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Investigation on Fatigue Life Behaviour of Sustainable Bio-Based Fibre Metal Laminate

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ABSTRACT

Fibre-Metal Laminate (FML) is a hybrid structure which offers various advantages over conventional material. It had been used in automotive and aircraft sector since many years ago due to its lightweight and low cost properties. Previous study had shown FML had excellent fatigue crack resistance characteristic compared to metallic alloy. This study shows the effects of different composition of oil palm empty fruit bunch (OPEFB) fibre on the fatigue life behaviour, hardness properties and mass of FML. FML was manufactured based on randomly oriented short OPEFB fibre and annealed aluminium alloy 6061. The FML panels were formed by bonding aluminium layers to composite by using the hot press compression moulding method with picture frame mould. Static test was conducted prior to fatigue test at quasi-static manner. The fatigue life of monolithic aluminium was investigated and set as a benchmark. The fatigue test was conducted at load levels of 80 to 95% of ultimate tensile strength using Universal Testing Machine. Results suggest that FML with 30% fibre loading had the highest fatigue resistance compared to other fibre composition. The mass of FML had been identified less than aluminium up to 30%. The hardness strength increases with increase fibre composition for composite while the hardness strength is relatively constant for FML.

Keywords: *Fatigue Properties, Fibre Metal Laminate, Aluminium 6061, Palm Fibre*

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Introduction

Lately, public awareness and consciousness on the environment and safety issues are continuously increasing throughout the world. Environmental problems such as air pollution and water pollution have become a serious problem not only in the developed country but also developing country. This problem can endanger animals, plants as well as deteriorate the health of human beings. According to World Health Organization (WHO), almost seven million people worldwide died in the year 2012 due to air pollution [1]. Combustion of vehicle fuel had been identified as the main factor which causes air pollution. One way to reduce vehicle fuel consumption is through weight reduction of the vehicle body structure. Studies showed a reduction of 100kg of vehicle weight lead to fuel saving from about 300L to 800L over the lifetime of the vehicle and this can also reduce the carbon dioxide emission to about 9g per kilometre [2]. Therefore, the applications of fibre-metal laminates (FML) consists of thermoplastics and natural fibres such as oil palm fibre, flax, hemp and jute fibre in the composite material have become an interest and hot topic among the researcher and public as it satisfies the required conditions in reducing this problem. FML is a good substitute for the metal alloy in automotive and aircraft industries due to its lightweight properties. Furthermore, thermoplastic and natural fibres in FML provide an additional advantage to the entire structure. The advantage of using natural fibre and thermoplastic as constituents of FML is that they can be recycled. A prior study had shown that palm fibre composite is a good candidate for recycling [3]. Thermoplastics such as polypropylene (PP), high density polyethylene (HDPE) and high impact polystyrene (HIPS) shows significant high recyclability and low volatiles characteristics compared to thermoset [4]. Moreover, thermoplastic-based FML greatly reduces the manufacturing time compared to thermoset-based FML since it only requires preheating before cooled to room temperature [5]. All of these characteristics are necessary for society and market to stimuli the economy level since the productivity will be highly increased due to short manufacturing time. The first generation FML, Aramid Fibre Reinforced Aluminium Laminate (ARALL) which consists of aramid fibre as reinforcement, epoxy as matrix and aluminium 2024-T3 sheets was successfully introduced at 1978 in the Faculty of Aerospace Engineering at the Delft University of Technology [6]. However, this type of FML still has its disadvantage due to the thermoset-based composite. Thermoset polymer is brittle and hence it only can be used in secondary structures [7].

Bio-based FML, shown in Figure 1 is a hybrid sandwich structure that consists of layers of metal and natural fibre reinforced thermoplastic composite. Fibre reinforced composite is among one of the popular materials used in industry due to its good damage tolerance, low energy consumption and corrosion resistance [8]. Generally, the natural fibre reinforced composite has lower mechanical strength compared to metal alloys and synthetic fibre reinforced composite. However, natural fibres, as one of the constituents in composite, have been widely used nowadays as they provide several superior advantages over synthetic fibre such as low cost, low density and biodegradability [9].

The synthetic fibre has cause catastrophic ecological and environmental problems due to its non-biodegradable characteristic [10]. The main disadvantage of using natural fibre reinforced composite is the hydrophilic characteristic in which the moisture absorption is very high, resulting in low mechanical strength. However, this moisture absorption can be significantly reduced by introducing layers of metallic alloy at the outer skin [11].

FML is formed by bonding composite layer with metal skin by means of adhesive agents. It had been used in many industrial sectors for so many years as it combines the excellent characteristics of metal and fibres. Although the initial intention of developing FML is due to its excellent fatigue crack resistance compared to the conventional material as fuselage material, recently the application of FML systems had moved towards automotive industries due to its improved impact properties. Fatigue crack resistance and impact properties are critical in the automotive industry to enhance the safety performance of vehicles. For fatigue resistance, the fibre content in FML system restrains the fatigue crack due to its stiffness property. Some of the load is transferred to the fibre and all of this lead to the reduction in stress intensity factor [12]. Vogelesang and Vlot (2000) stated that the crack growth rate in FML was one tenth or one hundredth corresponding to the monolithic aluminium alloy [13].

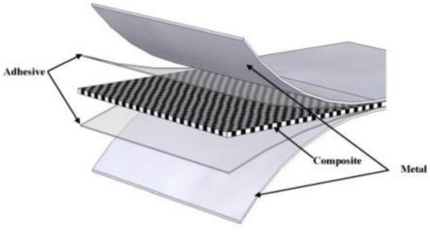

Figure 1: Fibre metal laminate system [14]

In this study, fatigue test was conducted according to ASTM E466. The FML system consists of two sheets of 0.5 mm aluminium and one sheet of 1.0 mm composite. The composite was fabricated by using polypropylene as the matrix and empty fruit bunch oil palm fibre as the reinforcement. The fatigue behaviours of the FML system with different composition of fibre and monolithic aluminium were evaluated and analysed.

Experimental set up

Materials

The FML panel used in this experiment consist of annealed aluminium 6061 and randomly oriented OPEFB fibre reinforced composite. The matrix used was polypropylene with a density of 0.9 g/cm^3. Modified polypropylene adhesive film with a density of 0.91 g/cm^3 was used to glue aluminium to composite.

Methodology

FML is a metallic sandwich structure which consists of layers of composite and metal. In this study, a 2/1 aluminium to composite ratio configuration of FML was achieved by combining two sheets of 0.5mm annealed aluminium 6061 and one sheet of 1mm composite through compression moulding process. Table 1 provides the percentage of chemical compositions in aluminium 6061. Before the FML is manufactured, composite had to be prepared by mixing OPEFB fibre as reinforcement with polypropylene (PP) as the thermoplastic matrix by using an internal mixer. PP supplied from Al Waha Petrochemical company in this study are belongs to the type of homopolymer with a density of 0.9g/cm^3 and melt flow rate of 1.2g/min. 3%wt of Maleic Anhydride Polypropylene (MAPP) was added to increase the adhesion level between matrix and reinforcement. It had been proven that 3-5% of MAPP coupling agent is optimum for good adhesion between fibres and matrix [15]. The coupling agent reacts with the -OH groups of the cellulose in fibres and functional groups of the matrix to facilitate the stress transfer between the fibres and the matrix [16]. Composite with four different fibre weight compositions which are 10%, 20%, 30% and 40% of OPEFB fibre were fabricated as shown in Table 2. Table 3 elucidates properties of oil palm empty fruit bunch fibres.

Table 1: Chemical composition of aluminium 6061

Material	Si	Fe	Mg	Ti	Mn	Zn	Cu	Cr	Al
Al 6061 (%)	0.80	0.70	1.2	0.15	0.15	0.25	0.40	0.35	96.00

Table 2: Fibre weight fraction in composite

Fibre Mass (g)	PP Mass (g)	MAPP Mass (g)	Total Mass (g)
5	43.5	1.5	50
10	38.5	1.5	50
15	33.5	1.5	50
20	28.5	1.5	50

OPEFB fibre was chemically treated prior to the composite fabrication process by soaking in 2% of sodium hydroxide solution for 30 minutes at room temperature to remove impurities and ensure good interfacial adhesion as well as to resist moisture absorption. Evidence shows treated natural fibre can resist up to 67% moisture absorption [17]. Mechanical properties of treated natural fibre composite had been proven higher than untreated natural fibre composite [18]. Treated natural fibre composite hence poses better tensile and micro hardness strength [19]. In order to increase the adhesion level between aluminium and composite, surface treatment of aluminium was carried out in this study. Aluminium plates were soaked into 5% of sodium hydroxide solution for 5 minutes and dried to increase surface roughness. Surface treatment using sodium hydroxide had been identified can increase the surface roughness with a linear increase in the surface area [20]. Annealing process was conducted before chemical treatment to increase its ductility. This process was conducted at 413^{o}C for three hours and followed by cooling process at a rate of 10^{o}C to 260^{o}C and then aluminium was allowed to cool naturally.

Table 3: Properties of oil palm empty fruit bunch fibres [21]

Properties	OPEFB Fibres
Cellulose (%)	49.6
Hemicellulose (%)	18.0
Lignin (%)	21.2
Microfibrillar angle (o)	46.0
Diameter (µm)	150-500
Density (g/cm3)	0.7-1.55
Tensile Strength (MPa)	50-400
Young Modulus (GPa)	1-9
Elongation at break (%)	8-18
Lumen width (µm)	6.9

Composites were developed through hot press moulding compression method at 175°C to completely melt the PP. The mixed PP and fibre was compressed using a picture frame with 1mm thickness for eight minutes followed by cooling to room temperature. FML was manufactured by stacking layers of aluminium plate with composite in a picture frame mould to control the final thickness of the fabricated FML and avoid over compressed. Two sheets of 0.91g/cm^3 thermoplastic adhesive film based on modified polypropylene were stacked between the aluminium plates and composite. The entire picture frame mould was inserted into the hot press machine for compression process at 155℃. The FML was allowed to cool down to room temperature before removed taken out from the hot press machine. Fabricated Completed FML is shown in Figure 2.

Figure 2: Pre-consolidated FML specimen

Fatigue test

In this study, fatigue test was performed to analyse the property of FML at room temperature. The fatigue test of FML was conducted using dynamic type INSTRON 8802 Universal Testing Machine (UTM). Fatigue test was carried out on the dog bone shaped FML specimens as shown in Figure 3 that were cut by using water jet cutter. The fatigue test was conducted at force controlled constant amplitude manners according to ASTM E466 standard procedure. Load levels of 80, 85, 90 and 95% of ultimate tensile strength were applied during the fatigue testing at a constant frequency of 10Hz and stress ratio of 0.1. Results of different composition of OPEFB fibres in FML were recorded and represented in Stress-Life (S-N) curve. The results were then evaluated and analysed in order to compare the fatigue behaviour against each other.

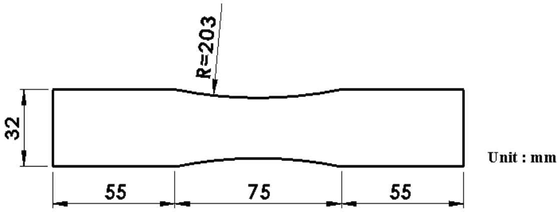

Figure 3: Dog-boned-shape FML Specimen

Results and discussion

Tension-tension fatigue properties

Static tensile test was first conducted before fatigue test and the results are presented in Table 4. For ferrous alloys, they have an endurance limit in their fatigue life. The endurance limit in S-N curve indicates the maximum load can be applied to the material without causing fatigue failure. However, nonferrous metal such as aluminium and polymer will not have an endurance limit [22]. This implies that FML will eventually fail as long as there is load applied on the material.

Table 4: Tensile properties of FML with different fibre weight composition and annealed aluminium

Materials	σ_{ult} (MPa)	Elongation (%)	E (GPa)
Aluminium 6061-O	118.4	18.33	70.23
FML (10wt% fibre)	57.46	11.90	28.88
FML (20wt% fibre)	59.70	12.30	30.24
FML (30wt% fibre)	59.85	11.71	31.49
FML (40wt% fibre)	63.45	12.90	39.94

Figure 4 and Figure 5 show the S-N curve for monolithic aluminium and FML with different fibre weight composition. The results show the life cycles of aluminium and FML increases with decreasing of applied stress. For the monolithic aluminium, the difference of life cycle to failure at the maximum and minimum load applied is four times. From these result, these materials were considered to have a high cycle fatigue since the life cycle of the materials exceed 10^4. The overall fatigue strength of monolithic aluminium was higher than FML system.

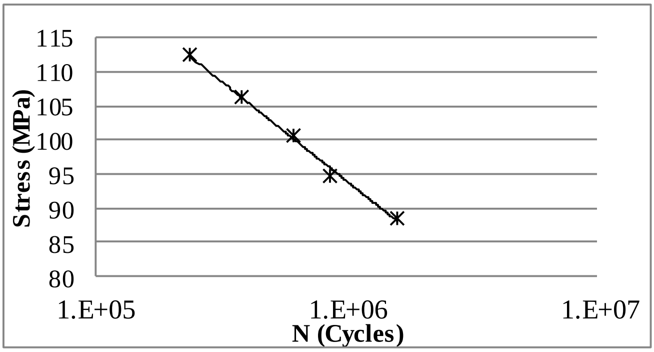

Figure 4: S-N curve for annealed aluminium

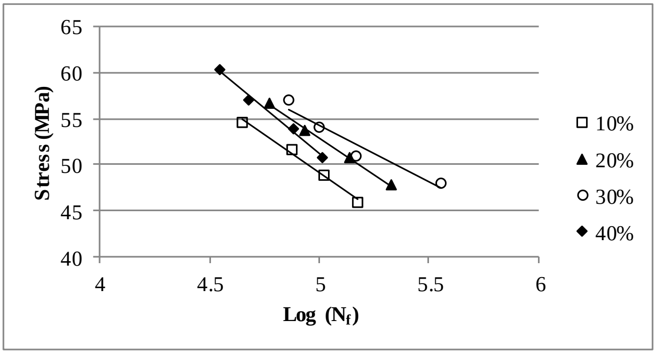

Figure 5: S-N curve for FML with different OPEFB fibre composition

Figure 5 shows fatigue life cycle of FML increases from FML 10wt% to 30wt% of fibre composition and then decreases drastically for FML with 40wt% fibre. The results imply that FML with 30wt% fibre composition offers the highest fatigue resistance. These overall results revealed that the fibre composition in FML plays an important role in restraining the fatigue crack through bridging effect and hence increase the life cycle of the material. Fibre bridging mechanism as shown in Figure 6 provides second load path for FML specimen, part of the load will be transferred to the composite and distributed evenly among fibre. Several previous researchers had studied the effect of fibre composition on the mechanical properties of composite and the results showed mechanical strength increases with increasing of fibre loading [23]. The increasing of weight percentage of fibre in composite creates more interfacial area between the fibre and matrix and hence, the stress exerted on FML can be distributed evenly and more fibre can help to withstand the load effectively but when the concentration of fibres increases until a certain level, the interfacial area between fibres and polypropylene decreases due to the lack of polypropylene.

Low fatigue cycle of FML at low fibre composition is due to the dilution of the matrix and the fibre composition is not enough to carry the load that is transferred from matrix efficiently. This will happen when the fibre composition in the composite is too low. Surprisingly, the fatigue life cycle for FML with 30% fibre composition is almost 3.5 times higher than FML with 40% fibre composition at the maximum load applied.

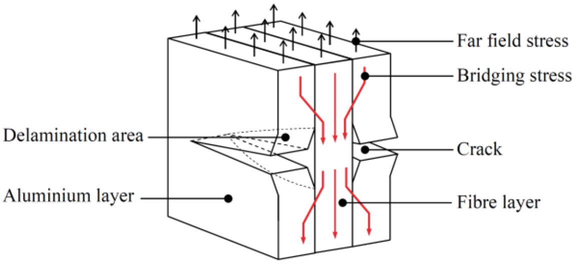

Figure 6: Fibre bridging mechanism [12]

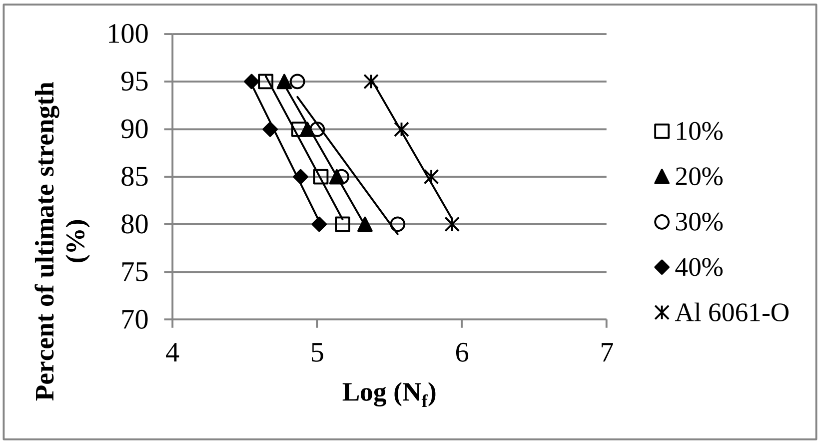

Figure 7: Normalized S-N curve for FML with different fibre composition

Due to the differences in the tensile strength of annealed aluminium and FML with different fibre composition, a normalized S-N curve as shown in Figure 7 was developed to allow better comparison and analysis between the fatigue sensitivity of the material. The slope of each line represents the fatigue sensitivity coefficient of each material, which indicates the fatigue performance of the material at different cyclic stress level. From Figure 4, result demonstrates annealed aluminium exhibits the highest fatigue strength compared to FML. However, the slope for annealed aluminium in Figure 7 is steeper than FML with 30% fibre composition, implying that the fatigue performance of annealed aluminium is lower than FML with 30% fibre composition at low load application.

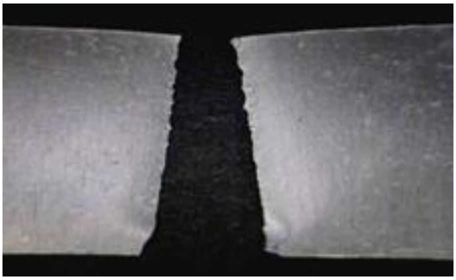

Figure 8: Optical micrograph of monolithic aluminium

For failed monolithic aluminium, obvious elongation and necking were observed along the fracture surface from the optical micrograph as shown in Figure 8. The elongation of monolithic aluminium was higher than FML since FML is less ductile due to the brittle behaviour of the composite. Figure 9 presents the optical micrograph of failed FML specimen with 30wt% fibre. The figure clearly shows fibres were pulled out from the composite and this implies that the fibres embedded in the composite acts as fibre bridging resulting in higher fatigue life cycle compared to FML with a different composition. Figure 10 shows optical micrograph of failed FML specimen with 40wt % fibre composition. This figure reveals the load applied on the specimen was mainly carried by the two aluminium sheets instead of composite. As a result, the fatigue life cycle of FML with 40wt% fibre composition was reduced drastically due to the inefficient fibre bridging mechanism. However, elongation and plastic deformation were found on both failed FML specimens at the end point of the fracture surface. This proves that the end point of the fracture surface of both specimens exhibited the highest load during the fatigue testing. Observation from the optical micrograph of monolithic aluminium and FML shows the failure mode for both materials is different from each other. The crack initiation point of monolithic aluminium exhibited a less elongation or plastic deformation but the level of elongation increase along the fracture surface. Nevertheless, failure modes of FML specimen are different from metal layers, adhesive and composite. The slight elongation of the metal layers is relatively constant along the fracture surface. This observation reveals the failure mode of monolithic aluminium is more ductile compared to FML specimen.

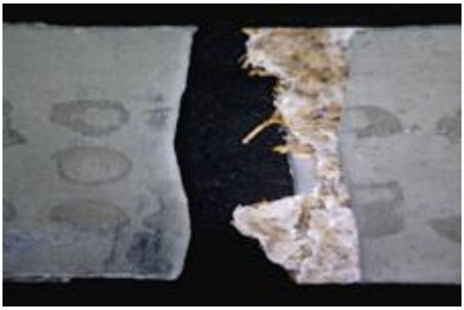

Figure 9: Optical micrograph of FML with 30wt% fibre composition

Figure 10: Optical micrograph of FML with 40wt% fibre composition

FML with 40wt% fibre composition has shorter life cycle compared to FML with 30wt% due to lack of effective polypropylene and fibre bond. This causes the stress exerted on FML cannot be transferred effectively between polypropylene and OPEFB fibre. One of the main aspects in increasing the strength of FML is to increase the efficiency of the interfacial area to allow a good adhesion level between fibre and polypropylene. When the force is applied to the specimen, the load will be transferred throughout the matrix until it reaches the interface between reinforcement and matrix, if there is a good interface region, the maximum load will be transferred to the fibres and spread evenly along the entire fibre [24]. This will result in high mechanical strength. In addition, natural fibres have poor dispersion characteristic, hence FML with 40% fibre composition is very difficult to achieve single fibre unit in the composite. As a consequence, the interfacial area between fibres and polypropylene is therefore reduced drastically. The previous study showed that mechanical strength increases with the increase in fibre composition up to 30%, however, mechanical strength drops significantly when the fibre composition goes above 30% [25].

Another possible explanation is the void content in FML with 40% fibre composition is higher than other compositions. According to Equation (1), the density of composite can be calculated by knowing the mass and volume of the composite using the weighing machine and Vernier calliper in order to obtain the thickness.

$$\rho = m/V \qquad (1)$$

Where ρ is density, m is mass and V is volume.

On the other hand, the Void content in a composite can be determined in accordance with Equation (24) [22].

$$V_p = 100 - M_d\left[\frac{r}{d_r} + \frac{g}{d_g}\right] \qquad (2)$$

Where V_p is void contents (%), M_d is density of composite, r is resin content (wt %), d_r is resin density (g/cm3), g is fibre content (wt %) and d_g is fibre density (g/cm3)

Therefore, the void content actually depends on the density of composite with the same materials according to Equation (1). From Equation (2), the density of composite is actually affected by its mass with constant volume. Since the density of fibre is higher than polypropylene, Hence, mass of composite increases when the composition of fibre increases. However, the mass of the FML with 40% fibre composition decreases and that causes its density to decrease and therefore it can be concluded that the void content in FML with 40% is higher than in FML with 30% fibre composition. As a consequence, the life cycle of FML with 40wt% decreases due to the present of void in the composite.

Fatigue crack initiation starts at the metal layers as shown in Figure 11. This behaviour proves the initial load was mainly carried by the aluminium layers. At this stage, FML with 30wt% fibre weight composition can reduce the rate of crack propagation by accepting part of the stress applied and transfer it evenly to fibre and polypropylene. The OPEFB fibre starts to elongate in order to restrain the fatigue crack propagation. The composite plays a crucial role in providing a bridging mechanism and hence create an alternative pathway for the load to be transferred so as to reduce the stress intensity and rate of crack growth. For the monolithic aluminium, the stress will be transferred directly to the metal crack. Therefore, the rate of propagation will become very fast since there is no fibre to restrain the fatigue crack. Furthermore, significant delamination in numerous samples had been observed after fatigue testing. In fact, delamination can be treated as one of the failure mechanism in which the layers of aluminium are separated from the composite.

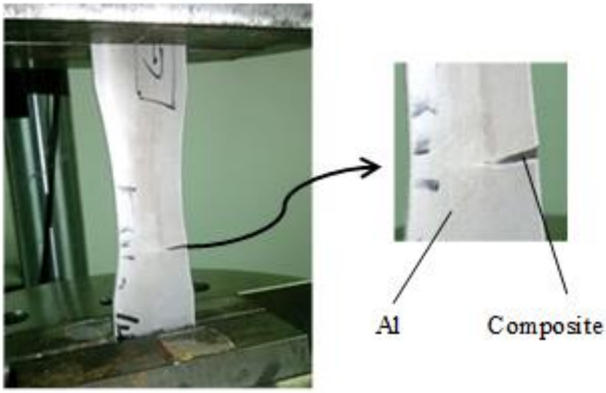

Figure 11: Specimen under fatigue testing

Delamination happened at the interfaces between aluminium sheets and composite implies that the critical values are reached. Since the yield strength of composite and aluminium sheets are different from each other, hence shear stress at the interface will be generated. Once the shear stress has reached the critical value, the specimen starts to delaminate. However, the level of delamination will also depend on the adhesion level between aluminium and composite. For the application of FML system in various fields, delamination is considered to have an advantage in some specific condition. With suitable level of delamination, fibre will be more difficult to fail as the load transferred to the composite can be reduced and the length of fibre elongates can be increased, resulting in reduction of the stress intensity [26]. In contrast, the crack propagation rate will increase if the level of delamination is too high. This is due to the fibre bridging mechanism has failed to perform its intended function.

Mass

Lightweight property is the main advantage of FML compared to other metallic alloys such as aluminium and steel as FML on average is 30% lighter than monolithic aluminium. Figure 12 shows the mass of aluminium and FML with different compositions. The result shows that FML systems with different fibre composition have lesser mass compared to monolithic aluminium. The maximum mass difference between FML and monolithic aluminium is 36.7% while the minimum mass difference is 24.47%. This implies that the weight of the vehicle on average can be reduced up to 30%

and hence usage of fuel can be reduced drastically. However, there is no constant mass for all the FML system with the same fibre composition. A possible explanation for this is the different in the mass of FML system is actually because of the difference in density of OPEFB fibre. According to Jawaid & Khalil (2011), the density of OPEFB fibre which has a range from 0.7 to 1.55 g/cm^3 [20]. Since the density of natural fibre is different, hence there will be a variation in the mass of FML.

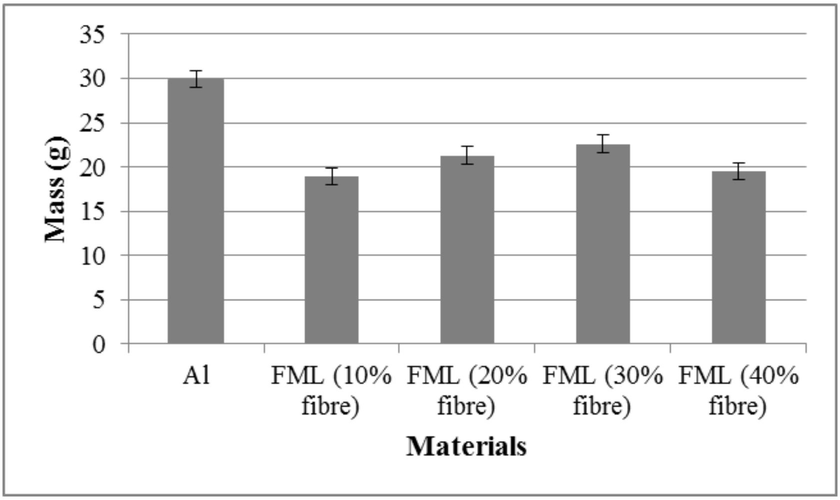

Figure 12: Mass comparison between aluminium and FML

Hardness Properties

The hardness property of composite depends on the type of reinforcement, matrix and composition. The results from hardness test as shown in Figure 13 and Figure 14 show the hardness strength of aluminium with different thicknesses and comparison of hardness strength between composite and FML respectively. The results show that aluminium with 2 mm thickness has the highest hardness level compared to FML and aluminium with 0.5 mm thickness. On the other hand, the hardness of composite increases with increases in fibre composition. Generally, the hardness of a composite depends on the composition of fibre which means that increasing in fibre composition within a composite increase the moduli of the composite and hence the hardness properties will also increase as the hardness properties of the composite is a function of both modulus and fibre composition [17]. However, From Figure 14, hardness strength of FML systems was relatively constant for all fibre weight composition. This behaviour implied that the hardness strength of composite between the aluminium layers had no effect on the entire FML system. The hardness strength of FML systems mainly depends on the outer layers of aluminium metal.

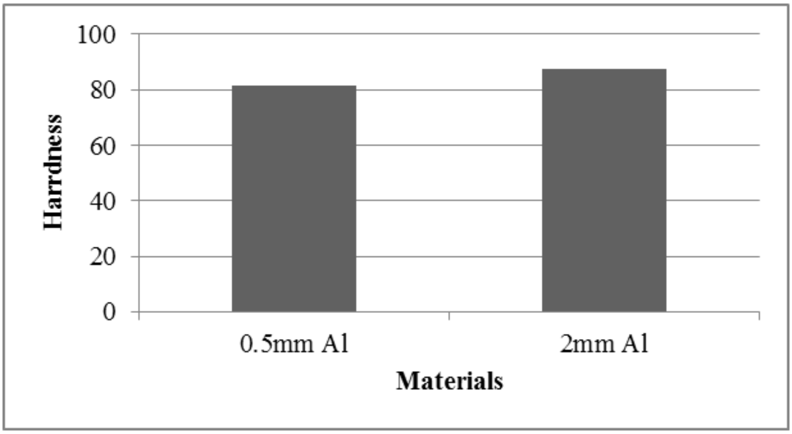

Figure 13: Hardness strength of aluminium with different thickness

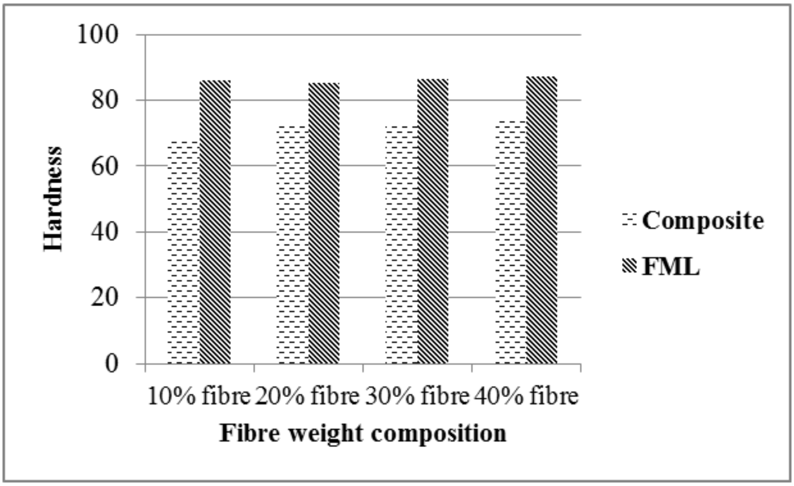

Figure 14: Comparison of hardness strength between composite and FML

Conclusion

Oil palm fibre reinforced metal laminate system was studied to identify the effect of fibre composition on the fatigue behaviour of FML under constant amplitude force controlled manner. Moreover, the hardness strength for both composite and FML was also determined to identify the effect of hardness strength of composite on the FML. The result shows that FML with 30wt% fibre loading had the highest fatigue life cycle compared to other fibre composition.

FML can be used in the automotive field for non-structural application since its density, mass and manufacturing cost is lower than thermoset FML. The OPEFB FML system is up to 30% lighter compared to monolithic aluminium.

The lightweight and high fatigue resistance properties of FML could be an added advantage for its use in automotive and aircraft sectors. The results from hardness test show hardness strength of composite increases when the fibre composition increases while the hardness strength of FML is relatively constant for all fibre compositions.

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