Investigating the Mechanical Properties of Cast Aluminium Rods Reinforced with Wet Filament Winding

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***Abstract*: Metal rods and pipes are often reinforced with dry and wet windings of fibre strands on their surfaces. Many research works had been carried out on this. However, this work investigates the impact energy, tensile, compressive and fatigue properties of aluminium rod without fibre winding, and aluminium rods reinforced with wet filaments made of carbon, glass and copper fibres impreginated in epoxy resin. As compared to 4.2 J impact energy displayed by unreinforced rod, rods with carbon, glass and copper windings yielded 4.7, 5.3 and 5.6 J respectively. The respective ultimate tensile strengths are 144.1, 160.8, 155.2and 227.3 MPa. Thus the corresponding percentage elongations are 10.40, 5.85, 7.55 and 3.95%. However, the corresponding ultimate compressive strengths are 111.3, 112.5, 118.5 and 122.1 MPa. Increase in fatigue stress amplitude was observed to reduce the fatigue life (number of cycles-to-failure, N_f) of the specimens, Fatigue limit of unreinforced specimen increases from 35 to 70, 105 and 175 MPa with carbon, glass and copper windings. And endurance limit correspondingly increase from $10^{5.0}$ to $10^{5.5,}$ $10^{6.6}$ and $10^{7.5}$ cycles-to-failure The findings in this work show that carbon, glass and copper filament windings offer remarkable resistance to impact, tensile compressive and fatigue deformations of the unreinforced rod.**

***Keywords*: Aluminium, mechanical properties, wet filament winding, carbon, glass and copper fibres**

I. INTRODUCTION

Aluminium is the most widely used non-ferrous metal for engineering applications due to its unique combination of properties; good corrosion resistance, high strength stiffness to weight ratio, good electrical and thermal conductivities, and prospects of recycling at low energy costs [1-3]. The properties of aluminium are normally improved by addition of alloying elements, manufacturing techniques and heat treatment [4-8]. Aluminium is often strenghtened by reinforcement with particles and fibres via casting (to obtain metal matrix composite) or with windings of resin-impregnated fibre strands (filaments) on its surface.

Many investigations have studied the effects of casting techniques and post-cast heat treatment schedules on cast aluminium alloys in order to improve strengths and provide acceptable ductility [7,9,10,11,12]. Typical heat treatment methods to which aluminium are subjected are solution heat treatment and stress relief annealing.

The results of study conducted by Ayoola et al. [11] on the rate of cooling and solidification of cast aluminium alloy in mould showed that hardness, impact resistance and strength the alloy are influenced by the type of mould used casting. These properties can be improved using mould with high thermal conductivity. Also, Stephen et al. [7] and Isadare et al. [9] showed the heat treatment (stress relief annealing) improved impact strength and ductility of cast aluminium alloy.

In addition, modern requirements for lightweight materials with good corrosion and chemical resistant, and desirable heat, electrical and mechanical properties in construction and structural design which cannot be obtained in a single conventional construction material have created interest in fibre reinforced metal-matrix composites with outstanding combination of desired properties [13].Experimental studies conducted by Adeosun et al. on 6063 aluminium-steel composite showed that hardness and tensile strength of the aluminium-steel composite depend on the percentage weight of steel dust in aluminium 6063 matrix [5].Reinforcing aluminium with fibre materials provides higher strength, stiffness and other mechanical characteristics than using common treatment schedules such as grain refinement, solid solution and precipitation hardening. Mitrović *et al.* showed that hybrid aluminium-zinc alloy matrix composites reinforced with particles of silicon carbide and graphite possesses lower coefficient of friction, better wear resistance, higher hardness and tensile strength than the base aluminium alloy [14].

Carbon fibres are specially used as reinforcing material owing to its light weight, high specific strength and modulus, high thermal and electrical conductivities and low coefficient of thermal expansion [15]. Abhilash and Joseph [16] revealed the production of aluminium matrix-carbon fibre composites with a good wettability and fibre/matrix bonding using squeeze infiltration technique. The density of the developed composites was found lesser than that of the matrix material (2.47 and 2.7 g/cc, respectively) whereas its hardness and impact energy was better than that of matrix aluminium alloy [16].

Mechanical and wear behaviours of aluminium based composites reinforced with quarry dust and silicon carbide using double stir casting was carried out by Alaneme and Bamike[17]. The results of the study showed that ductility and fracture toughness of the composites were noticeably improved, whereas marginal decrease were observed in hardness and wear resistance characteristics of the composites. Furthermore, the results of response of coconut shell ash and E-glass fibre reinforced aluminium hybrid composites to heat treatment (Pinto *et al.* [18]) showed that micro hardness and tensile strength increase significantly for non-heat treated samples due to increase in percentage weight of glass reinforcement whereas micro hardness of the heat treated specimens is lower that the base material. Wear rate was also found to reduce in both heat treated and non-heat treated samples. Rahman and Shivanand [19] fabricated aluminium alloy (Al 2219) matrix composites with E-glass and flyash particulate as reinforcement through liquid metallurgy technique using stir and permanent mould castings. Evaluation of its mechanical properties revealed that hardness, ultimate tensile and compressive strengths increase with increase in percentage composition of constituent material (especially the E-glass) in Al 2219 matrix.

Also, Subramani and Ganesh [20] produced hybrid low-cost and light-weight A6061/Al2O3/glass fibres/SiCp/B4C composites with better strength, corrosion and wear resistant than the based metal using stir casting technique. Reinforcement increases the strength and reduces the weight of the composites.

Ramchandra and Patel [21] did design and analysis of composite drive shaft for automobile by replacing traditional two-piece steel drive shafts with one-piece automotive hybrid aluminum/composite drive shaft. The shaft was developed with a new manufacturing method which invovles co-curing a carbon fiber epoxy composite layer on the inner surface of an aluminum tube instead of wrapping on the outer surface to prevent the composite layer from being damaged by external impact and absorption of moisture, and to improve the torque capacity.

Composite drive shafts offered advantage of reduced weight, noise and vibration than metals drive shafts [22]. Arun and Vinoth[23] developed hybrid aluminium E glass/epoxy composite drive shaft for an automotive application. The aluminium has a role to transmit the required torque, whereas the E-glass epoxy composite was to increase the bending natural frequency. The drive shaft was designed and produced; glass mat fabrics with epoxy were wounded around aluminium tube (AA6063). The results obtained showed that torsional strength of the composite shaft was 66% higher than that of pure aluminium shaft, whereas a mass reduction of 42% was achieved. However, Khoshravan and Paykani claimed that a full composite drive shaft designed recorded weight reduction of 72% when compare to steel drive shaft [24].

Furthermore, Mutasher*et al.*[25] investigated static and dynamic characteristics of a hybrid aluminium composite drive shaft fabricated by wetted filament winding method, using carbon and glass fibres with different layers and stacking angles as reinforcements. A winding angle of 45° was found to result in higher static and dynamic torque capacity than 90° for both fibres, and approximately 7-15 percent difference exists between their static and dynamic torques. However, shafts with different stacking sequence of [90/ + 45/-45/90] and [+45/ -45/90/90] showed close torque-angle and the twist performance, and power transmission capacities.

Also, studies showed that torque capacity increased 14 folds for aluminium tube reinforced with carbon fibre at 45^o winding angle when compare to aluminium tube alone. In addition, for the failure mode under torsion, failure was observed to occur at the central of the aluminium tube and then propagated and caused delamination of composite layer. Fatigue results showed that failure occurred when aluminium tube composite was loaded perpendicular with bending load and no fibre failure was observed rotating bending fatigue[26, 27].

Efforts, especially in aerospace, have also shown that properly designed composite components have inherently superior fatigue and vibration damping characteristics compared to metals [28]. Hybrid laminates panel that consist of glass fibre reinforced plastics bonded with thin aluminium sheets on either side were fabricated with varying aluminium thickness fractions, fibre volume fractions and orientation in the layers by Periasamy*et al.*, and its impact performance evaluated. The laminated sandwich panel displayed belter impact performance than aluminium alone and also, panel with cross-ply fibre orientation exhibit better performance that unidirectional fibre orientation. Increase in aluminium thickness and fibre volume improved impact strength of the laminated panel [29].

The present research investigates the mechanical properties of cast aluminium rods reinforced with carbon, glass and copper fibres using wet filament winding method, with focus on impact, tensile, compressive and fatigue properties.

II. MATERIALS AND METHODS

A. Materials

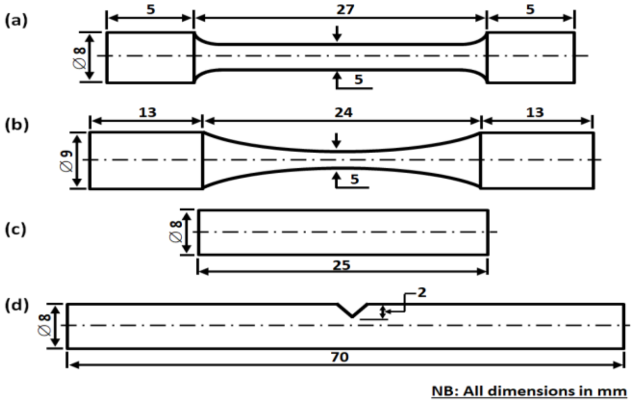
The materials used for this research study are aluminium alloys (obtained from motorcycles internal combustion engine parts (piston and connecting rod) and aluminium electric cables (E9VE)), reinforcement materials (carbon, glass and copper fibres strands) and epoxy resin. Epoxy resin (MW 215 A) and hardener (MW 215 B) were mixed in ratio 4:1by weight. The fibre strands were purchased in Lagos, Nigeria.

Foundry sand mould was prepared with silica sand, coal-dust, clay and starch that were mixed with the right proportion of water. Wooden cylindrical patterns were cut to obtain the shape of the pattern needed for the mould cavity by incorporating them in the sand mould assembly of drag and cope. Thereafter, the patterns were removed leaving a mould cavity that would contain the melted aluminium alloy. A gating system for sprue and riser pins was incorporated to allow the flow of the molten metal. The drag and cope were allowed to dry naturally and then clamped together waiting the pouring of molten metal.

Aluminium scrapswere melted in an open earth furnace. The molten aluminium alloy was uniformly mixed (to obtain uniform composition) before being poured into the mould cavity through the sprue until the the cavity was filled up as confirmed from the riser. After about 45 minutes of pouring the molten metal into the mould cavity, the drag and cope assembly was dismantled (shaken-out), leaving a solidified cast metal. The cast samples were then surface-finished to obtain clean surface.

B. Specimens Machining

The specimens were machined to form tensile, compression, impact and fatigue test specimens. The tensile, fatigue and compression test specimens were machined to the dimensions shown in Fig. 1 (a-c), whereas the impact specimens were machined to lengths of 70 mm and diameter of 8 mm, and were notched at an angle of 45^0 to a depth of 2 mm at the middle of the specimen using Hounsfield notching machine (Fig. 1d). For impact, tensile and compression tests, three specimens each of unreinforced rod, carbon, glass, and copper fibres wound rods were prepared with the aim of finding average values in the respective tests. However, sixteen specimens each of unreinforced rod, carbon, glass, and copper fibres wound rods were prepared to accomodate series of stress amplitudes in fatigue test.



NB: All dimensions in mm

Fig. 1: Schematic diagrams of the machined(a) tensile; (b) fatigue; (c) compression and(d) impact tests specimens

C. Wet Filament Winding

Wet filament winding was then carried out on the test specimensby applying epoxy resin on their gauge lengths and manually winding the respective fibres strands on them. Epoxy resin was also applied immediately after winding. Epoxy resin was employed to give a great binding effect between the test specimes gauge lengths and the fibre layers. The specimens were allowed to dry at room temperature. The thickness of the layers of windings oncarbon, glass and copper fibres on the specimens was 3.0 ± 0.1 mm.

D. Impact Test

Impact test was carried out to evaluate the resistance of the specimens to sudden blow (force). Impact testing was conducted on an Izod impact testing machine according to ASTM E602-91 standard. The respective specimen was fixed on the machine as simple beam with the opposite face of the notch fixed to receive the hammer blow. The impact strength of a specimen was determined from the energy absorbed when swing hammer of the machine released from a fixed height hit and fractured the specimen.

E. Tensile Test

Tensile specimens with and without fibre windings were respectively subjected to constant extension rate tensile (CERT) test on a HoundfieldTensometer in accordance with ASTM E-8 standard. As straining continued the maximum force (or ultimate load) exerted on each specimen before fracture, was recorded via a mercury column. Ultimate tensile strength was obtained by dividing the ultimate load with the original cross-sectional area of the gauge section of the specimen. Also, the percentage elongation at fracture of respective specimen was determined. Repeated tests showed good agreement within a measurement accuracy of ±3%.

F. Compression Test

Compression test was carried out on the same Tensometer according to ASTM E9-09 standard to obtain compression strength of the respective specimens.The direction of loading on the specimens was opposite the direction displayed in tensile test. Maximum applied loads on the specimens were recorded and compressiive strengthswere then evaluated.

G. Fatigue Test

The fatigue properties of a specimen with copper fibre windings was evaluated by clamping it on the grips of a completely reversed Avery Deninson 7305 Bending Fatigue Testing Machine with a zero mean stress (in accordance with ASTM Standard E606/E606-12). A bending load was exerted on the specimen by an oscillating spindle driven by a connecting rod, crank and double eccentric mechanism until a bending moment that corresponds to a maximum fatigue stress of amplitude of 560 MPa was attained. While under bending moment, as it was rotated via a flexible couplimg by a high-speed motor, tensile and compressive stresses were applied alternatively on the surface of the specimen. A counter mounted on the motor recorded number of cycles (N) as the specimen rotated. When the specimen failed, the number of cycles-to-failure (N_f) was recorded. This procedure was repeated on other specimens with copper fibre windings at decreasing stress amplitudes of 525, 490, 455, 420, 385, 350, 315, 280, 245, 210, 175, 140, 105, 70, 35 MPa. However, testing was stopped at any stress ampltude that signifies fatigue limit.

Similar tests were carried out on specimens with glass fibre windings, specimens with carbon fibre windings and specimens without windings (unreiforced). As done before, testing of identical specimens was stopped at any stress ampltude that indicates fatigue limit. The fatigue stress amplitudes of identical specimens versus the number of cycles-to-failure were then plotted to obtain the S-N curve.

Fatigue limit is the maximum stress below which the specimen can theoretically endure an infinite number of stress cycles. The fatigue life (number of cycles-to-failure) at the fatigue limit is called endurance limit.

III. RESULTS AND DISCUSSION

Table I shows the variations of impact energy, tensile properties and compressive strength of wet filament winding specimens. The graphical representation impact energy variation is shown in Fig. 2. As compared to 4.2 J impact energy displayed by unreinforced rod, rods with carbon, glass and copper windings yielded 4.7, 5.3 and 5.6 J respectively. This shows that carbon, glass and copper windings offer appreciable resistance to deformation by impact (sudden blow) in an increasing order.

Table I: Variations of impact energy, tensil and compressive properties of the specimens

Type of Fibre	Impact Energy (J)	Ultimate Tensile Strength, σ_u(MPa	Percentage Elongation at fracture (%)	Ultimate Compressive Strength,σ_c (MPa)
None	4.2	144.1	10.40	111.3
Carbon	4.7	160.8	5.85	112.5
Glass	5.3	155.2	7.55	118.5
Copper	5.6	227.3	3.95	122.1

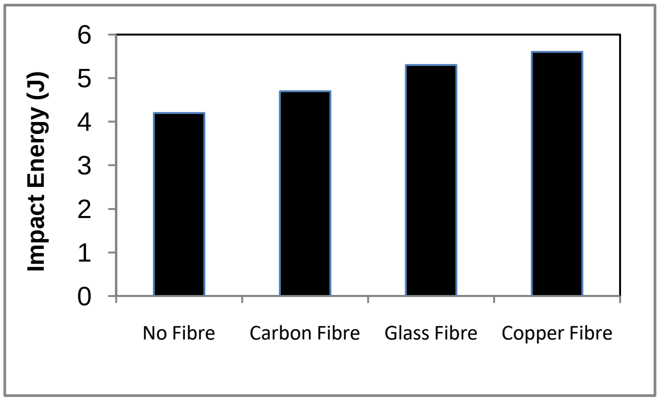


Fig. 2: Plot of impact energy variationsfor the specimens

Fig. 3shows the ultimate tensile strength variation for the specimens. Filament windings with carbon, glass and copper fibres yielded an increase in ultimate tensile strength of the unreinforced rod from 144.1 MPa to 160.8, 155.2 and 227.3 MPa respectively. This shows that carbon fibre winding offer more tensile strength than glass fibre winding. Fig. 4shows the variation of percentage elongation at fracture for the specimens. As depicted in Fig. 4, the respective windings reduce the percentage elongation at fracture of unreinfoced specimen from 10.40 to 5.85, 7.55 and 3.95%. It is observed here that glass fibres offer more percentage elongation-at-fracture than carbon fibres. The increase in tensile stregth and reduction in percentage elongation-at-fracture of the unreinforced rodby fibres windingsis attributed to the improved surface strength that offers resistance to tensile deformation of the unreinforced specimen.

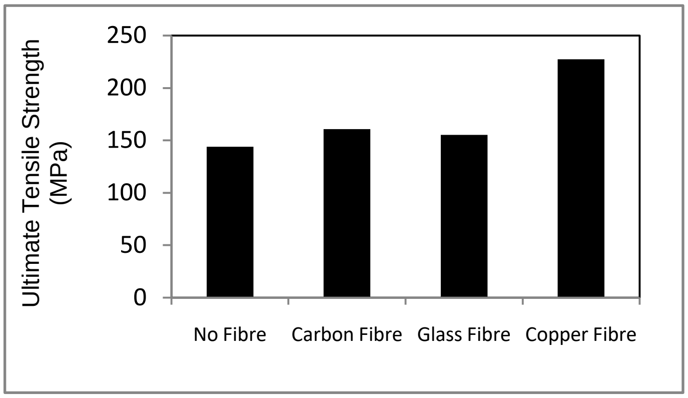


Fig. 3: Plot of ultimate tensile strengthvariations for the specimens

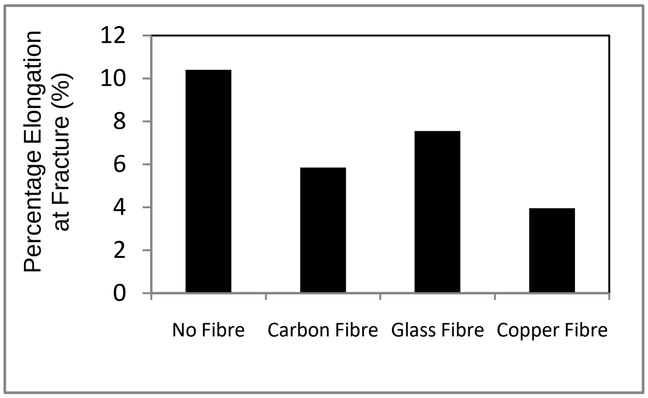


Fig. 4: Plot of percentage elongation at fracturevariations for the specimens

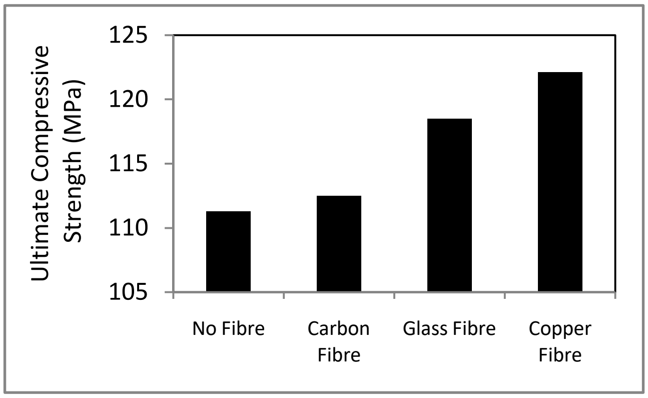


Fig. 5: Plot of ultimate compressive strength variations for the specimens

Table II: Variations of Fatigue atress amplitude with Logarthmic scale of number of cycles-to-failure

Fatigue Stress Amplitude, S (MPa)	No Fibre Winding		Carbon Fibre Winding		Glass Fibre Winding		Copper Fibre Winding	
	N_f	log N_f	N_f	log N_f	N_f	log N_f	N_f	log N_f
560	16	1.20	32	1.50	63	1.80	160	2.20
525	25	1.40	56	1.75	100	2.00	253	2.40
490	32	1.50	80	1.90	127	2.10	565	2.75
455	40	1.60	100	2.00	225	2.35	1415	3.15
420	50	1.70	112	2.05	450	2.65	2520	3.40
385	71	1.85	126	2.10	503	2.70	5625	3.75
350	100	2.00	178	2.25	1585	3.20	19960	4.30
315	158	2.20	501	2.70	3170	3.50	31630	4.50
280	182	2.26	630	2.80	4470	3.65	100000	5.00
245	251	2.40	1260	3.10	8915	3.95	398120	5.60
210	447	2.65	2240	3.35	39810	4.60	3162500	6.50
175	562	2.75	3165	3.50	316240	5.50	31623000	7.50
140	1000	3.00	12590	4.10	891255	5.95	-	-
105	3548	3.55	100000	5.00	3981075	6.60	-	-
70	19955	4.30	316230	5.50	-	-	-	-
35	100000	5.00	-	-	-	-	-	-

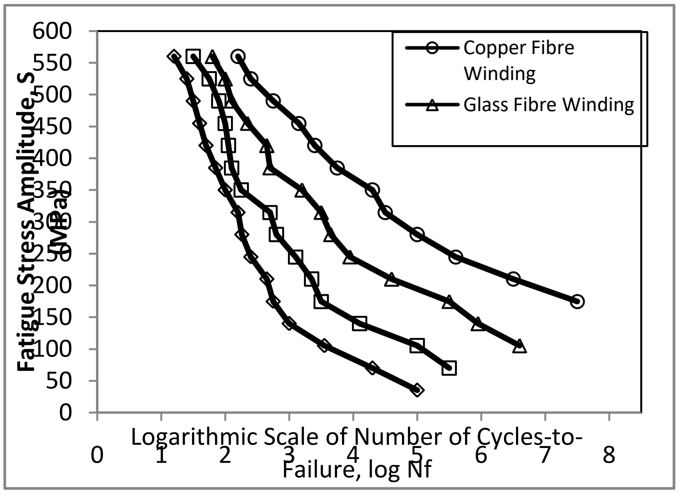


Fig. 6: Plot of fatigue stress amplitude versus logarithmicscale of number of cycles-to-failure for the specimens

Fig. 5 shows the ultimate compressive strength variation for the specimens. Filament windings with carbon, glass and copper fibres exhibited an increase in ultimate compressive strength of the unreinforced rod from 111.3MPa to 112.5, 118.5 and 122.1 MPa respectively (here carbon fibre winding offers less compressive strength than glass fibre winding unlike the trend displayed in ultimate tensile strength). This is attributed to the fact that carbon fibre is strong in tension but weak in compression.

Table II shows the variations of fatigue stress amplitude with logarithmic scale of number of cycles-to-failure. The plot of fatigue stress amplitude versus logarithmic scale of number of cycles-to-failure for the specimens is shown inFig. 6. Increase in fatigue stress amplitude was observed to reduce the fatigue life (number of cycles-to-failure, N_f) of the specimens. Fatigue limit (i.e. fatigue strength at endurance limit) of unreinforced specimen increases from 35 to 70, 105 and 175 MPa with carbon, glass and copper windings. This is shown in Fig. 7.

And endurance limit correspondingly increase from $10^{5.0}$ to $10^{5.5,}$ $10^{6.6}$ and $10^{7.5}$ cycles-to-failure. This is shown in Fig. 8.

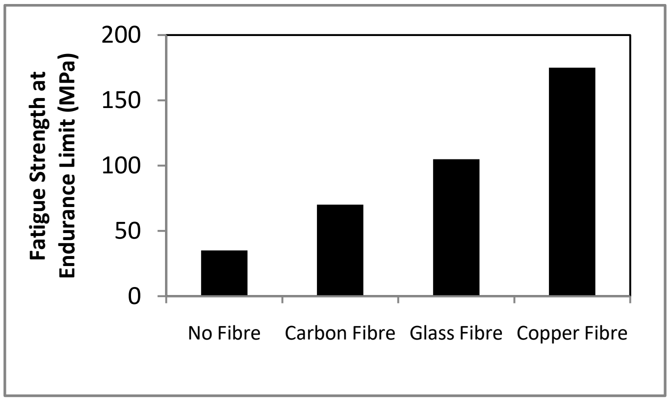


Fig. 7: Plot of fatigue limit (fatigue strength at endurance limit) for the specimens

Also, at fatigue stress of 280 MPa, windings with carbon, glass and copper fibres increase fatigue life of unreinforced rod from $10^{2.26}$ to $10^{2.80}$, $10^{3.65}$ and $10^{5.0}$ cycles. These observations show that carbon, glass and copper filament windings also offer remarkable resistance to fatigue deformation of the unreinforced rod in an increasing order.

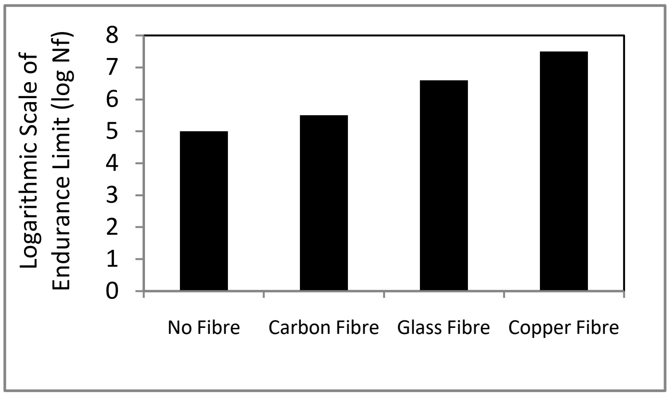


Fig. 8: Plot of endurance limit (fatigue life at fatigue limit) for the specimens

IV. CONCLUSIONS

This work investgates the impact energy, tensile properties, compressive strength and fatigue properties of unreiforced aluminium rod (i,e, without fibre winding), and aluminium rods reinforced with wet filaments made of carbon, glass, and copper fibres impreginated in epoxy resin. Findings show that carbon, glass and copper windings offer appreciable resistance to impact and tensile deformations of the unreinforced rod in an increasing order. Thus the corresponding percentage elongations are in an increasing order. However, carbon fibre winding was observed to offer less compressive strength than glass fibre winding. This is attributed to the fact that carbon fibre is strong in tension but weak in compression.

Increase in fatigue stress amplitude was observed to reduce the fatigue life of the specimens, Fatigue limit of unreinforced specimen increases with carbon, glass and copper windings. This implies that carbon, glass and copper filament windings also offer remarkable resistance to fatigue deformation of the unreinforced rod in an increasing order.

To expand the frontier of knowledge, the effect of other fibres winding (apart from carbon, glass and copper windings) should be investigated.

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