THE 21st SCIENTIFIC CONFERENCE OF THE MICROSCOPY SOCIETY OF MALAYSIA

Failure of Woven Fiber Glass Epoxy Composite Under Charpy Impact Loading

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Woven glass fiber reinforced epoxy composite at 55 vol% fiber content was fabricated using conventional hand lay-up method. The impact strength of the prepared samples were measured under Charpy impact test at +50°C and -50°C temperature. The fractured surface of composite samples were investigated using scanning electron microscope. The impact energy for samples fractured at +50°C was at 380 KJm^{-2} whereas the low temperature of -50°C showed impact energy of 178 KJm^{-2}. The high plastic deformation from the sample tested at +50°C is the evidence from the high amount of absorbed energy compared to -50°C which revealed lower deformation. At this subzero temperature, the increased brittleness produced extensive matrix cracking and fiber splitting. However, scanning electron fractograph at +50°C showed mixed failure mode of large delaminations, fiber splitting and matrix cracking. The impact values of 380 KJm^{-2} and 178 KJm^{-2} tested at +50°C and -50°C respectively would suggest that this composite is suitable to replace steel for impact applications and is safe to be used at both high and low environmental temperatures.

INTRODUCTION

Polymer based fiber composite are used extensively in fabricating commercial structures as they are well known for high strength to weight ratio. With the increased of application as a structural components, a thorough understanding needs to be undertaken for better knowledge of their dynamic impact properties. Since the established standard technique to determine the toughness of metallic material has no doubt of its result likely by Charpy, it may be reasonable to use this impact technique to assess the dynamic response of this fiber composite material.

The interpretation of fiber composite fractography propelled by dynamic impact loading makes significant accomplishment may not possible to be achieved. Because of the non homogenous structure in the fiber composite than metallic components, researchers could only predict failures from clear evidence of damage patterns. Limited number of works were found in literatures to represent details of fractography using fiber glass epoxy composites[2, 3]. Research on fractured behaviour of fiber composites in literatures had been in the interest on failure mechanism [4, 5].The research involving fractography analysis on the woven fiber glass epoxy composite under Charpy impact loading is yet to be further investigated. As such, experimental studies were conducted at the Department of Manufacturing and Materials Engineering to investigate the impact values and fractured mode of the 55 vol% fiber composite samples at +50°C and -50°C. The present result would be useful to suggest either of these composite materials are reliable and safe to be used at low and high temperatures of application

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EXPERIMENTAL

The woven glass fiber type TGFW-800 (plain weave) supplied by Hightech Polymer Sdn Bhd was used for fabrication of composite samples in this investigation. The epoxy resin WM-215 TA and WM-215 TB hardener supplied by Wah Ma Chemical were mixed at a ratio of 8:1.The general properties of fiber and matrix are shown in Table. 1.

Table 1 Properties of Fiber and epoxy [1]

Properties	Fibers	Epoxy
Specific gravity	2.54	1.2-1.3
Tensile strength, GPa	3.45	0.055-0.13
Modulus, GPa	72.4	2.75-4.10
Poisson ratio	0.2	0.2-0.33
Coefficient of thermal expansion, mm/°C	5×10^{-6}	$50\text{-}80 \times 10^{-6}$

17 plies of woven glass fibers were cut into 200 mm × 150 mm size for composite processing. The liquid matrix was impregnated using hand lay up method with the fiber plies placed in unidirectional position. This prepared sample where pressed under the load of 390 N and cured for 14 hours before it was cut using abrasive water-jet machine type Excel WJ 4080 to the standard Charpy samples . Milling process using Ajax AJ1UM milling machine was conducted to form a V-notch of 45° with 2 mm depth at the center of each sample. To attain the elevated testing temperature before fracturing, the samples were heated at 50°C for 1 hour in the oven. The low temperature samples were placed in the beaker containing alcohol. Liquid nitrogen was poured into the beaker with magnetic stirrer continuously stirring it until the required temperature of -50°C is achieved measured using thermometer. Tinius & Olsen Model 84 Charpy impact tester with 700 kg pendulum was used to perform the impact test. JEOL 5400 scanning electron microscope was used to determine the fracture mode of both samples at +50°C and -50°C.

RESULT AND DISCUSSION

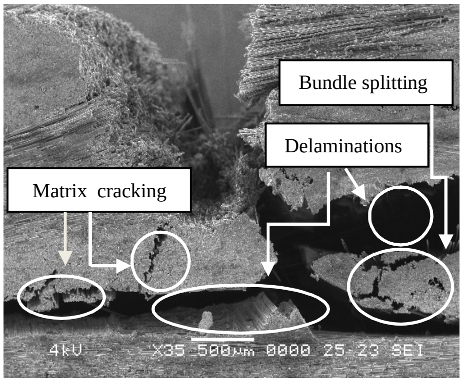

Fig. 1. V-notched failure tested at +50°C under the Charpy impact loading

Fig. 1 shows SEM micrograph of the fractured surface sample at the V-notched area tested at +50ºC that gives failures of fiber delamination, fiber bundle splitting and matrix cracking. The delamination on both tested samples are thought to initiate at the notch tip and progressively failed towards the samples end in the presence of peeling force. Higher tensile energy is responsible to peel the V- notched in greater size for the +50°C compared to the one at -50°C where brittle fracture is dominant for size reduction in failures as shown in Fig. 2.

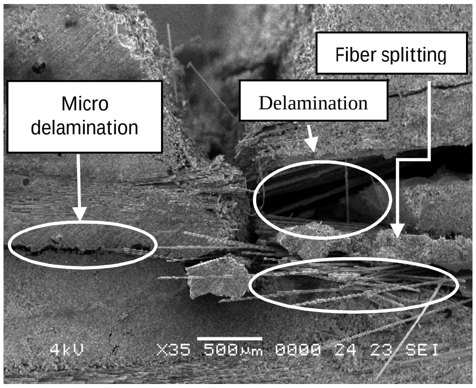

Fig. 2. V-notched failures on the sample tested at -50°C

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The greater energy absorption caused by higher tensile stress on the right side of the V-notched area at -50^{o}C produces larger delamination with fiber splitting than the left side which had only micro delamination at reduced energy absorption at fiber interlayers depicted in Fig. 2. Bader et al. [6] explained that the low value of flexural strength at the notch base causes delamination to occur. Tomita et al. [7] found that crack initiated at the V-notched area was parallel to the specimen length due to the tensile stress with three point bending testing.

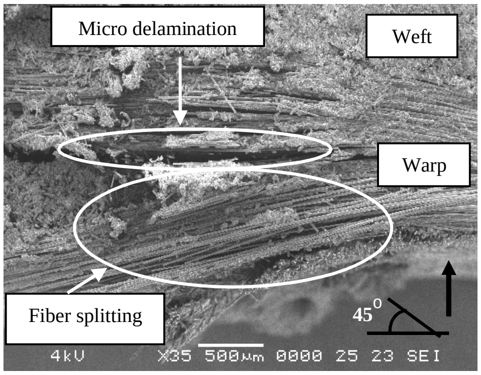

Fig. 3. The left pendulum striking area defects at +50^{o}C. The bolded arrow shows the pendulum striking direction.

The left side of the pendulum striking area in Fig. 3 clearly shows filaments in the warp strand which had individually splitted without fiber breakage that is believed to be caused by ductile matrix failure and micro delamination. The right side possesses matrix cracking that is interconnected in the weft bundle along with fiber fracture at the pendulum contact area in Fig. 4. Due to the pendulum impact shock, the right side of the pendulum striking area (Fig. 4) had these distinguished fractograph of fiber fracture and interconnected matrix cracking that may contribute for a modest increased of absorbed energy compared to only micro delamination observed on the left side (Fig. 3). Kalthoff [8] explained that the weak interface of matrix between plies give failure at one side of the specimen under Charpy impact test. Equal deformation in sizes observed on the left and right side at this pendulum striking area suggests almost consistent energy absorption along this contour before the sample failed upon impact. The warp strand that is the closest to the pendulum striking tip was highly deformed along several composite failures are presumed to absorbed higher impact energy than the interior where the defects seen much lesser (Figs. 3 and 4). Because of stress concentration during impact, both areas showed failure of fiber buckling to be propagated away into the interior of the sample at inclination of 45^{o}.

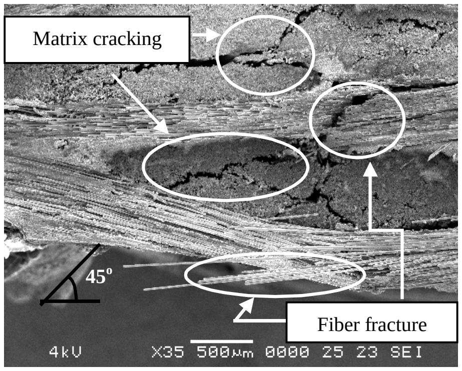

Fig. 4. Mixed mode failures on the right side of pendulum striking area at 50^{o}C.

In the presence of high ductility at +50^{o}C, the compressive strength from Charpy impact blow forced the contact surface at the samples center to deform (Figs. 3 and 4) rather than brittle fracture observed on those tested at -50^{o}C (Figs. 5 and 6). The ductile fracture at this temperature of +50^{o}C produces impact energy of 380 KJm^{-2} while the brittle fracture at -50^{o}C had 178 KJm^{-2} of absorbed energy.

The pendulum striking area tested at –50^{o}C produces almost no deformation on the left in Fig. 5 and lesser one on the right side in Fig. 6 compared to those tested at +50^{o}C shown in Figs. 3 and 4. Such difference of composite failure may be due to the increased sample brittleness at -50^{o}C thus restricting the pendulum striking area to be deformed in favour fracturing the matrix for micro delamination (Fig. 5) and massive splitting of fiber filaments (Fig. 6). With the low temperature, the energy absorption for

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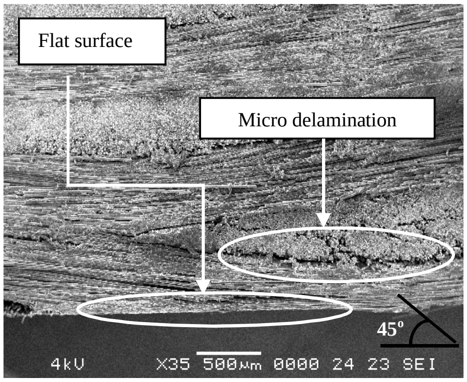

Fig. 5. Almost no deformation at pendulum striking area at -50°C.

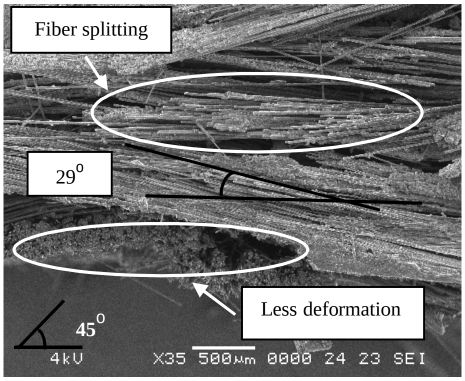

Fig. 6. Moved up warp strand at 29° with enormous fiber splitting and less deformation at pendulum striking area

this composite to fail was at 178 KJm^{-2}. The phenomenon of immense failure at one side of pendulum striking area is with agreement in literatures [2, 8] . Similar trends of fracture propagation with the high temperature one at 45° away to the interior was observed on both side of the pendulum striking areas (Figs 5 and 6). The presence of sample brittleness at this temperature had resulted the hard warp strand on the right side of pendulum striking area to alleviate at an inclination 29° (Fig. 6) and this was difference on the same area at +50°C where the increase of sample ductility had deformed the warp strand which is according to the shape of pendulum tip. Since the matrix is brittle and deformation is low at this subzero temperature, the cracked matrix from the high compressive strength during impact gives easiness for the individual fiber filaments to be fractured and debonded, thereafter protruded away from the sample structure as seen in Fig. 6

The heavy stress concentration from the impact blow caused the matrix to easily crack which had resulted fiber splitting at greater distance together with large delamination observed in this V buckling area in Fig. 7. Delaminations are reported to take place at the low shear strength area that relates with reduce of fiber volume fraction fabricated using lower compaction load. [2, 6].

The delamination at fiber interplies entrapped with high volume of matrix can be envisaged to have low in interlaminar shear strength causing crack to initiated thus propagating away from impact blow areas. The high matrix content at the bundle edge gives matrix microcracking failure for the individual fibers to be splitted compared to the center where presumably no energy absorption involved to fracture this small region (Fig. 7) .

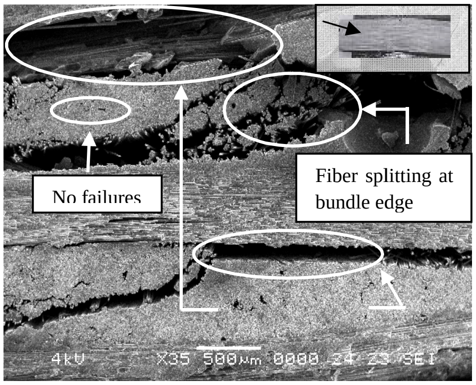

Fig. 7. Absence of failure obser.ved at the center of the weft bundle at **-50°C. Insert shows location of V buckling area.**

The evidence of matrix rich area at fiber bundle can be verified as shown in Fig. 8 where only micro delamination had propagated at the interface of warp and weft presenting a limited amount of absorbed energy happened for this failure (Fig. 8,

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bottom). This was different for the higher energy absorption areas that had resulted slightly greater of continuous matrix cracking across the weft (Fig. 8, top). Matrix is lower in properties than fiber (Table 1) and the absence of this reinforcing fiber especially at resin rich areas commonly between fiber plies and fiber crimping sites, reduces the composite strength causing crack to initiates and possibly propagates for severe failures. Matrix rich areas on woven crimping are crack initiators and this may be one probable reason for delamination to grow [9].

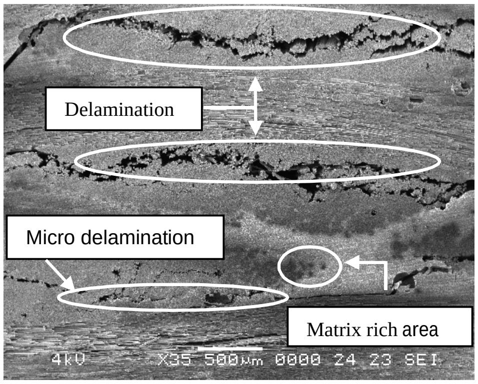

Fig. 8. Defects from failure **propagation** at inclination of 45° from the pendulum striking area using +50°C

At elevated temperature of +50°C, the matrix and fiber underwent differential thermal expansion which probably caused the composite samples to experience stress between the matrix and fiber interface. The matrix possesses about 10 times higher thermal expansion than that of the fiber filament (Table 1) resulting a tremendous interlocking between the matrix and fiber interface. This will generate compressive stress in the composite. This compression is considered to be a reason of having a higher energy absorption at +50°C compared to the low temperature of -50°C. With increased of temperatures, fiber dominated properties has lower effect than the matrix dominated as reported in literatures [1, 2]. Asad [10] demonstrated that the impact energies increases with increase of test temperature using aramid, glass and mild steel samples by dynamic Charpy impact test. Thomason [11] explained Charpy impact energy increases linearly with increase of test temperatures from -40°C to +80°C using samples fabricated at different fiber content and sizes. Amin Salehi et al. [12] observed almost constant impact energies variation on the fiberglass composite samples and fiberglass reinforced with layers of Kevlar composite samples tested at temperature ranging from +125°C to -50°C using potential pendulum energy at 8 and 15J. Badawy [13] found that the impact strength reduction of the 23.2 vol % of fiber content under Charpy impact test with decreased of temperature. The profound effect of reduced bonding strength between matrix and fiber at -10°C made the fractured fibers to be pulled out from the matrix involving an amount of energy dissipation. Samples tested at +80°C gave matrix softening which enhances the bonding between the fiber and matrix resulting dominance of fiber fracture in failure [13]. Apart from those mentioned, it is generally accepted that sample geometry is one important factor to influence energy absorption [4, 6].

In this research the low temperature of -50°C gave lower energy absorption than those tested at +50°C. The value over 178 KJm^{-2} using sample tested at this subzero temperate is approximately equivalent with 215 KJm^{-2} [1] for low alloy steel at ambient temperature which suggest that this composite is suitable to replace steel for impact applications and is safe to be used either in low and elevated environmental temperatures

CONCLUSION

The fiber and matrix thermal expansion differences generated the compressive stress and is believed to be the reason for increased of energy absorption at +50°C with a value of 380 KJm^{-2} compared to only 178 KJm^{-2} than those failed at -50°C. Tensile stress and compressive stress are the dominant forces that are presumed to have delaminated the V notch and fractured the pendulum striking areas resulting high energy absorption. Increased of sample ductility at +50°C produces sample with lesser matrix cracking

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and deformation was the dominant failure suggesting higher sample toughness in properties. Brittle matrix cracking at -50°C reduces the energy absorption giving low in deformation prior to fracture of the matrix and splitting the fibers individually. The increased of the sample hardness at -50°C is proposed to be reason for such brittle failure behaviour.

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