DEFENCE S&T TECHNICAL BULLETIN

VOL. 10 NUM. 3 YEAR 2017 ISSN 1985-6571

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Ministry of Defence
Malaysia

SCIENCE & TECHNOLOGY RESEARCH INSTITUTE
FOR DEFENCE (STRIDE)

QUASI-STATIC INDENTATION BEHAVIOUR OF KENAF BAST FIBRE REINFORCED METAL LAMINATE SYSTEM

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ABSTRACT

Fibre Metal Laminate (FML) is hybrid material that has the combined advantages of metallic materials and fibre reinforced matrix. It has been widely used in the aircraft industry for impact prone applications due to its excellent fatigue and impact resistance. This research focuses on the quasi-static indentation behaviour of fibre metal laminates based on NaOH treated and untreated kenaf bast fibre with fibre loading wt% of 50, 60 and 70 and fibre length in cm of 3, 6 and 9. Aluminium 5052-O has been used as the skin layers of FML in this study. Hot compression moulding method has been used to fabricate the composite and FML panels for this study. The prepared specimens were tested in accordance with ASTM D 6264 using Instron 5585 universal testing machine to assess their quasi-static indentation performance. The results revealed that treated FMLT-60(9) with fibre loading 60wt% and fibre length of 9cm exhibited the highest energy absorption at 30.82 J.

Keyword: *Fibre metal laminate; thermoplastic; indentation; kenaf fibre; quasi-static.*

1. INTRODUCTION

Over the past decade, there has been an increasing interest in developing high-performance and lightweight structures for impact prone applications in numerous engineering sectors especially aerospace and motorised industries. The low fatigue strength of the aluminium alloys and the problems related to the damage tolerance in fibre reinforced composites (FRPs) has called for the development of a hybrid material which is known as fibre metal laminate (FML). These hybrid materials can overcome the limitations of metals and FRPs by combining composites and conventional metallic alloys (Vogelesang & Vlot, 2000). FML is a hybrid structure consisting of thin sheets of metallic alloy sandwiching a FRP layer. The FMLs as shown in Figure 1 have collective benefits of fibres in the composite material which acts as a barrier against crack propagation and of metallic materials which improves the ductility and impact resistance properties of the structure (Cortes & Cantwell, 2006). According to prior studies, it was found that FMLs are nearly 20-30% lighter than monolithic aluminium (Chai & Manikandan, 2014; Dharmalingam *et al*., 2014; Sivakumar *et al*., 2016; Sivakumar *et al*., 2017). Furthermore, the FMLs offer additional advantages such as superior fatigue toughness and impact damage tolerance in contrast to conventional metals (Santiago *et al*., 2017). A series of localised blast loadings conducted by detonating PE4 plastic explosive shows FML has tremendous potential in resisting explosion (Langdon *et al*., 2007; Lemanski *et al*., 2007).

The past decades have seen the rapid development of several types of FMLs such as the Aramid fibre reinforced Aluminium Laminate (ARALL), the Glass Laminate Aluminium Reinforced Epoxy (GLARE) and the Carbon Reinforced Aluminium Laminates (CARALL) (Sinmazçelik *et al*., 2011). FMLs used in aerospace industry were based on thermoset-based polymer matrices, which is stronger and stiffer with enhanced performance in high temperature applications. However, thermoset-based FMLs require long processing cycle whereas thermoplastic-based FML offers low manufacturing cost since it requires short processing cycle (Cortes & Cantwell, 2006). Composton *et al*. (2001) found that the thermoplastic-based FMLs require nearly 23% more specific energy to perforate than thermoset-based FMLs during impact loading. Thus, the use of thermoplastic-based FMLs has been growing in recent years as it is considered as potential alternatives for thermoset-based FMLs.

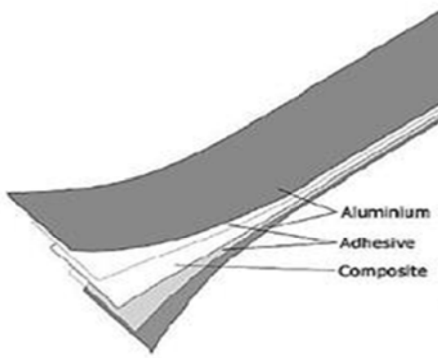

Figure 1: A sample of FML layup (Dharmalingam *et al*. 2009).

New regulations on environment and the growing concerns in reducing the use of petroleum based products in the production of engineering materials have led to the development of composites based on natural fibres such as kenaf, coir, hemp, sisal and jute (Ramesh, 2016; Ng *et al*., 2017). The application of natural fibres in composite materials has been driven by the need of manufacturing eco-friendly materials due to its biodegradable and low cost characteristics (Vieira *et al*., 2017). Kenaf is the common name for *hibiscus cannabinus* which is originated from Africa. Kenaf bast fibres have low density and exhibit high specific mechanical properties which make them suitable for structural applications (Avella *et al*., 2008; Sivakumar *et al*., 2017). It has been shown that kenaf fibres possess excellent potential and economic feasibility for future applications (Cieh *et al*., 2017; Sulaiman *et al*., 2017). Furthermore, flexibility is one of the significant technical characteristics of kenaf fibres, which enhances their energy dissipation capabilities, damage tolerances and impact resistance properties (Salman *et al*., 2017). Previous research on the kenaf fibre reinforced polypropylene composites has provided insights of its tensile and flexural strength as well as its applications in several industries such as automotive and aerospace industry (Zampaloni *et al*., 2007).

Numerous experimental works have been reported on the quasi-static response of the natural fibre reinforced FMLs. Abdullah *et al*. (2014) investigated the indentation fracture behaviour of fibre metal laminates based on kenaf/epoxy with varying thicknesses and the FML lay-ups. It was concluded that thickness and lay-up of the FMLs have a significant effect on their energy absorbing properties where the increasing number of lay-up and thickness led to improved energy absorption as well as better resistance towards deformation. More recently, Pang *et al*. (2015) studied the indentation behaviour of fibre metal laminates based on kenaf/epoxy with different loading rate. It was found that the maximum contact force and energy absorption of FMLs increased with the increment of loading rate. Yahaya *et al*. (2014) conducted an experimental work to determine the quasi-static penetration properties of non-woven kenaf fibre/Kevlar reinforced epoxy hybrid composite for ballistic armour spall-liner application. Significant improvement in term of energy absorption and the resisting load was found when a layer of kenaf mat was placed in between two layers of high strength Kevlar fabric. Moreover, the outer Kevlar fabrics can resist the shear plug formation and prolong the load-displacement curve. To date, limited research studies were established on the natural fibre reinforced thermoplastic-based FML. This research presents an experimental study on the quasi-static indentation behaviour of kenaf bast fibre reinforced polypropylene metal laminates (KFML). The response of the KFML under quasi-static loading is evaluated, where the effect of fibre loading, length and treatment are studied.

2. METHODOLOGY

2.1 Composite and FML Preparation

In this research, kenaf bast fibres were used as the reinforcement while polypropylene (PP) granules were used as the matrix. The PP granules used in this study has a density of 0.95 g/cm^3 was supplied by Basell Asia Pacific Ltd, Malaysia. The chemical treated fibres were prepared by soaking in 5% Sodium Hydroxide (NaOH) solution at room temperature for 4 hours to produce a clean and rough surface on the fibre. Chemical treatment enhances the interfacial bonding of polymer and kenaf fibre owing to the better interlocking between fibres and matrix (Mahjoub *et al.*, 2014). The fibres were then filtered out and washed with tap water until the traces of sodium hydroxide were removed. The treated fibres were then dried at room temperature overnight followed by drying in an oven at 40 °C for 24 h. The fibres were then cut into short pieces with three different lengths; 3, 6 and 9 cm. The PP sheets were prepared by compressing PP granules in a 200 mm × 200 mm × 1 mm (width × length × thick) picture frame mould using the hot press machine at 175 °C. Random kenaf fibre mats were formed by compressing the fibres at 180 °C for 2 min according to the respective fibre length and compositions. The fibre mats and PP sheets are then stacked alternately in a picture frame mould with a size of 200 mm × 200 mm × 3 mm. It was then compressed for 8 min at a temperature of 180 °C and pressure of 5 MPa in the hot press machine to form composite panels with a consistent thickness of 3 mm as shown in Figure 2. The 0.5 mm thick aluminium 5052-O sheets were cut to a dimension of 200 mm x 200 mm. To increase adhesion level between the aluminium and the composite, the surface of aluminium sheets was mechanically coarsen using sandpaper grit size 80. KFMLs with 2/1 configuration was formed by stacking two aluminium layers to the composite in which a 0.05 mm thick modified PP adhesive sheet was placed between the layers of aluminium and the composite panels as shown in Figure 3. The prepared FML assembly was subjected to hot compression moulding process at the temperature of 170 °C and pressure of 0.4 MPa for 10 min. The KFML panel was removed upon reaching room temperature. The composition of KFMLs prepared for this research is presented in Table 1. The KFML panels were cut using a shearing machine according to dimension shown in Figure 4.

2.2 Quasi-Static Indentation Test

The quasi-static indentation test was repeated three times to study the damage mechanism and energy absorption of KFMLs. The indentation tests were conducted with reference to the ASTM D 6264 using Instron 5585 universal testing machine with a 150kN load cell. A series of quasi-static tests were performed using 12.7mm diameter hemispherical tip indenter in an edge supported configuration. The KFML samples were bolted between the top plate and bottom support plate by four screws with sufficient force to prevent slippage of the specimen during the test as shown in Figure 5. The load versus displacement curves were recorded, at a crosshead displacement rate of 1.25 mm/min. The energy dissipation was calculated by integrating the area under the curve. The specimens were then visually examined to analyse the failure mechanisms.

Figure 2: Kenaf reinforced polypropylene composite.

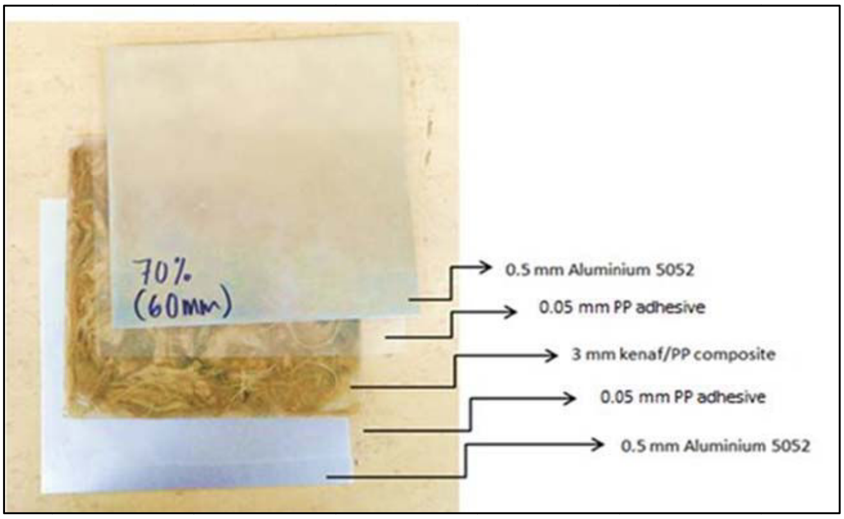

Figure 3: Typical stacking sequence of KFML.

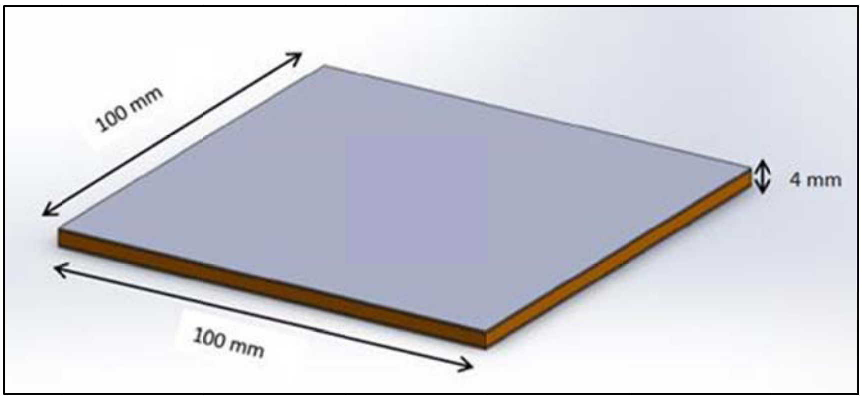

Figure 4: Schematic illustration of the specimen for quasi-static indentation test.

Table 1: Specifications of the KFMLs fabricated.

Specimen code	Fibre weight (%)	Fibre length (cm)	Fibre treatment
UT-50(3)	50	3	Untreated
UT-60(3)	60		
UT-70(3)	70		
UT-50(6)	50	6	
UT-60(6)	60		
UT-70(6)	70		
UT-50(9)	50	9	
UT-60(9)	60		
UT-70(9)	70		
T-50(3)	50	3	Treated
T-60(3)	60		
T-70(3)	70		
T-50(6)	50	6	
T-60(6)	60		
T-70(6)	70		
T-50(9)	50	9	
T-60(9)	60		
T-70(9)	70		

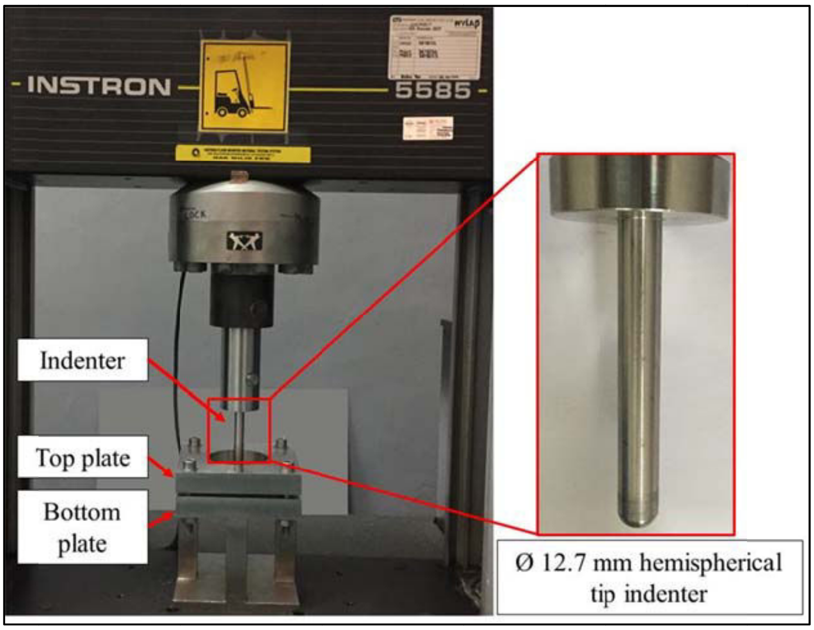

Figure 5: Quasi-static indentation test setup.

3. RESULTS AND DISCUSSION

Quasi-static indentation experiment was performed to study the effect of kenaf bast fibre length, loading and treatment on the energy absorption and damage mechanisms of KFMLs. Figures 6 and 7 show the average load versus displacement curves for each composition of FMLs with untreated and treated kenaf fibres respectively.

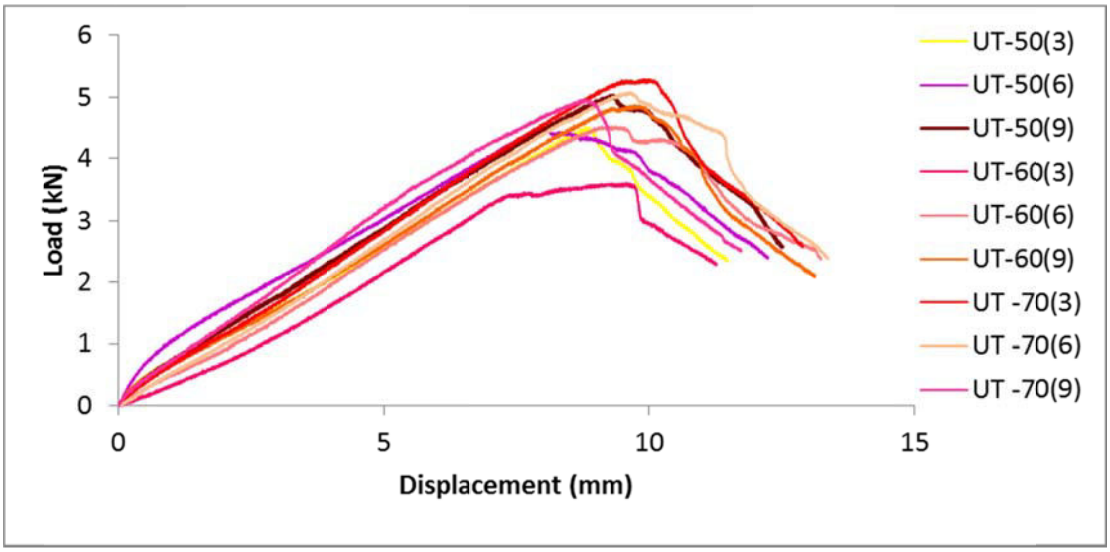

Figure 6: Load versus displacement curves of KFMLs with untreated fibre.

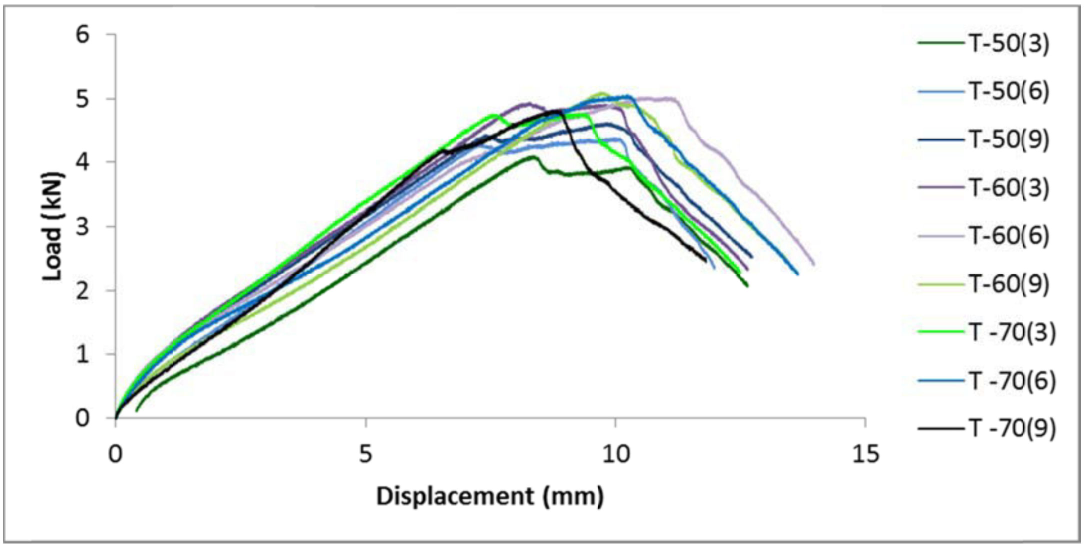

Figure 7: Load versus displacement curves of KFMLs with treated fibre.

These curves exhibit similar trend but with a different maximum load for each specimen tested. The trend of the load versus displacement curve can be divided into three distinct phases as indicated in Figure 8. Initially, the curve increases linearly with displacement up to a knee point. Beyond the knee point, the curve continued to increase in a non-linear behaviour until a maximum peak load is achieved. The initial increase in load is due to the plastic deformation of the indented surface (top surface) of the FMLs. The indenter then moves through the composite thickness of the FMLs by pushing the top aluminium sheet through the matrix and kenaf fibres to the bottom surface. Finally, when the indenter penetrates the bottom aluminium sheet, the curve plummeted drastically. This marks the failure of the specimens. The maximum load-carrying capacities were found to vary with each composition of FML tested, as shown in Figure 9. Figure 10 shows the average maximum energy absorbed during the quasi static indentation measured by integrating the area under the force versus displacement curves up to respective maximum load. The average maximum load and maximum energy for each composition tested are summarised in Table 2.

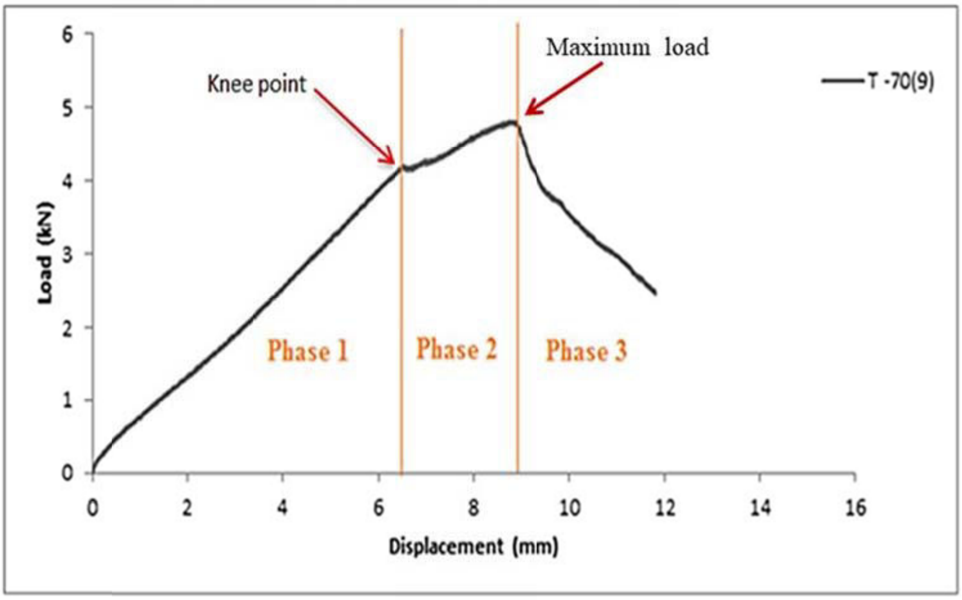

Figure 8: Phases of a load versus displacement graph for FML with 70% weight composition of 9mm untreated kenaf fibre.

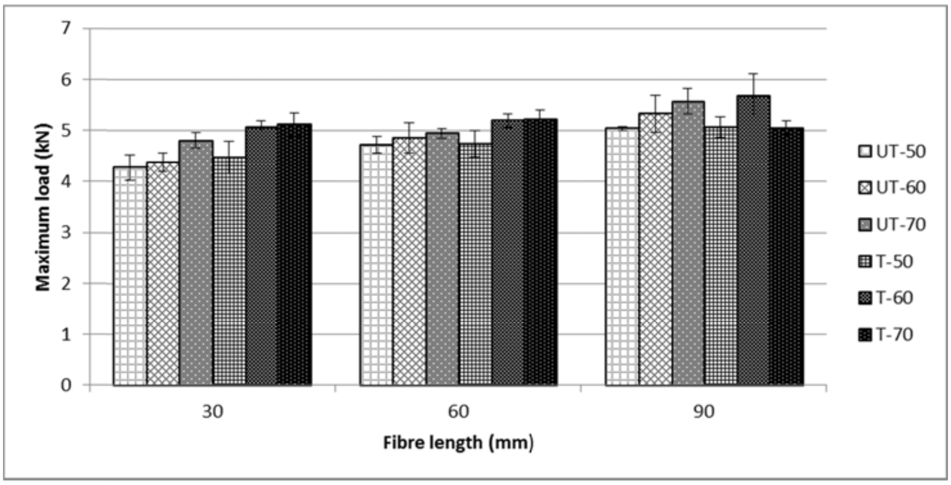

Figure 9: Maximum quasi-static indentation load.

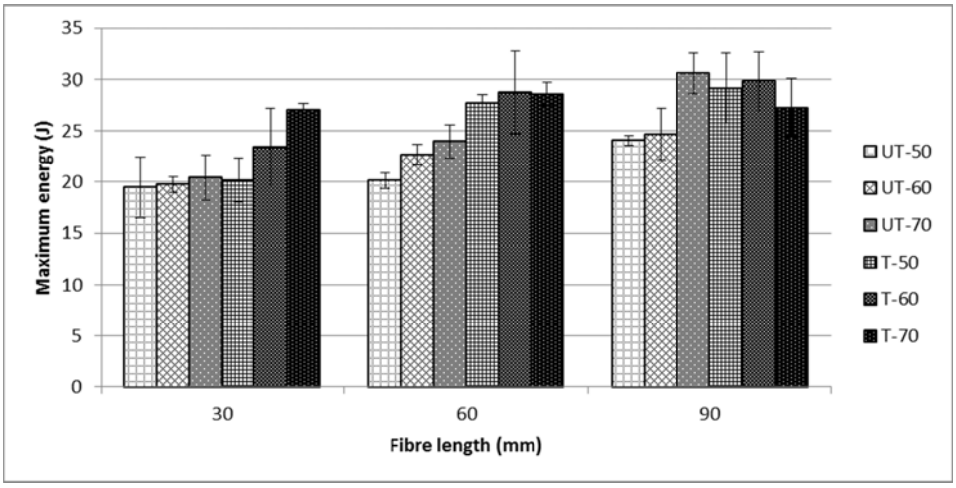

Figure 10: Maximum quasi-static indentation energy.

Table 2: Maximum load and energy absorption of quasi-static indentation.

Specimen code	Maximum load (kN)	Maximum energy (J)
UT-50(3)	4.27 ± 0.25	19.48 ± 2.93
UT-60(3)	4.38 ± 0.18	19.79 ± 0.77
UT-70(3)	4.81 ± 0.15	20.43 ± 2.22
UT-50(6)	4.72 ± 0.16	20.14 ± 0.78
UT-60(6)	4.86 ± 0.30	22.67 ± 1.03
UT-70(6)	4.95 ± 0.10	23.98 ± 1.62
UT-50(9)	5.04 ± 0.04	24.05 ± 0.46
UT-60(9)	5.33 ± 0.36	24.66 ± 2.52
UT-70(9)	5.57 ± 0.25	30.58 ± 1.97
T-50(3)	4.48 ± 0.31	20.18 ± 2.17
T-60(3)	5.07 ± 0.11	23.42 ± 3.76
T-70(3)	5.12 ± 0.23	27.06 ± 0.62
T-50(6)	4.74 ± 0.26	27.74 ± 0.77
T-60(6)	5.20 ± 0.13	28.76 ± 3.98
T-70(6)	5.21 ± 0.2	28.61 ± 1.10
T-50(9)	5.07 ± 0.19	29.21 ± 3.41
T-60(9)	5.68 ± 0.42	30.82 ± 1.83
T-70(9)	5.05 ± 0.16	27.28 ± 2.84

It is evident that the maximum penetration load of FMLs increases as the fibre length increases for both treated and untreated fibre. FMLs with 50 wt% untreated fibre loading (UT-50) and 50 wt% treated fibre loading (T-50) showed an average increase of 4.92 and 0.60% respectively in terms of the maximum load when the fibre length was increased from 3cm to 9cm. This may be due to uneven stress distribution along the fibre when shorter fibre was used. Shorter fibre form more fibre ends that act as stress concentration points which will eventually lead to fibre breakage followed by a crack on the matrix and metal layer (Farahani *et al.*, 2012). Thus, certain fibre length is required to ensure efficient and uniform distribution of stress between fibre, matrix and metal layer in FMLs.

The maximum energy absorbed is generally higher in FMLs with treated kenaf fibre compared to FMLs with untreated fibre irrespective of fibre loading and length. The maximum energy absorption for FMLs with 70 wt% treated 3 cm kenaf fibre, T-70(3) indicated an improvement of 32.5% compared to FMLs with 70 wt% untreated 3 cm kenaf fibres, UT-70(3). The trend was similar for FMLs with 6cm kenaf fibres at 50 wt% loading where the maximum energy recorded for FMLs T-50(6) is 37.7% higher than FML UT-50(6). The result is consistent with the study conducted by Bakar et al. (2010) that noted the improvement in mechanical properties of composite reinforced with treated kenaf fibre. The increase in energy absorption properties of FMLs can be explained in terms of fibre-matrix interfacial bonding. Alkaline treatment performed on kenaf fibres removes lignin hemicelluloses and impurities from the fibre surfaces. This increases the surface area of kenaf fibre and provides better interlocking between the polymer and fibre. Thus, FMLs with treated fibres has stronger fibre-matrix interfacial bonding compared to FMLs with untreated fibres. However, for FML with 9cm kenaf fibre at 70 wt% loading, the ones with treated kenaf fibre showed a decline of 10.79% in maximum energy absorbed in comparison to FMLs with untreated fibre.

In terms of fibre loading, it is observed in Figure 10 that the overall energy absorbing properties of FMLs increases as the fibre weight percentage increases for both treated and untreated kenaf fibre. For instance, the maximum energy absorbed by FMLs with treated 3cm kenaf fibre recorded an increment of 16.1% when the fibre loading was increased from 50 to 60 wt%. The energy absorption rose by 15.5% when the fibre loading was further increased to 70 wt%. As the fibre content in FMLs increases, more energy was required to weaken the fibre-matrix interfacial bonding. However, for certain combination, the value of maximum energy absorbed reduces when the fibre content was increased beyond 60 wt%. The maximum energy absorbed by FML T-70(9) was 11.5% lower than FML T-60(9).The increased fibre content results in agglomeration of fibres which disrupts the distribution of stress along the fibres (Tay *et al.*, 2012). In general, FML T-60(9) recorded the highest energy absorption at 30.82 J, indicating that this configuration provides a better penetration resistance compared to other configurations tested.

4. DAMAGE MECHANISM

Post-test examination of the selected specimens was performed in the rear and indented surface to analyse the failure mechanisms during the quasi-static indentation tests for various fibre loading. The photographs of specimens are presented in Figure 11. In general, all three specimens showed similar failure mechanism where the initial failure started from a dent on the indented surface. It was then followed by a small crack on the aluminium sheet placed on the rear surface. The size of the indentation increased along with the crack length on the rear surface as the load increases. This causes the formation of a second crack that propagated in a perpendicular direction to the initial crack.

Cracks at the rear surface of the specimens were also observed to be longer in comparison to cracks on the indented surface which indicated that the rear surface exhibited more deformation compared to the indented surface as the indenter moves through the composite thickness of the FMLs. It is also visible in Figure 11, the presence of petaling failure on the rear surface of the all three specimens examined. The petaling failure is caused by of crack propagating away from the centre point which was subjected to the pressure of penetrating indenter during indentation. However, a circular crack that replicates the shape of the indenter which is a result of aluminium sheets and kenaf fibre being pushed through the rear surface as the load increases is visible in Figure 11(c).

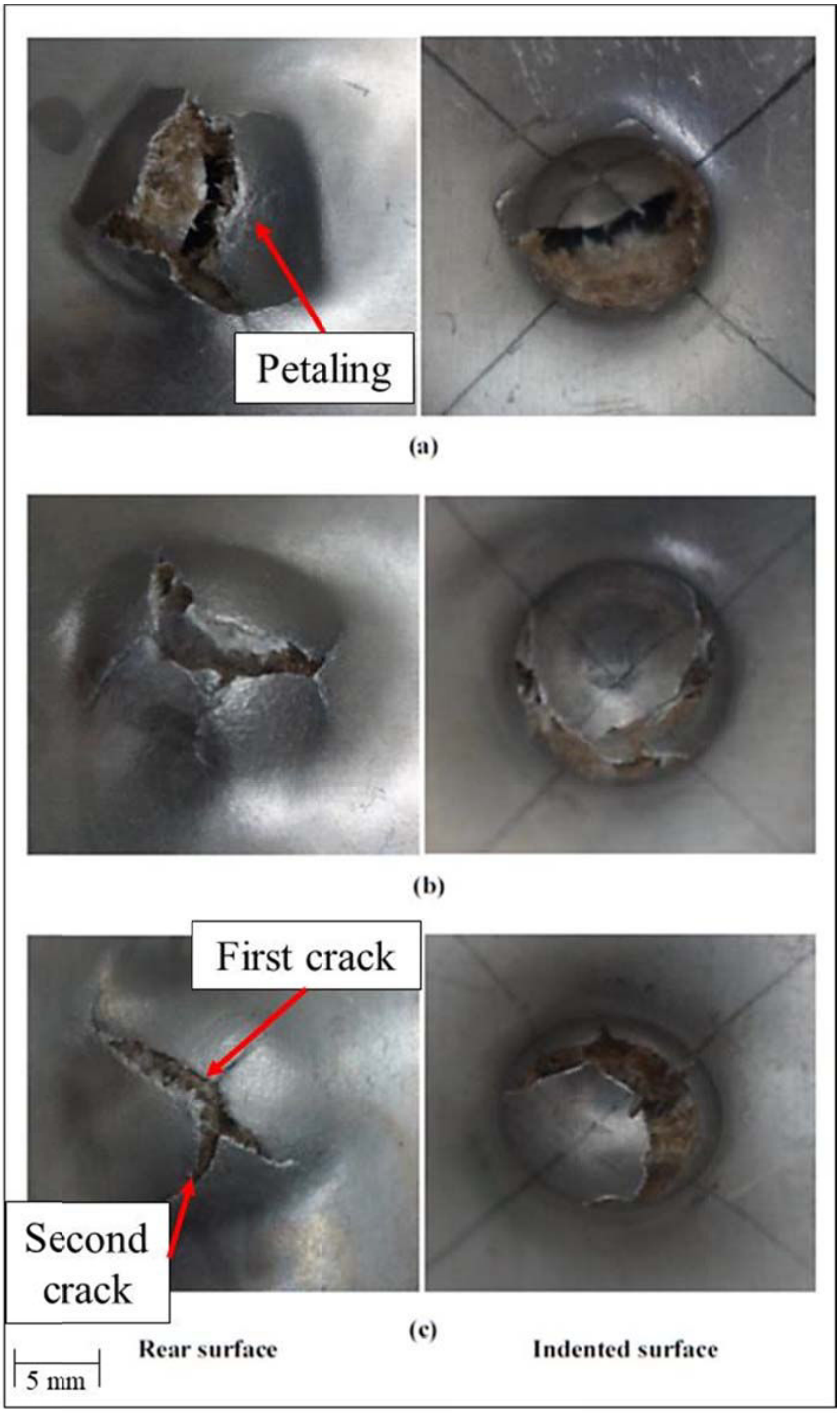

Figure 11: Photographs of indented FMLs (a) T-50(3) (b) T-60(3) (c) T-70(3).

4. CONCLUSION

The effect of fibre length, loading and treatment of kenaf bast fibre reinforced metal laminates on the energy absorption under quasi-static indentation loading and the damage mechanisms were investigated. Based on the results, the following conclusions were drawn. FMLs reinforced with treated kenaf fibre recorded an average of 19% increments in energy absorption and 4% increments in maximum load compared to FML reinforced with untreated kenaf fibre. This study has found that FMLs with a fibre length of 9 cm showed better energy absorbing properties compared to FMLs with a fibre length of 6cm and 3 cm regardless of fibre treatment and loading. FML reinforced with 50 wt% untreated 9cm kenaf fibre absorbed 30.59 J of energy which is 19.4 and 23.5% higher than FML reinforced with untreated 6 and 3cm kenaf fibre respectively at similar loading. Likewise, FML reinforced with 60% treated 9cm kenaf fibre recorded an increment of 7.16 and 31.6% in energy absorption compared to the ones with treated 6 and 3cm fibre respectively at similar fibre loading. The second major finding was that the energy absorption properties of FMLs increases as the fibre weight percentage increases from 50 to 70% regardless of fibre length and treatment. The energy absorbed by FML reinforced with 60 wt% treated 3 cm kenaf fibre was 16.1% higher than FML reinforced with 50 wt% treated 3 cm kenaf fibre. Similarly, there was an increment of 15.5% in energy absorption when the treated fibre loading is further increased to 70 wt% at similar fibre length.

ACKNOWLEDGEMENT

Authors would like to thank Universiti Teknikal Malaysia Melaka for the continuous support on this research project. Authors would also wish to express their gratitude towards grant FRGS/1/2015/SG06/FKM/03/F00276 from Ministry of Higher Education Malaysia.

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