Faculty of Mechanical Engineering

CHARACTERISATION OF KENAF/PINEAPPLE LEAF FIBRE REINFORCED COMPOSITE-METAL LAMINATES WITH ENHANCED MECHANICAL PROPERTIES

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DECLARATION

I declare that this thesis entitled "Characterisation of Kenaf/Pineapple Leaf Fibre Reinforced Composite-Metal Laminates with Enhanced Mechanical Properties" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ……………………………

Name : …….Ng Lin Feng ………...

Date : ……………………………

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature : ……………………………………………………………

Supervisor Name : ..Associate Professor Dr. Sivakumar Dhar Malingam.....

Date : ……………………………………………………………..

DEDICATION

I would like to express my gratitude to my beloved father and mother for the continuous support and patient towards the completion of this thesis. Besides, I would like to give a special feeling of gratitude to my siblings who always motivate and support me from the beginning until the final stages of this research study. Once again, I would like to express my deepest gratitude to those who have supported me throughout the process.

ABSTRACT

The mechanical properties of fibre metal laminates (FMLs) are worth investigating since such materials offer several superior characteristics over conventional metallic alloys. Majority of the research has focused on the mechanical properties of hybrid composite materials and conventional synthetic fibre-based FMLs. However, the mechanical properties of polypropylene-based short kenaf/pineapple leaf fibre reinforced hybrid composites and woven kenaf/pineapple leaf FMLs still remain unexplored. This study aims at investigating the influences of fibre weight compositions, chemical treatments and relative fibre ratios on the mechanical properties of non-hybrid and hybrid composites based on short kenaf/pineapple leaf fibres. In addition, the mechanical tests were performed to characterise the non-hybrid and hybrid woven kenaf/pineapple leaf fibre-based metal laminates with various fibre architectures and stacking configurations. In this research study, the kenaf/pineapple leaf fibre reinforced composites and FMLs were manufactured through the hot press moulding compression method. A series of mechanical tests were conducted to determine the mechanical properties of the materials. In accordance with the results obtained, the composites had evidenced the highest mechanical properties when the fibre weight composition was fixed at 30 wt% regardless of types of fibre. The mechanical properties of both kenaf and pineapple leaf fibre reinforced composites increased with the increase of fibre weight composition up to a critical limit of 30 wt %. The drop in the mechanical properties was noticed when the fibre weight composition was above the critical limit. In the context of chemical treatments, the NaOH and silane treated kenaf and pineapple leaf fibre-based composites showed higher mechanical properties over those of untreated composites. It was noticed that 5 % NaOH and 3 % silane treatments could provide excellent mechanical properties to the composite materials. However, the composites with the combination of the 5 % NaOH and 3 % silane treatments were shown to have the highest mechanical properties. When looking into the effect of hybridisation, the mechanical properties of the composites increased with the increase of pineapple leaf fibre content. Overall, the composites with the relative fibre ratio of 0 : 100 (kenaf : Pineapple leaf) evidenced the superior mechanical properties. When comparing the mechanical properties of FMLs with different fibre architectures, twill woven FMLs had outperformed those of plain woven FMLs irrespective of types of fibre. Furthermore, it was revealed that the hybrid pineapple leaf/kenaf/pineapple leaf fibre-based FMLs exhibited comparable mechanical and indentation properties to the non-hybrid pineapple leaf fibre-based FMLs particularly when subjected to out-of-plane loadings. Kenaf fibre has been shown to have high availability and economic value while pineapple leaf fibre is currently regarded as agricultural waste having high mechanical strength. Therefore, it can be concluded that the hybridisation of kenaf and pineapple leaf fibre in FMLs could develop a material with high economic value and mechanical strength while reducing the agricultural waste on the earth.

PENCIRIAN LAMINASI KOMPOSIT-LOGAM BERTETULANG SERAT KENAF/DAUN NANAS DENGAN SIFAT MEKANIKAL YANG DIPERTINGKATKAN

ABSTRAK

Sifat-sifat mekanikal serat bertetulang lamina logam (FMLs) penting untuk dikaji kerana bahan-bahan tersebut menawarkan beberapa ciri unggul berbanding dengan aloi logam konvensional. Kebanyakan penyelidikan telah memberi tumpuan pada sifat-sifat mekanikal bahan komposit hibrid dan FMLs konvensional berasaskan serat sintetik. Walau bagaimanapun, sifat-sifat mekanikal komposit hibrid kenaf/daun nanas pendek dan FMLs anyaman kenaf/daun nanas berasaskan polipropilena masih belum diterokai. Kajian ini bertujuan untuk menyiasat pengaruh komposisi berat serat, rawatan kimia dan nisbah serat relatif terhadap sifat-sifat mekanikal komposit bukan hibrid dan hibrid berasaskan serat kenaf/daun nanas pendek. Di samping itu, ujian-ujian mekanikal telah dilakukan untuk mencirikan lamina logam anyaman kenaf/daun nanas bukan hibrid dan hibrid dengan pelbagai seni bina serat dan konfigurasi serat. Dalam kajian ini, kenaf/daun nanas bertetulang komposit dan FMLs telah dihasilkan melalui kaedah pengacuan penekanan panas. Satu siri ujian mekanikal telah dijalankan untuk menentukan sifat-sifat mekanikal bahan-bahan. Selaras dengan keputusan yang diperolehi, komposit telah membuktikan sifat-sifat mekanikal tertinggi apabila komposisi berat serat ditetapkan pada 30 wt% tanpa mengira jenis serat. Sifat-sifat mekanikal kedua-dua kenaf dan serat daun nanas bertetulang komposit meningkat dengan peningkatan komposisi berat serat sehingga batas kritikal sebanyak 30 wt%. Pengurangan sifat-sifat mekanikal diperhatikan apabila komposisi berat serat melebihi batas kritikal. Dalam konteks rawatan kimia, komposit berasaskan serat kenaf dan daun nanas yang dirawat dengan NaOH dan silane menunjukkan sifat-sifat mekanikal yang lebih tinggi berbanding dengan komposit yang tidak dirawat. Ini telah diperhatikan bahawa rawatan dengan 5 % NaOH dan 3 % silane dapat memberikan sifat-sifat mekanikal yang sangat baik untuk bahan komposit. Walau bagaimanapun, komposit dengan kombinasi rawatan 5 % NaOH dan 3 % silane menunjukkan sifat-sifat mekanikal yang tertinggi. Apabila melihat pada kesan penghibridan, sifat-sifat mekanikal komposit meningkat dengan peningkatan kandungan serat daun nanas. Secara keseluruhannya, komposit dengan nisbah serat relatif 0 : 100 (kenaf : daun nanas) membuktikan sifat mekanikal yang unggul. Apabila membandingkan sifat-sifat mekanikal FMLs dengan seni bina serat yang berbeza, FMLs anyaman kelarai telah menunjukkan sifat-sifat mekanikal dan lekukan yang lebih tinggi daripada FMLs anyaman polos tanpa mengira jenis serat. Tambahan pula, ternyata FMLs serat daun nanas/kenaf/daun nanas hibrid menunjukkan sifat-sifat mekanikal dan lekukan yang setanding dengan FMLs serat daun nanas bukan hibrid terutamanya apabila mereka tertakluk kepada beban luar satah. Serat kenaf telah dibuktikan mempunyai ketersediaan dan nilai ekonomi yang tinggi manakala serat daun nanas kini dianggap sebagai sisa pertanian yang mempunyai kekuatan mekanikal yang tinggi. Oleh itu, ini dapat disimpulkan bahawa penghibridan serat kenaf dan daun nanas dalam FMLs boleh menghasilkan satu bahan yang mempunyai nilai ekonomi dan kekuatan mekanikal yang tinggi serta mengurangkan sisa pertanian di bumi.

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LIST OF SYMBOLS AND ABBREVIATIONS

ARALL	-	Aramid reinforced aluminium laminate
ASTM	-	American society for testing and material
CARALL	-	Carbon fibre reinforced aluminium laminate
CCCs	-	Carbon-carbon composites
CMCs	-	Ceramic matrix composites
D	-	Diameter
E_A	-	Total absorbed energy
E_f	-	Flexural modulus
E_T	-	Impact strength
F	-	Flexural force
FCC	-	Fluid catalytic cracking
FMLs	-	Fibre metal laminates
FRPs	-	Fibre reinforced polymers
GLARE	-	Glass fibre reinforced aluminium laminate
IMCs	-	Intermetallic matrix composites
K	-	Woven kenaf fabric
L	-	Support span
L_c	-	Critical fibre length
m	-	Slope of the load-displacement curve
MMCs	-	Metal matrix composites
n	-	Number of woven fibre fabrics in the laminate
NaOH	-	Sodium hydroxide
P	-	Woven pineapple leaf fabric
PALF	-	Pineapple leaf fibre
ρ_c	-	Density of composite laminate
ρ_f	-	Fibre density
PMCs	-	Polymer matrix composites
PP	-	Polypropylene
R_a	-	Surface roughness value
t	-	Thickness
τ_y	-	Shear strength
σ_f	-	Flexural strength
σ_{fibre}	-	Ultimate tensile strength of fibre
V_f	-	Fibre volume fraction
w	-	Width
W_c	-	Composite weight
W_f	-	Fibre weight fraction
W_{ff}	-	Fibre weight

LIST OF PUBLICATIONS

Journals

1. Ng, L.F., Malingam, S.D., Ishak, N.M., Kathiravan, S., 2020. Novel Sandwich Structure of Composite-Metal Laminates based on Cellulosic Woven Pineapple Leaf Fibre. *Journal of Sandwich Structures & Materials*. (Published Manuscript; Scopus/ISI; Q1/Q1; IF: 5.616)
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Book chapter

Ng, L.F., and Malingam, S.D., 2019. Monotonic and Fatigue Responses of Fiber-Reinforced Metal Laminates, In: Jawaid, M., Thariq, M., and Saba, N. (eds) *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, pp. 307–323. Cambridge: Woodhead Publishing.

CHAPTER 1

INTRODUCTION

1.1 Background

During the past few decades, the enormous evolution of technology has aroused the development of new categories of metal-composite hybrid materials, namely Fibre Metal Laminates (FMLs). The FMLs concept is based on the synthesis of metallic skin layers and composite materials as the core constituent. FMLs are considered as the sandwich materials that are formed by consolidating the monolithic metallic alloys to the composite materials by means of adhesive agents. Over the years, it has been demonstrated that FMLs possess several superior advantages over those of monolithic metal and composite materials. Indeed, the main purpose of combining the constituents of metallic alloys and composite materials is to remedy the obstacle of the poor fatigue resistance of the monolithic aluminium alloys (Ferrante et al., 2016). The metal-composite interfaces allow effective energy dissipation and retard the rapid crack growth propagation through the fibre bridging mechanism, thus, improving the resistance of the materials against cyclic loading (Alderliesten, 2015). Although the initial intention of developing FMLs is to tackle the poor fatigue resistance of monolithic aluminium alloys, however, it was found that the metal-composite interfaces play an important role in dissipating energy, having an excellent impact resistance as well. It should be highlighted that the partial substitution of metallic alloys with composite materials in FMLs leads to significant overall weight reduction, resulting in low energy consumption (Chai and Manikandan, 2014; Sivakumar et al., 2017). The achievement in FMLs has continuously motivated the research communities to explore the mechanical properties of FMLs with different concepts. Due to the outstanding advantages in FMLs, these sandwich materials have gained wide acceptance as an alternative structural material to substitute the monolithic aluminium alloys, particularly in aerospace industries in order to ensure structural integrity and safety performance.

In aerospace industries, FMLs are considered as a part of the third evolution materials to further improve the aerospace efficiency without deteriorating the safety performance. FMLs that combine the advantages inherited from their respective composite materials and metallic alloys are currently being used as fuselage materials. The first generation of aircraft materials is exemplified by the wooden materials in the year 1903 when the Wright brothers, who are the inventors of the aeroplane, successfully develop the first aeroplane in the world using spruce wood as the construction materials. Wooden materials have gained widespread usage due to their high availability and low-cost characteristic. Environmental impacts such as high moisture uptake, termite attacks and degradation after a certain period are those of the disadvantages of employing wooden materials as the construction components. The second generation of aircraft materials is represented by aluminium alloys which were used to replace wood as the essential components in aircraft structures in the year 1930. In the 1930s, the aluminium alloy was employed for the construction of Douglas C-47 military transport aircraft. Owing to the high strength to weight ratio characteristic of aluminium alloys, they have been widely employed in the aircraft industries for structural applications. However, the evolution of the technology has inclined towards the utilisation of composite materials in aircraft industries in the 1990s. The composite materials can be tailored to achieve the specific mechanical properties by the proper selection of fibre types, fibre orientation and stacking configurations to fulfil the structural requirement for aircraft components.

The commercially available FMLs are glass fibre reinforced aluminium laminate (GLARE), Aramid fibre reinforced aluminium laminate (ARALL) and Carbon fibre reinforced aluminium laminate (CARALL). The first generation of FMLs is ARALL, consisting of aramid fibre reinforced epoxy composites bonded to the aluminium skin layers. ARALL was successfully developed at the Faculty of aerospace engineering of the Delft University of Technology (TU Delft) in 1978 (Villanueva and Cantwell, 2004). It has been demonstrated that ARALL possesses excellent fatigue crack resistance over the monolithic aluminium. To further improve the mechanical strength of FMLs, high strength carbon fibre was incorporated in FMLs instead of aramid fibre. However, carbon fibre exhibited poor fatigue resistance due to fibre failure during the fatigue test at elevated stress levels (Sinmazcelik et al., 2011). Due to the disadvantages of carbon fibre, glass fibre as an alternative reinforcement was introduced into FMLs in 1990 to improve the properties (Ammar et al., 2019).

The alternate stack configuration in FMLs has offered excellent damage tolerance and fatigue crack resistance via the fibre bridging mechanism (Zhou et al., 2015). Due to the combination of advantages in metallic alloy and composite materials, the strength and durability of the materials have been drastically improved. The relatively low fatigue crack growth rate of FMLs compared to monolithic aluminium is particularly vital for the mechanical structures as the inspection interval of the structures can be increased, which directly avoids the secondary damage to other components. Because of the excellent mechanical properties of FMLs, the applications of FMLs have been further extended to various fields and they are currently being proposed in the automotive field to improve vehicle efficiency. Apart from that, the stringent environmental rules and regulations aligned with the increasing environmental awareness and consciousness have inspirited the researcher to search for lightweight materials to reduce energy consumption as well as contaminant emission. Reducing vehicle weight is one of the known techniques that could be applied to reduce the energy consumption and harmful contaminant of a vehicle. Since FMLs are lighter than metallic alloys, introducing the FMLs into manufacturing of vehicle components leads to the overall weight reduction, resulting in less fuel consumption and less contaminant emission. Hence, the overall vehicle efficiency is undoubtedly enhanced.

The composite materials indeed have a major contribution to the mechanical properties of FMLs. Fibre types, fibre orientation and fibre configurations are factors influencing the mechanical properties of FMLs. The demand for composite materials has been continuously increasing in almost every branch of engineering applications since the past few decades, from the aircraft industries to the automotive industries. The advent of composite materials in various applications could be due to their outstanding advantages such as high specific mechanical properties and excellent heat and corrosion resistance (Arju et al., 2015). However, the most commonly available composite materials that have been widely used are based on synthetic fibres, particularly with glass fibre. Before the development of FMLs, metallic alloys and composite materials were two favourite materials that were being used in aircraft industries. Nevertheless, both materials exhibited disadvantages such as poor impact resistance and residual strength in composite materials and low fatigue resistance in metallic alloys. Therefore, an attempt to combine these two competing materials had been successfully conducted to remedy their respective shortcomings. As a result, FMLs with excellent performance had been developed, which play an important role in improving the efficiency and performance of vehicle and aircraft.