix. The research included designing and manufacturing of carbon fiber hollow shafts using filament winding process. The design included a combination of helix and hoop winding patterns. Hoop winding along with helix winding is required in order to maintain structural integrity in the circumferential direction. The fabricated shafts were subsequently tested for hardness and torsional behavior to determine maximum torque. Finally, the results were compared to describe the effects of composite layer orientation on the torsional performance of hollow shafts.

2 Experimental

2.1 Finite Element Analysis

The initial step of research included analysis of the design using computer-aided engineering techniques. Finite element analysis of composites in the layered structure is extensively used for analyzing the behavior of shafts [6]. For this study ABAQUS system was used to develop a model of the composite shaft upon which virtual experiment was performed. The model of shafts was generated as per actual dimensions. Figure 1 shows a pictorial view of the developed model in CAD along with its meshing characteristics. The dimensions of the model included the length of 300 mm and an internal diameter of 20 mm as per actual samples. Meshing configurations include approximate element size of 0.0046 and number of elements were optimized to 1690 using mesh sensitivity analysis. The analysis included changing the size of element until a constant value of parameter such as stress was achieved.

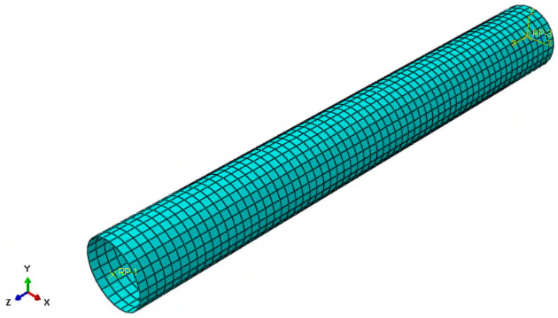

Figure 1: CAD Model of shaft in ABAQUS software

Virtual experiment on shafts included determination of torsional behavior. Table 1 gives details of parameters that are varied for this research. Variable parameters included number of layers and type of layer. The constant parameters for this research included type of material, layup scheme and orientation angle. For choice of material, carbon fiber impregnated with epoxy resin was chosen due to their proven higher strength than other reinforcement types. Layup scheme was locked to alternate sequence between hoop and helix layer and angle of orientation was ±45^{o}. The rationale of selecting orientation angles is that when a torque is applied on a shaft, shear stresses are produced within the material and fibers oriented at 45^{o} provides the best resistance to shear. Moreover, alternate sequence is required to maintain structural rigidity and circumferential strength along with shear strength.

The number of layers were varied between 3 and 5 to investigate the direct effect of winding layer. The explicit effect of winding layer is exploited with increase of just one layer from the preceding design. The structure will not be rigid enough if less than three layers are used. Higher number of layers (i.e. greater than 5) are not considered as the purpose of the investigation is not to analyze the effect of shaft thickness.

Table I: Detail of factors and level values for design of experiments (DoE)

Level	**Factors**	
	No. of Layers	**Layer Type**
1	3	Hoop
2	4	Helix
3	5	

Detail of Samples	
Sample ID	**Layer Orientation**
Sample A	0, ±45, 0
Sample B	0, ±45, 0, ±45
Sample C	0, ±45, 0, ±45, 0

Composite layup module in ABAQUS was utilized to develop a model for the composite material. Helix winding layer was characterized as ±45^{o} as its fibers are oriented along both directions. Composite continuum shell element S8R was employed for simulation purposes. Material properties used for model development are shown in Table II. The material type used was orthotropic in nature. Layers were oriented in 0 or ±45° as per stacking sequence using composite section tool.

Table II: Material Properties

Property	**Value**
E1	34.8 GPa
E2	6.88 GPa
Poisons Ratio	0.33
G12	2.72 GPa
G23	2.89 GPa
G31	2.89 GPa
Density	1.33 GPa

Boundary conditions applied on the model included constraining one side of the shaft in all dimensions and applying twisting moment on the other end. The boundary conditions were dictated by actual experimental setup which was used to perform real-time experiments. Verification of simulated results were made by comparing data extracted from real-time testing. A display of boundary conditions on both ends of the shaft is shown in Figure 2. It shows a cut of model explicitly displaying fixed end and rotation end.

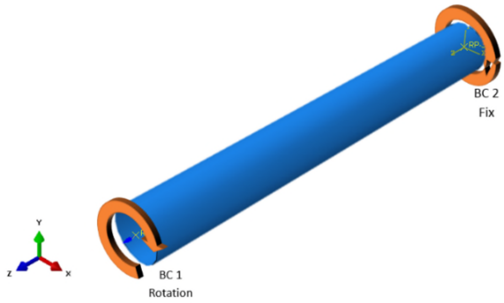

Figure 2: Boundary conditions applied

Figure 3 shows a visual representation of stress generation and deformation of the shaft. The red areas are the areas of maximum stress whereas blue areas exhibits minimum.

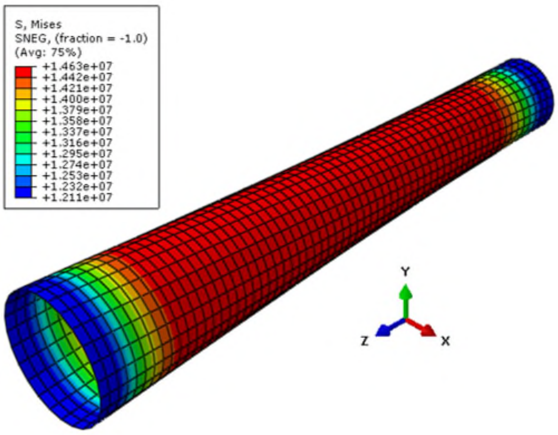

Figure 3: FEA of shaft in ABAQUS software

For calculation of torque from stress, following formula was used [15].

$$Torque = \frac{\pi}{16}\sigma_{max}\frac{(D^4 - d^4)}{D} \qquad (1)$$

where,

σ_{max} = Maximum Stress,

D= Outer Diameter

d= Internal Diameter

2.2 Composite Manufacturing

2.2.1 Material

The aim of the research was to achieve higher degree strength at low weight hence carbon fiber and the epoxy matrix was selected as materials of fabrication. Carbon fiber tow was used for winding which has a size of 12K and filament diameter approximately 7-8µm. Bobbins of carbon fiber have a net weight of 6 Kgs and unwounded externally. The matrix of choice was Epoxy resin Epolam 2040 which cures at ambient temperatures.

Fabrication of shafts was carried out using filament winding process. The machine used in fabrication utilized two axis degree of freedom to wound helical pattern on a rotating mandrel.

The spools were normalized at ambient condition. Two spools of carbon fiber were weighted first and then mounted on a fixed creel. Filaments from both the spools were passed through a resin bath and converging ring to achieve a bandwidth of 2mm.

Mandrel used for fabrication was made up of mild steel and was tapered along its length. Mandrel had a maximum diameter of 21 mm and was mounted in chuck from larger diameter. After mounting, surface preparation for easy removal of the shaft was performed. Figure 4 shows a picture of mandrel along with release agent.

Figure 4: Mandrel used for fabrication of shafts

The process of fabrication involved winding of impregnated fiber on rotating shafts. Firstly, the machine was programmed for the hoop and helical winding, then the machine was operated for a dry run. After assurance of pattern by a dry run, wet layup through winding was started. The resin to be feed from resin bath was prepared in small batches in order to provide a fresh resin for impregnation. The resin impregnation was controlled using doctors blade in order to minimize excessive resin flow and in turn high resin volume fraction. The shafts were manufactured layer by layer and then allowed to cure at an ambient temperature for 24 hrs. Figure 5 gives a pictorial view of the fabrication process.

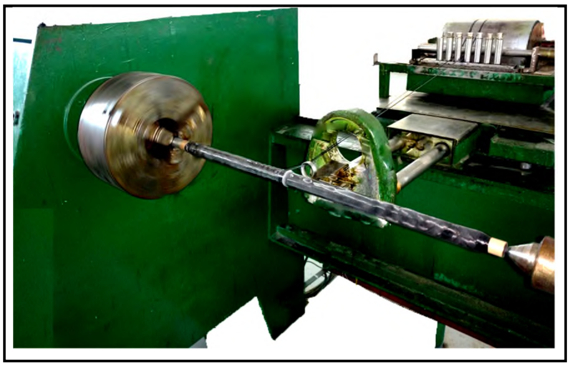

Figure 5: Illustration of filament winding process

After curing of shafts, they were extracted from the mandrel through hydraulic puller machine. The shafts were further cut to give the standard size of 300 mm length in order to achieve relative results as torque depend upon length of shaft. For the even surface, shafts were faced at the end. Table 1 gives information on the design of shafts and fabricated shafts are shown in Figure 6. The volume fraction of fibers achieved during the process was approximately 60%. Volume fraction defines the amount of compaction in fabricated composites and as fibers are the prime load carrying elements, the more the value, better are allied properties.

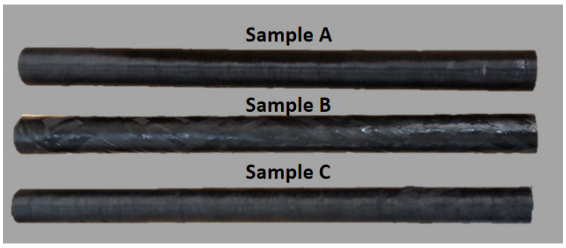

Figure 6: Fabricated Shafts

2.3 Testing

The main objective of the study was to measure the torsional characteristics of samples. To evaluate fabricated samples, torque at rupture was measured against the angle of twist. Testing of shafts was carried out on the torsional testing machine. One end of the shaft was clamped to remain stationary, while torque was applied on the other end. The output results provided maximum torque the shaft endured and the maximum angle of rotation till rupture. For secondary characteristics, hardness test was performed on manufactured shafts using Vickers hardness testing procedure.

3 Results and Discussion

Testing of shafts as per procedure explained in Section 2.2 and FEA simulations as given in Section 2.1 provides comparison data for experimental and simulation results. Figure 7, Figure 8 and Figure 9 illustrates the assessment of experimental results as compared to simulation results.

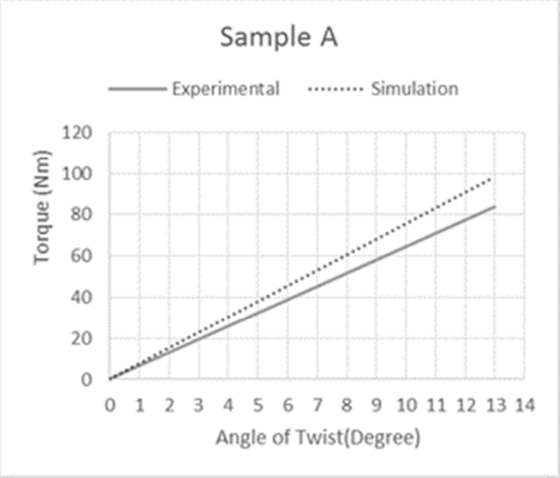

Figure 7: Experimental vs Simulation results (Sample A)

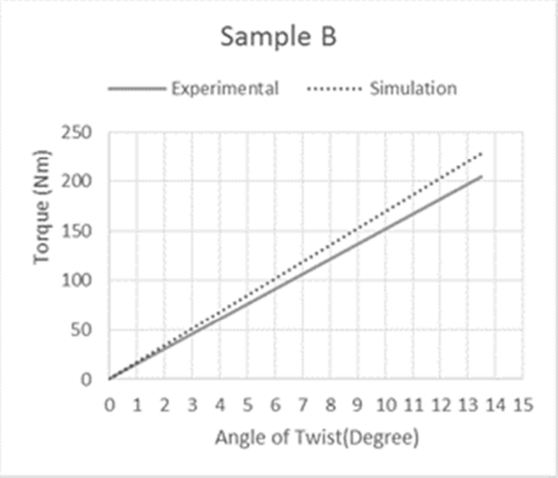

Figure 8: Experimental vs Simulation results (Sample B)

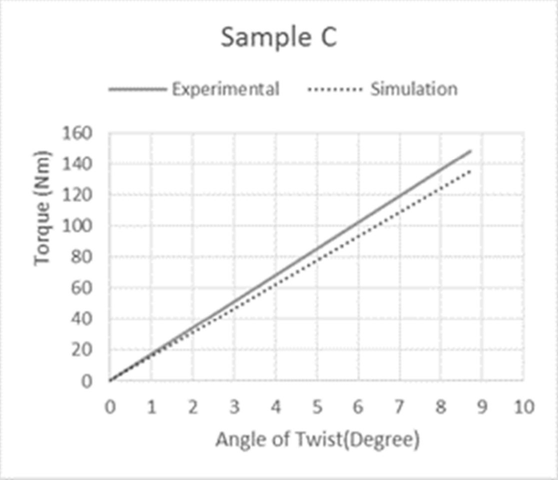

Figure 9: Experimental vs Simulation results (Sample C)

By analyzing comparison results, it is apparent that simulation and experimental results fairly complement each other. Three tests were performed for each design and average results were plotted. For Sample A and B, the torque extracted by simulation results was greater than the experimental results while for Sample C, the experimental results showed higher values. The deviation of experimental values from simulated values were attributed to environmental and human constraints such as temperature, humidity, and operational skills.

Another aspect of findings of this research is to compare properties of manufactured samples in comparison with each other. Figure 10 illustrates comparison of torsional values to manufactured shafts. Sample B shows 38% times more strength than Sample C and 144% times more as compared to Sample A. For comparison among maximum angle of twist, Sample A and B shows slightly similar values with angle for Sample B i.e. 3% more than for Sample A. Sample C exhibits angle of twist 64% less than Sample B and 66% less than Sample A.

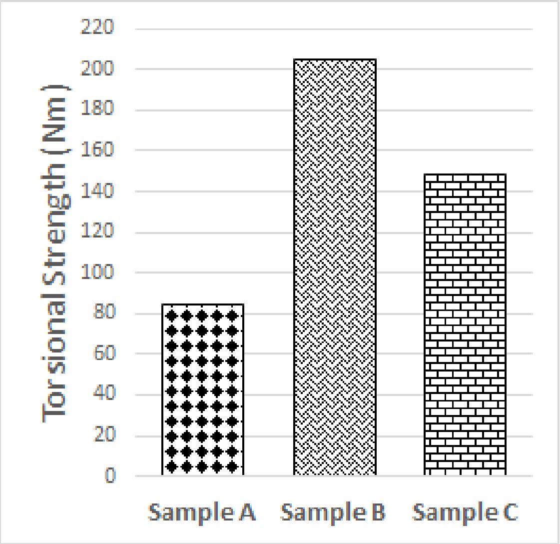

Figure 10: Comparison of Torsional Strength

By analyzing the results of shafts, it is evident that maximum torque offered by Sample B is greater than Sample A because of increased lamina and thickness of the shaft. Although Sample C contains more laminas than Sample B, but maximum torque offered by latter is more. This decrease in torque of Sample C is credited to increased thickness without a significant increase in shear rigidity. As a layer of hoop winding is added which offers less resistance than helix winding, Sample C shows low strength even though it contains the most layers. Based on the results, Sample B shows maximum torsional strength and it shows the significance of adding helix winding layer in the design of Sample A.

For an angle of twist, Sample A shows the maximum value whereas Sample C depicts the minimum value. This is credited to a thickness of shaft as Sample A possesses the lowest thickness than other samples, it offers more angle of a twist. The angle of twists narrates the amount of stiffness in a shaft. By analyzing the results, it is found that angle of twist is more influenced by a number of layers rather than the type of layers. As evident from results, adding helix or hoop layer have no characteristic effect on the angle of twist.

Another aspect of comparison of torsional characteristics is the Torsional stiffness as given by equation 2. Stiffness marks the ability of a material to resist deformation and particularly in case of shafts, it is resistance to rotation. When a torque is applied on a body, a twisting moment is generated. The resistance to the twisting moment is the torsional stiffness. A comparison of torsional stiffness of fabricated shafts is given in Figure 11. The bar graphs define resistance ability of each shaft.

$$Torsional\ Stiffness = \frac{Torque}{Angle\ of\ twist} \tag{2}$$

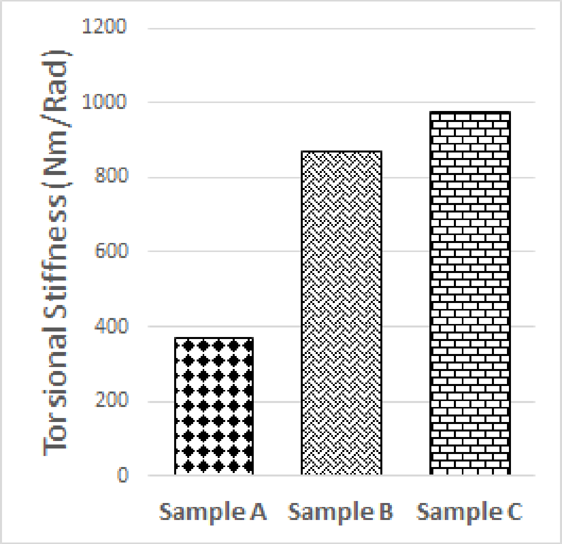

Figure 11: Comparison of Torsional Stiffness

By analyzing the results in Figure 11 it is deduced that Sample C exhibits maximum value of stiffness. Value of Sample C is 11% more than Sample B and 62% more than Sample A. As Sample C showed least angle of twist than others, its relative value of torsional stiffness is also higher. The reason for high value is more thickness which increases rigidity of shafts. The trend of increase in thickness is carried out in values of torsional stiffness as well. Moreover, by analyzing effect of winding layer, Sample B offers 57% more strength than Sample A hence it is evident that adding a helix layer increased the torsional stiffness by 57%. Similarly, value of Sample C is just 11% more than Sample B meaning that hoop layer offers 11% increase in stiffness value. Hence to conclude, helix layer offers more stiffness as compared to hoop winding layer.

An inherent property of materials includes absorption of energy when a force is applied on them. In case of torsional force, the energy absorbed by a material is defined as Torsional resilience. Mathematical form of torsional resilience is given in equation 3. By definition, torsional resilience is the amount of energy absorbed in a material when a rotational force is applied on it. Figure 12 provides a comparison graph of torsional resilience values of fabricated shafts.

$$Torsional\ Resilience = \frac{\sigma_{max}^2}{4C}\frac{(D^2-d^2)}{D^2} x\ V \qquad (3)$$

(3)

where,

σ_{max} = Maximum Stress
D = Outer Diameter
d = Internal Diameter
C = Modulus of Rigidity

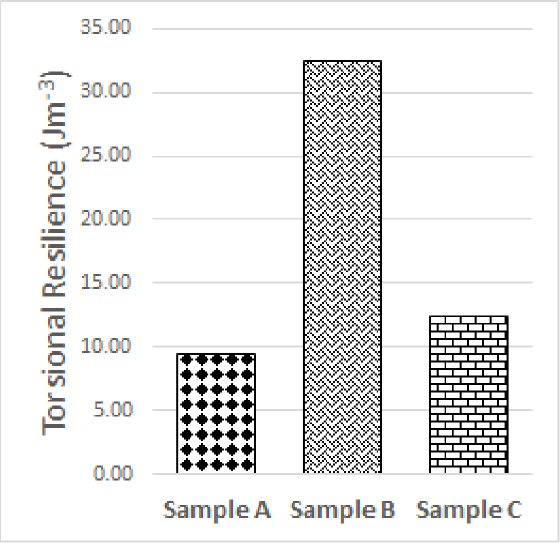

Figure 12: Comparison of Torsional Resilience

Examination of Figure 12 gives an insight of comparison of fabricated shafts. The bar graph manifests that sample B shows considerably higher values of resilience than sample A and sample C. Quantitatively, Sample B exhibits 71% more resilience than sample A and 61% more than Sample C. the relative value of sample B is much higher than others because of much higher value of maximum torque. When comparing Sample, A and Sample C, there is only 26% change in values. Henceforth, while comparing the effect of type of layer, adding helix layer significantly increases resilience values while adding a hoop layer have no considerable effect on resilience values.

Secondary test performed on shafts was hardness test. The test used Vickers hardness scale to determine surface hardness. The results are shown graphical in Figure 13 with 5% error bar.

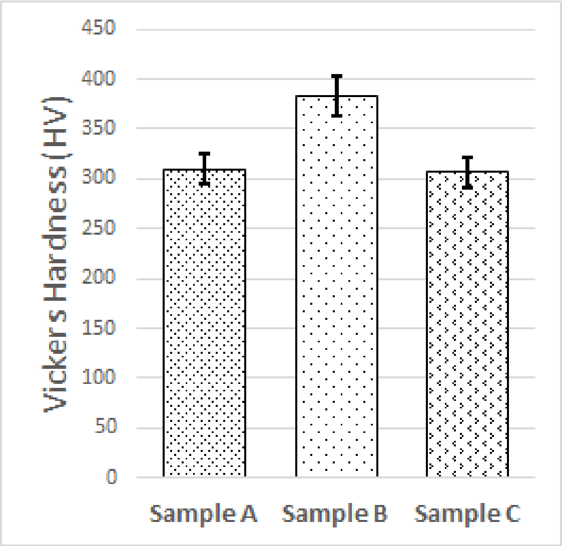

Figure 13: Comparison of Hardness

As evident from Figure 13, Sample B exhibits maximum hardness whereas Sample A and B show low surface hardness. The reason is attributed to a top layer of cross-linked helix winding in Sample B as compared to other samples where the top layer is hoop winding. Values of hardness explicitly narrate the effect of the winding pattern. As seen in Figure 9, the value of hardness for Sample A and Sample C are almost identical as they have similar type of winding layer on surface i.e. hoop winding layer. On the contrary, Sample, B shows the value of helix winding as its topmost layer is helix by design. Hence, helix winding pattern shows more hardness than hoop winding pattern.

4 Conclusions

Composite material shafts comprising of carbon fiber and epoxy matrix were developed in this study. Filament winding technology was employed to manufacture hollow shafts. Shafts were subsequently tested for torsional strength using the torsional testing machine. Three composite material shafts having variations in an orientation and number of layers were tested for maximum torque and for the angle of twist. It is concluded that adding helix winding layer to filament wound composite shafts considerably increases the torsional strength. Moreover, with the addition of hoop winding layer instead of helix layer led to a decrease in the torsional strength. It is found that by increasing the number of layers, the maximum angle of twist decreases due to increased rigidity of the structure. In case of torsional stiffness, the values increase with increase in thickness irrespective of the layer type. Helix layer however offers more stiffness as compared to hoop layer. Torsional resilience values for helix layer is also considerably high, dignifying the use of helix layer for torsional performance. It is also inferred that surface hardness depends on the type of winding layer on the surface. Shaft with helix winding on top surface showed improved hardness as compared to shafts with top surface hoop layer.

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