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Characterization of Fiber Metal Laminates for the Development of Subsea Housing

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Fiber Metal Laminates (FML) are hybrid composites comprising metals and Fiber Reinforced Plastics (FRP). FMLs are the most widely used in aerospace, defence and automotive sectors due to their superior qualities like light weight, tensile, compression, flexural, excellent fatigue and impact resistance. The properties like strength-to-weight ratio, susceptibility to corrosion and good heat conduction of FML make it suitable for subsea applications. Commonly, FML with a combination of aluminium (Al), titanium (Ti), stainless steel (SS) alloys and FRP are widely used for ocean applications. Compared to other FML, the SS alloy-based FML is typically used in subsea applications as it has more creep and excellent corrosion resistance. In India, under the Ocean Acoustics programme of the National Institute of Ocean Technology (NIOT), an autonomous underwater Ambient Noise Measurement System (ANMS) has been developed and deployed in the shallow waters of Indian seas for the past 12 years to study the background noise prevailing in the sea. To accommodate electronics and power packs for the measurement of ambient noise at an ocean depth of 100 m, subsea housing with stainless steel 316L (SS316L) material for a pressure rating of 1 MPa has been developed. The objective of this study is to develop the FML with SS316L and FRP for reducing the weight of the housing. Based on the literature studies and Classical Laminate Theory (CLT), the FML has been fabricated as a 0.45 m (450 mm) panel with a sequence of SS316L as outer layers and E-glass fibre and carbon as the inner layers. The total thickness of the laminates is 0.006 m (6 mm). The developed FMLs are processed with water jet cutting machines to carry out various testing such as tensile, compression and flexural, which are relevant to the characterization of FML and the experimental results are described in the paper.

Keywords: fiber metal laminates, subsea housing, classical laminate theory, external hydrostatic pressure.

1. INTRODUCTION

The structural materials for developing subsea pressure housing are mostly metallic with aluminium, steel and titanium alloys. However, austenitic stainless steel is typically selected for shallow water ambient noise measurements because of its formability, high tensile strength, and low cost. In India, under the Ocean Acoustics programme of the National Institute of Ocean Technology (NIOT), an autonomous ambient noise measurement system has been indigenously developed and operated for the past 12 years for time-series measurements of ambient noise in the shallow waters of the Indian seas. The subsea pressure housing accommodates the electronics for the ambient noise measurement system. The housing has been designed with SS316L material for withstanding an external hydrostatic pressure of 1 MPa (10 bar) to operate in the ocean's shallow water depth of 100 m. Density plays a major role in the material selection of the subsea pressure housing design. Developing pressure housing with alternate materials of less density is necessary. Since late 1970, many researchers have continuously focused on developing new materials that yield less weight with good mechanical properties. Fiber Metal Laminates (FML) are advanced hybrid materials with alternative layers of thin metallic sheets, and fiber-reinforced plastics [1]. The main components are metal alloy and the remaining matrix material and resin. The thickness, orientation and number of layers contribute to various laminations. The combination of FML produces a material with superior properties like strength-to-weight ratio, fatigue, impact resistance, low density and fire resistance [2]. The most commercially available FMLs are ARALL (Aramid-Reinforced Aluminium Laminate) based on aramid fibre, GLARE (Glass Reinforced Aluminium Laminate) based on high-strength glass fibre and CARALL (Carbon Reinforced Aluminium Laminate) based on carbon fibres. Other possible FMLs types are magnesium, titanium and ateel alloys [3]. Modern FML having lightweight properties, is established to be used instead of other materials for various applications from space to underwater [4]. The fiber with zero orientation in FML improves the modulus of elasticity, yield stress and ultimate tensile strength [5]. Hygrothermal conditioning, which involves the subjection of fibre metal laminates to moisture and temperature, their behaviour and mechanical properties, is one of the important studies of FML [6]. The new natural fiber FML has a low density and is highly economical compared to CARALL. The jute fibre is added between the carbon fibre and aluminium material. This is an alternative FML meant for improved corrosion resistance. The CAJRALL and CAJRMAL, made of 8 and 13 layers with carbon-reinforced magnesium laminate, were tested for

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tensile strength, and the values were 160 and 172 MPa [7]. Since the FMLs developed were mostly used in aerospace industries only, the application of the FMLs for marine/ocean environments is limited due to important properties like durability, corrosion and water absorption. Materials used to develop pressure housing must survive in a salty environment longer. While a considerable amount of information is available on the durability of Polymer Matrix Composites (PMC) for marine environments, due to the lack of a comprehensive feasibility study on the usage of FMLs in marine structures, there are not much well-documented data on the durability of these materials under marine environments [8]. Normally, the water absorption due to hygrothermal conditions can change the physical, chemical and mechanical properties of PMC, and it will not affect much in the FMLs due to the outer layers being of metal. SS-based FMLs can become the tempting choice for marine applications due to their excellent corrosion resistance [9]. The FMLs with SS 304 and glass/fibre epoxy exhibited better corrosion resistance and higher peel strength than mild steel-based FMLs. The FMLs comprising a solid Glass Fiber Reinforced Plastics (GFRP) core protected by thin SS316L layers offer excellent protection against water absorption, thus preventing the loss of mechanical properties [10]. The FMLs, composed of a solid GFRP core, co-cured with protective outermost steel AISI316L layers, provide wear resistance and protection from moisture absorption, thereby not affecting the impact resistance of the laminate. The hardness of the steel allows for higher pressure, drastically increasing the wear resistance. Nonetheless, the reduced thickness of steel layers does not introduce any stress concentration at the steel-GFRP interface [11]. FMLs which consist of magnesium alloy layers and a continuous carbon fibre-reinforced Zn-Al alloy composites layer (the mass fraction of Al is 8 %), were fabricated by the diffusion bonding method [12].This paper mainly investigates the tensile behaviour of FML under various temperatures ranging from 25 °C to 175 °C combining experimental measurement, theoretical model and numerical technique [13].The presence of steel layers in the FML sample helps increase the energy absorption, stiffness and displacement concerning other FML samples. The FML consisting of SS316/AA-1050/GRP laminates were subjected to tensile, bending and impact tests. The ultimate strength of the FMLs was from 145 MPa to 450 MPa; similarly, the bending yield stress ranged from 19.3 MPa to 447.4 MPa. The Charpy impact results ranged from 24 (KJ/m^2) to 340 (KJ/m^2). The presence of steel longer in FML specimens helps increase energy absorption, stiffness and displacement concerning other FML samples [14]. The mechanical properties of Ti/CF/PMR polyamide fibre metal laminates with various layup configurations and fibre layer orientation (0°, 90° and ±45°) were systematically investigated [15]. Tensile properties of the lightweight titanium-based carbon fibre/epoxy laminates were investigated under quasi-static loading [16]. The CAGRALLs FML consists of four sheets of aluminium and four layers of carbon fibre, and two layers of glass fibre had a tensile strength of 200 MPa and flexural strength of 320 MPa [18]. The CAGRALLs as FMLs are made of three sheets of Al 2024 T3 reinforced by carbon and glass fibre with epoxy resin and a tensile strength of 262 MPa and flexural strength of 300 MPa [19]. The hand layup method produced three FML materials with AA5052/GF/AA5052. The tensile testing of the FML sheets showed that the sample cut along the 0° had a superior direction with a tensile strength of 108 MPa, flexural strength of 147 MPa, and Impact strength of 5.21 J [20]. The strength of FMLs with Al-2024-T3 alloy composite layers together (Glare-I) is higher than when the composite layers are separated by metallic layers with a tensile strength of 322 MPa [21].

The primary aim of the FML is to reduce the weight of significant elements. The elements are mainly metals and composites. FMLs are typically classified based on the metal constituents, reinforcements, laminates and direction of the laminates. Stainless steel, titanium, aluminium and magnesium are mainly used as metal constitutes and whereas glass, carbon, aramid and Kevlar fibres are used as reinforcement for the development of FML. FMLs are also arranged on the layup configuration of metal and composite layers and the orientation of the laminates. Most of the aluminium-based FMLs like GLARE, ARALL and CARALL are used for passenger aircraft, Fighter planes and space shuttles etc.; the application of Titanium bases FMLs are aerospace, automotive, infrastructure and marine engineering industries due to their excellent properties like high strength /stiffness, high-temperature competence and corrosion resistance. Because of the lower density and better fatigue properties, magnesium-based FMLs are used in aircraft structural applications. Stainless steel-based FMLs are mainly used for marine applications because of their anti-corrosion properties. SS304 and SS316L are used for air and underwater applications, respectively. The main advantage of these FMLs is their strength-to-weight ratio, fatigue, impact and corrosion properties. The bonding problem can be improved with suitable surface preparation of metallic layers and proper selection of bonding adhesive.

The pressure housing considered here comprises FML with SS316L and e-glass/carbon epoxy composites and is assumed as a cylinder. It is customary to select E-Glass fibre as reinforcement materials for marine applications. The combination has been chosen based on the various calculations with classical laminate theory and composite software. It is less weight, cost-effective, solid and durable. Carbon is advantageous as it is almost six times stronger than glass fibre. Hence combining these materials ultimately yield better hybrid composites or FML. The thickness of the pressure vessel has also been verified with lamina failure theories. The total thickness of FML pressure housing remains the same as 6mm for SS316L metallic pressure housing. The weight reduction of the metal ratio is varied to 50 %. The metal layer thickness will be 1.5 mm e-glass, and carbon layers of equal quantities are used at the inner layers with unidirectional orientation. Before the development of pressure housing, the FML was fabricated as a panel of 450 × 450 × 6.0 mm. The panels are further processed for various sizes with underwater abrasive cutting to conduct the mechanical testing. The details of the experiment results and Scanning Electron Microscopy (SEM) images are described in the following sections.

2. MATERIALS AND METHODS

2.1. Materials

The present study used e-glass and carbon with unidirectional fibres and SS 316L sheet to fabricate fibre metal laminates. The outer layers are SS 316 L metallic sheets with a thickness of 1.5 mm each, and the inner layers are a combination of E-glass and Carbon fibres with a thickness of 0.34 mm each. The orientations of the fibres are unidirectional, and the total layers are 11 numbers with a total thickness of 6.06 mm. The suitable resin L Y 556 and hardener HY951 are used to develop fibre metal laminates. The layer orientation and sequences are shown in the following Fig. 1. The properties of the SS316L and glass and carbon fibres are listed in Table 1 and Table 2.

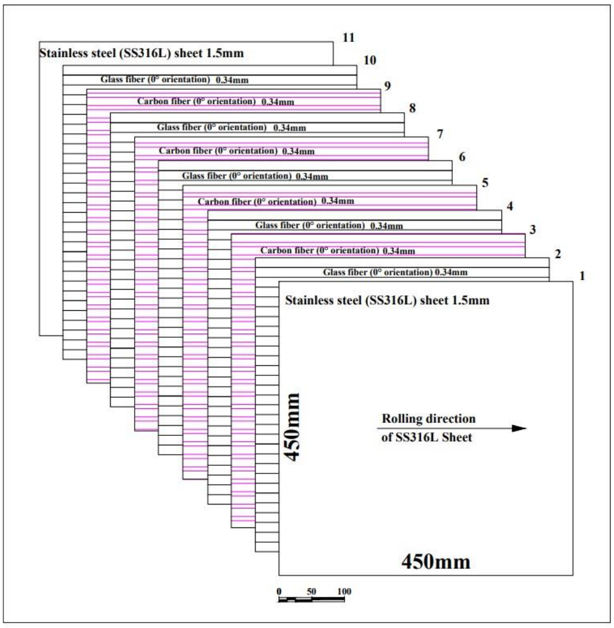

Fig. 1. FML orientation

Table 1. Properties of fibre reinforcement materials

Fiber	Specific gravity, g/cc	Maximum temperature of applications, °C	Elongation at break, %	Elastic modulus, GPa	Tensile strength, MPa
Glass	2.50	370	4.8	72.4	2700
Carbon	1.76	130	1.5	230	3530

Table 2. Properties of SS316L materials

Modulus of elasticity, GPa	Tensile strength, MPa	Yield strength, MPa	Poisson's ratio	Density, g/cc
193	485	170	0.31	7.75

2.2. FML fabrication

The SS316L-based FML was fabricated by hand lay-up and later followed by a compression moulding machine. The volume fraction ratio of fibre and resin was 50:50. The fabrication process involves stages like preparation, bonding, compression and curing. The preparation stage includes SS sheets that were cut as per the size of glass and carbon fibre unidirectional mat of 450 × 450 mm with predefined thickness. SS sheets were subjected to surface grinding using 60-grit alumina to increase the surface roughness and adhesive property. Dimethyl ketone was used to degrease the surface. The e-glass and carbon fibre were impregnated with resin and hardener before bonding with SS sheets. Unidirectional glass and carbon fibres of 230 GSM and 260 GSM were used to develop FML. The prepared glass and carbon fibre sheets were stacked between the two layers of SS metallic sheets on a compression moulding machine under the pressure of 0.1 MPa at ambient temperature. The fibres were fixed in the rolling direction of SS sheets. The FML was kept under the same pressure for 24 h. Combined thickness and bonding were achieved between metallic and fibre sheets using Bondtite adhesive. Later, the panels were cut using an abrasive water jet with various sizes per ASTM standards for testing like Tension, Flexural and Impact, as shown in Table 3.

Table 3. Details of FML specimen used

S.No	Type of specimen	ASTM Standards used	Length, mm	Width, mm	Thickness, mm
1	Tensile	D-3039	250	15	6.06
2.	Flexural	D-790	127	13	6.06
3.	Impact	D-256	63.5	13	6.06

2.3. Specimen preparation and testing

Five test specimens of FML and the base metal of SS316L were prepared and used for various tests like tensile, flexural and impact as per ASTM standards to get average and accurate results. The specimens (coupon) were prepared with a constant cross-section of rectangular shape. Tensile tests were carried out for all five specimens in the FIE make Universal Testing Machine (UTM) with a capacity of 100 KN. The three-point flexural test was carried out with 50 KN capacity UTM for the five specimens. Similarly, Izod impact tests were done in the impact pendulum testing machine of capacity 100 Joules. The testing of five specimens and results are presented in the following sections.

3. RESULTS AND DISCUSSION

In earlier research for Ocean/Marine applications, the FMLs combined with fibre-reinforced composites and metallic layers of aluminium, titanium and SS316L were used for various tests like tensile, flexural and impact. In this article, the test results of FML with two sheets of SS316 L reinforced with carbon and glass fibres obtained from various testing like tensile, flexural and impact are presented for the analysis. Five specimens were used for testing and to get the average strength of the FML specimen. Fig. 2 represents the tensile results of the FML specimen compared to the base metal of SS316L. The stress-strain curve indicates a lower strain value of 0.25 mm to a higher strain value of 1.60 mm for the corresponding stress value. The peak value of the stress is lesser (420.76 MPa) than the base metal (SS316L), with an ultimate stress of 556.05 MPa, and the average stress value of the FML is 253.07 MPa. The flexural results of the specimen are shown in Fig. 3, with a maximum stress value of FML is 130 MPa with a strain value of 0.05.

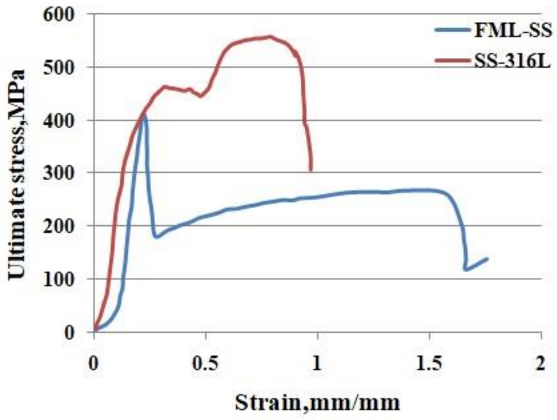

Fig. 2. Tensile test results: stress-strain graph

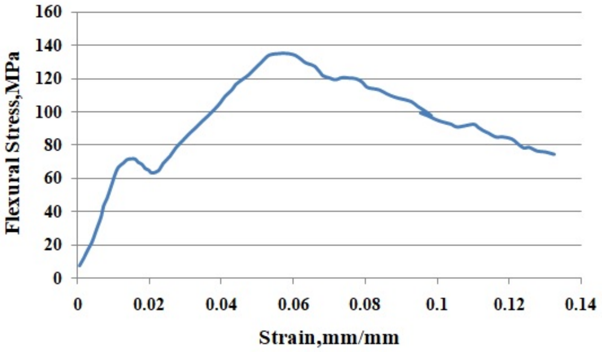

Fig. 3. Flexural test results: stress-strain graph

The maximum value of the FML specimen is 82 joules when compared to all other FML specimens, and the impact results are shown in Fig. 4.

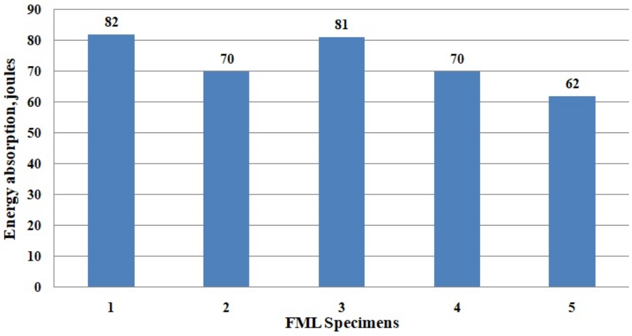

Fig. 4. Impact test results of FML specimen

It has been observed that the proposed FML possess excellent flexural and impact properties compared the other kind of fibre metal laminates like ARALL, CARALL and GLARE [17]. Combining E-glass and carbon fibre with SS316L has more tensile and Impact strength advantages. The results of the earlier research on the FMLs for tensile, flexural and impact were inferior to the present FMLs combinations.

The straight-sided specimen with a uniform cross-section per ASTM D-3039 standard was developed to develop SS316L-based FML. The five specimens were used to get the average value of the result for both tensile and flexural. The tensile specimen failure of SS FML occurred in three steps. First of all, inner glass and carbon fibre epoxy sheet failed at an ultimate tensile load of 42 KN with an ultimate stress of 420 MPa.After that, outer stainless-steel sheets failed one after another with considerable strain. The tensile stress-strain of SS316L FML is shown in Fig. 5. The result shows a better improvement in the ultimate tensile load with a combination of SS316L FML and glass and carbon fibre compared to the tensile stress-strain combination of SS304 and glass fibre used [10].

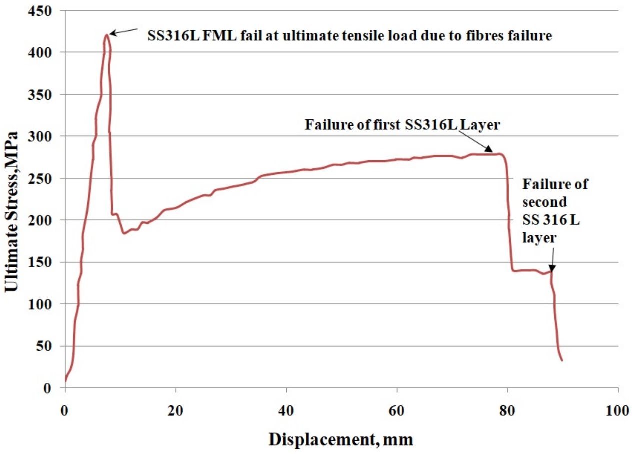

Fig. 5. Tensile stress-strain behaviour of FML

Many researchers found that FMLs with unidirectional composites always have interlaminar shear strength and better flexural strength along the direction. FMLs with Stainless steel layers have good tensile and bending strength. The defects like fibre breakage, metal breakage and necking will occasionally occur in the FMLs with unidirectional laminates. The materials' tensile strength decreases with the increase of metal volume fraction. If the number of layers are more and subjected to elevated and low temperature, the tensile strength will always be low. The major manufacturing defects like porosity, blister, void, foreign objects, uneven resin mixtures, wrinkles, matrix crack, debonding, delamination and broken fibres are the few that will occasionally occur during the FMLs development. Defects and damages can be avoided when FMLs are designed and developed with a determined size, shape, and thickness. Delamination is a crack that starts and develops between the different lamina of a composite material. An intralayer crack is a crack that is initiated at the tip of an embedded delamination and grows through the neighbouring 90° ply. It always jumps to the neighbouring interface and changes the orientation. Usually, these types of defects occur mostly other than unidirectional composites. An interlayer delamination is a crack that develops in the interface of the two laminas without breaking the laminas. It always has the same direction. The composite laminate will fail if the shear stress exceeds the interlaminar shear stress. The different mechanical, chemical and electrochemical surface treatments will increase the interlaminar shear strength of FML. The impact test result shows metal layer cracking, fibre layer fracture and interfacial debonding. Debonding mainly occurs between metal and fibre laminas as the damage percentage increases and the fibre deforms along the length, it will gradually pull out. The SEM images of the tested specimen surfaces are shown in Fig. 6 and

Fig. 7. It has been observed that the proper bonding between metal and fibre laminates is sufficient to form uniform stress concentration in FML. Microstructure of SEM for unidirectional FML analysis reveals that various dominating modes of failures such as mirror, mist and fibre breakage, no delamination, and pull-out occurred between metal and fibres. A proper adhesion between metal and fibre with matrix will influence the breaking strength of the FML. Minor debonding and delamination are observed between the metal and fibres.

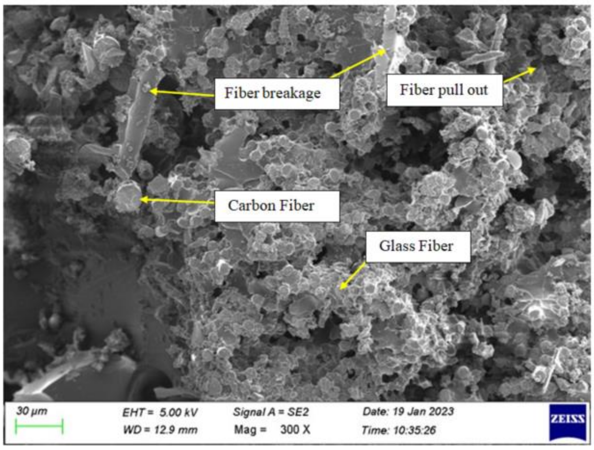

Fig. 6. SEM Images of FML specimen with mag.300X

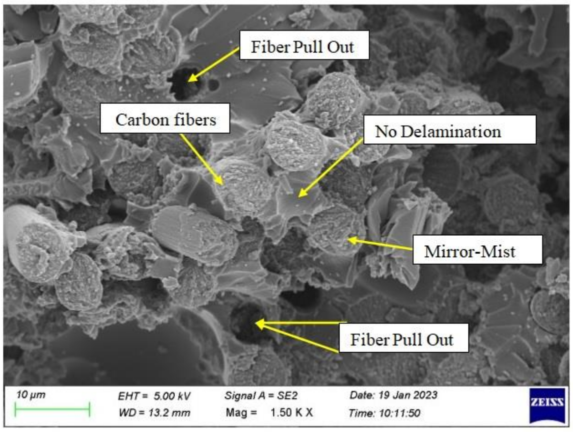

Fig. 7. SEM Images of FML specimen with mag.1.5KX

It has been observed that the interface bonding between composites and metal layers is improving the mechanical properties of FML. The perfect bonding of the matrix and metal layer can be ensured with precise manufacturing processes.

4. CONCLUSIONS

In the current study, FML with a combination of SS316L/glass/carbon laminates has been developed with hand layup with compression moulding to characterize its mechanical properties. The following results were obtained from the experiment

1. The developed FML shows a comparable tensile strength (420 MPa) with the base metal SS316L tensile strength (556 MPa).
2. Flexural and Impact properties have shown a higher level when compared to other FML like ARALL, CARAL and GLARE [17].
3. SEM microstructure analysis indicates fibre breakage, fibre pull out, mirror, and most of the FML specimen.
4. The testing of FML subjected to external hydrostatic pressure for 1 MPa and high/low temperature is conducted, and the test results show prominent results compared to other types of FMLs.
5. SS316L-based FMLs are the tempting choice for marine applications due to their excellent corrosion resistance, strength-to-weight ratio, wear resistance and protection against moisture absorption.
6. The developed FML is ultimately suitable for marine applications like subsea housing and offshore structures.

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