The Influence of Different Circular Hole Perforations on Interlaminar Shear Strength of a Novel Fiber Metal Laminates

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This study characterizes surface treated classic type Fiber Metal Laminates (FMLs) interlaminar shear strength (ILSS) based on a glass mat reinforced Polyphenylene Sulphide composite and an aluminium alloy. The effect of concentration of γ-glycidoxypropyltrimethoxysilane surface treatment on ILSS of adhesive bonding between aluminium sheet and composite laminates has been investigated. After determining the silane concentration, novel FML material is manufactured using a compression moulding process which involves aluminium sheets with different circular hole perforations (Array type A and B) with two circular hole diameters (5/9 and 5/5 mm) and two total hole area/closed area: 0.05 and 0.06) to develop mechanical interlocking between aluminium layers and composite laminates. Tensile tests are performed to investigate the effect of different circular hole perforations on ILSS properties of FMLs. Test results show that ILSS is improved with increasing the circular hole diameter and decreased with the number of holes as correlated with undrilled FMLs. Failure modes, damage initiation, and progression of FMLs with different open hole perforations are determined with optical microscope. POLYM. COMPOS., 00:000–000, 2014. © 2014 Society of Plastics Engineers

INTRODUCTION

Fiber Metal Laminates (FMLs) are hybrid composites consisting of alternating thin layers of metal sheets adhesively bonded to fiber-reinforced prepreg. Within the FMLs family, glass fiber reinforced aluminium (GLARE) composes of glass fiber reinforced plastic laminae and thin sheets of aluminium alloy (Al) and has been evaluated for many potential applications in aircraft structures. GLARE has been integrated into primary aircraft structure as the upper fuselage skin for the Airbus A380, where weight reduction and improved damage tolerance are crucial [1]. The good characteristics of metals such as ductility, specific stiffness, impact, and damage tolerances, together with the benefits of fiber composite materials such as high specific strength, good corrosion, and fatigue resistances are obtained. These hybrid laminates are used to substitute monolithic metal, resulting in weight savings without much compromise to the strength-to-weight ratio. In particular, these materials find application in tension-dominated structural components and where a small saving in weight could lead to a large saving in fuel cost, as in aerospace and automobile structures, in the long run. These materials can be used where a glossy fine metallic surface finish is required as in automobiles [2]. Fuselage structures and other components such as many hatches, windows, doors in aircraft applications contain many holes at riveted, and bolted joints. Therefore, more extensive application of GLARE not only to aircraft structures but also to components for general transportation structures require more detailed understanding of the hole strength of GLARE [3]. Most of investigations in the literature so far mainly focus on the behavior of notched strength [4–7] and bearing strength of FMLs [8–11]. All these investigations have been conducted on the hole strength and bearing strength of continuous fiber reinforced laminated metal laminates (FMLs) in both pin and bolt loadings. Conversely, there is not any information about the influence of circular hole perforations on the mechanical behavior of glass mat reinforced metal laminates in the literature. The mechanical behavior of a novel GLARE which involves different circular hole perforations on Al layers is a paramount importance from a design point of view.

The elastic mismatch between fiber reinforced composites and metallic layers makes joining them difficult. One way to reduce this mismatch is to decrease the average stiffness of the metallic layer by introducing perforations. Further, this has the possible advantage of mechanical interlocking [12]. The aim of this study is to manufacture a novel FML based on a glass mat reinforced thermoplastic and 5,000 series of Al sheets. Surface treatments processes of Al sheets and compression moulding process of a novel
FML were determined. Also the effect of concentration of \( \gamma \)-glycidoxypropyltrimethoxysilane (\( \gamma \)-GPS) surface treatment on interlaminar shear strength (ILSS) of adhesive bonding between Al sheets and composite laminates has been investigated. After determining the silane concentration, tensile tests were performed to investigate the effect of different circular hole perforations (Array type A and B) with two circular hole diameters (\( \phi 3 \) and \( \phi 5 \) mm) and two total hole area/closed area (THA/CA) (0.05 and 0.06) on ILSS properties of FMLs. Obtained interlaminar bonding strength values of FMLs by experimental results were given as a function of circular hole perforations. Moreover, optical microscope (OM) was used to determine the failure modes and damage characterisation of FMLs.

### MATERIALS AND METHODS

#### Materials and Manufacturing Technique

FMLs used in this experimental investigation were manufactured in Advanced Materials Laboratory of Kocaeli University using hot press compression moulding technique. 4/3 configurated a FMLs consist of two layers of 5,005 Al sheets with 0.5 mm thickness, one layer of 5,005 Al sheet with 1 mm thickness, four layers of glass mat laminate, and eight layers of powdery form of Polyphenylene Sulphide (PPS). The matrix material, powdery form PPS, which is used for forming FMLs, is provided from Ticona, Germany. The commercial code of powdery PPS is FORTRON PPS, 0205B4. The mechanical, thermal, and physical properties of PPS are given in Table 1 [13]. PPS is a high-performance semicrystalline polymer that has been used in a variety of market segments such as electrical, electronic, automotive, aviation, appliance, industrial, and chemical sectors. The reasons for its use in many products are its high mechanical properties, easy processability, excellent thermal stability, chemical resistance, flame resistance, and electro-insulating property [14]. However; the low-cost efficiency of thermoplastic composite components reflects the cost of raw materials, which can be by more than 30% higher compared with thermosets with comparable technological properties, and primarily, the high cost of the processes involved to manufacture thermoplastic composites [15].

Commercial code of glass mat fiber rolls is MAT 8. MAT 8 chopped strand mat is made from "E" glass fiber which is sized with silane coupling agent for a better bonding with polymer matrix. Specific properties of glass mat fiber rolls are given in Table 2.

For manufacturing the FMLs Carver 25-12-2H Hot-Press was used. Hot-Press has a 25 ton loading capacities with four fully threaded columns. Two 300 × 300 mm\(^2\) plates can be separately heat controlled up to 340°C. Cooling system is provided by pressured water. Layers of the glass mat fiber laminates and powdery PPS were stack alternated with Al sheets with two different thicknesses and placed in a picture frame stainless steel mould. Teflon films of 0.5 mm in thickness were inserted at bottom and top of the mould halves to provide better surface finishing of FMLs with different circular holes. Placement of 4/3 configurated FML specimen to the mould halves are shown in Fig. 1.

From the literature survey, early experiences in bonding techniques demonstrated that surface treatment prior to bonding is the single most critical step which cannot be disregarded, even for tertiary-loaded structures, since it is

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**TABLE 1.** The mechanical, thermal, and physical properties of PPS [13].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
<th>Test Standard</th>
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<tbody>
<tr>
<td><strong>Physical properties</strong></td>
<td></td>
<td></td>
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<tr>
<td>Density</td>
<td>1.350</td>
<td>kg/m(^3)</td>
<td>ISO 1183</td>
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<tr>
<td>Water absorption</td>
<td>0.02</td>
<td>%</td>
<td>ISO 62</td>
</tr>
<tr>
<td><strong>Mechanical properties</strong></td>
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<tr>
<td>Tensile modulus (1 mm/min)</td>
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<td>MPa</td>
<td>ISO 527-2/1 A</td>
</tr>
<tr>
<td>Tensile Stress at break (5 mm/min)</td>
<td>66</td>
<td>MPa</td>
<td>ISO 527-2/1 A</td>
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<tr>
<td>Tensile strain at break (5 mm/min)</td>
<td>2</td>
<td>MPa</td>
<td>ISO 527-2/1 A</td>
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<tr>
<td>Flexural modulus</td>
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<td>MPa</td>
<td>ISO 178</td>
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<tr>
<td>Flexural Stress At Break</td>
<td>130</td>
<td>MPa</td>
<td>ISO 178</td>
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<tr>
<td><strong>Thermal properties</strong></td>
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<tr>
<td>Melting temperature (10°C/min)</td>
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<td>°C</td>
<td>ISO 11357-1.-2.-3</td>
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<tr>
<td>Glass transition temp. (10°C/min)</td>
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<td>°C</td>
<td>ISO 11357-1.-2.-3</td>
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<td>Coeff.of linear therm.expansion (paralel)</td>
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<td>(E-4/°C)</td>
<td>ISO 11359-2</td>
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<tr>
<td>Coeff.of linear therm.expansion (normal)</td>
<td>0.52</td>
<td>(E-4/°C)</td>
<td>ISO 11359-2</td>
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</table>

**TABLE 2.** Specific properties of glass mat fiber rolls.

<table>
<thead>
<tr>
<th>Specific properties</th>
<th>Glass type</th>
<th>Fiber diameter (( \mu ))</th>
<th>Fiber diameter (( \mu ))</th>
<th>Fibre diameter (( \mu ))</th>
<th>Fibre diameter (( \mu ))</th>
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</thead>
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<tr>
<td></td>
<td>E</td>
<td>Nom.12</td>
<td>Polyester</td>
<td>225 ± 7%</td>
<td>50</td>
</tr>
<tr>
<td>Roll width (mm)</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
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</tr>
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</table>

**FIG. 1.** Placement of 4/3 configurated FML specimen to the mould halves.
essential to achieve long-term service capability [16, 17]. Considering the previous studies, surface treatments processes of 5005 Al sheets are defined in Table 3. The first three surface treatments which are defined in Table 3 remained same for undrilled and drilled Al sheets. Conversely, to determine the effect of silane concentration on adhesive bonding between undrilled Al sheets and PPS matrix-glass mat fiber laminates, 1 wt%, 2 wt%, and 3 wt% $\gamma$-GPS concentration were selected. Preliminary tensile experiments were performed to find the silane concentration for adhesively bonded FMLs. After determining the silane concentration, aluminium sheets with 0.5 thickness were drilled with different circular hole perforations to compose mechanical interlocking between metallic layers and polymer matrix-glass mat fiber laminates (composite laminates). Figure 2 illustrates the mechanical interlocking between metallic layers and composite laminates. From Fig. 2, it is easily seen that the mechanical interlocking

<table>
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<tr>
<th>Processing steps</th>
<th>Applied methods and used materials</th>
<th>Method of implementation</th>
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<tr>
<td>1</td>
<td>Degreasing Methyl ethyl ketone (MEK)</td>
<td>Aluminium sheets were immersed in MEK solution for 10 min. After immersing in MEK solution, aluminium sheets were washed for 5 min in cold running tap water and finally dried in an oven at 100(^\circ)C for 15 min.</td>
</tr>
<tr>
<td>2</td>
<td>Mechanical Sandpaper (180 grit)</td>
<td>Degreased aluminium sheets were abraded with sand paper of 180 grid size using a random orbital sander. After abrasion with sand paper, surfaces were washed then dried with pressured air. Finally sheets were dried in an oven at 100(^\circ)C for 15 min.</td>
</tr>
</tbody>
</table>
| 3                | Chemical (Acid Etching) | Mixing Ratio: 1 liter sulphuric acid (97% v/v) + 50 ml/l distilled water with 50 g/l potassium dichromate. 
Aluminium sheets were immersed CAE solution at 40\(^\circ\)C for 10 min, and rinsed in tap water. |
| 4                | Coupling agent (Silane) $\gamma$-glycidoxypropyltrimethoxysilane ($\gamma$-GPS) | Mixing Ratio: %50 v/v Ethyl Alcohol + %50 v/v Distilled Water For 1 liter of ethyl alcohol water solution, 1 wt%, 2 wt%, and 3 wt% $\gamma$-GPS concentration were selected and poured in this solution. The $\gamma$-GPS solutions were prepared with proper weight ratios of $\gamma$-GPS to a mixture of ethyl alcohol and water under continuous stirring for 30 min. After surface silanization of aluminium sheets for 10 min, sheets were rinsed with ethyl alcohol then dried in an oven at 100\(^\circ\)C for 60 min. |

FIG. 2. Mechanical interlocking between metallic layers and composite laminates with columns of PPS + glass mat fibers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
between metallic layers and composite laminates is required to create columns of PPS + glass mat fibers. To create the mechanical interlocking with columns of PPS + glass mat fibers, Al sheet layers with 0.5 mm thickness were drilled. It is considered that ILSS of drilled FMLs could be further improved according to undrilled FMLs. This improvement could be attributed to much more shear load which was necessary for deforming the columns of PPS + glass mat fibers.

Drilling process of Al sheets was done before the surface treatment applications. The circular hole perforations have different circular hole diameters (ϕ3 and ϕ5) are shown in Fig. 3. The effect of circular holes on adhesive bonding between Al sheets and composite laminates were determined at three main parameters; (a) two different array types of circular holes, (b) two different hole diameters (ϕ3 and ϕ5), and (c) two different THA/CA ratios (Fig. 3). Studied hole configurations was given the better results. It is concluded that not only the interface bonding but also the configurations of the holes were affected the strength of the FMLs. More information about the effect of the configurations on strength of FMLs can be found in Ref. 18.

Numerous studies [19–23] have investigated the manufacturing process parameters of composite laminates and FMLs with compression moulding and the same general procedure has been adopted in this investigation. Al sheets, glass mat fiber laminates, and powdery PPS were
placed in a picture frame mould with dimensions $125 \times 200$ mm. The mould was then heated to $340^\circ C$ in hot press. Temperature of the hot press decreased to $300^\circ C$ due to mould temperature ($50^\circ C$). Within 20 min, mould temperatures were raised to $340^\circ C$. At this temperature, mould was kept in hot press for 5 min, and then a pressure of approximately $10$ MPa was applied for 1 min. The FML panel remained under pressure in the hot press until it was cooled to ambient temperature. This ensured a rapid rate of cooling. After the laminate has cooled to room temperature the pressure is released, the mould is removed from the press and the finished laminate is retrieved. The dimensions of manufactured undrilled and drilled FMLs are $125 \times 200 \times 5$ mm.

**Tensile Test**

Tensile tests were conducted using Zwick Z250, 30 kN, instrumental test machine, keeping the crosshead speed as 5 mm/min and the temperature at $25^\circ C$. Tensile tests were performed both undrilled and drilled FMLs. In preparation for testing, tensile test specimens with dimensions $120 \times 40 \times 5$ mm were removed from the moulded plates using a horizontal band saw. Five specimens were tested. Symbolic schemes of undrilled and drilled FMLs on tensile clamping jaws are shown in Fig. 4.

**Optical Microscope**

The macrostructural damage evaluation due to the different circular hole perforations and hole diameter of FMLs were associated with the interlaminar bonding between Al sheets and PPS matrix-glass mat fiber laminates using OM (Leica S6D Stereo Microscope-80×). Beside this, after failure, FMLs with two different circular hole diameters ($\phi 3$ and $\phi 5$ mm) were examined optically with a digital camera to elucidate the failure modes during tensile loading.

**RESULTS AND DISCUSSION**

Organosilanes are good candidates for the replacement of chromium (VI)-based pretreatments for Al as well as in various other applications where improvement of interfacial interactions is required to increase the lifetime of a finished product, that is, the durability of an adhesive bond or organic coating on a metallic substrate [24]. The formation of a covalent bond between oxidised metal surfaces and organosilanes has long been postulated and, indeed, proven indirectly via the improvement of joint strength and hydrolytic stability [25]. In this study, an organosilane ($\gamma$-GPS) was selected to form adhesive bonding between Al sheets and composite laminates. To determine the silane concentration, tensile tests were conducted to undrilled FMLs. Figure 5 shows the load-% strain curves of FMLs with three different silane concentrations (1 wt%, 2 wt%, and 3 wt%). From Fig. 5, it can be concluded that the best adhesive bonding between Al sheets and composite laminates could be achieved by pre-treatment of the Al sheets with 2 wt% concentration of $\gamma$-GPS solution. Low concentrations, that is, 1 wt% $\gamma$-GPS (Fig. 5a), only a few of the hydrolysed $\gamma$-GPS
molecules adsorbed on the surface of the Al sheets and the chain network between the molecules could not be created. As the concentration of \( \gamma \)-GPS solution increases at a level of 2 wt\%, more hydrolysed \( \gamma \)-GPS molecules are adsorbed onto the Al surfaces (Fig. 5b). With a higher concentration of \( \gamma \)-GPS solution (greater than 2 wt\%), in Fig. 5c, the hydrolysed \( \gamma \)-GPS molecules are physically adsorbed onto the Al surfaces of the adsorbed \( \gamma \)-GPS molecules after the surfaces of Al sheet are saturated by the hydrolysed \( \gamma \)-GPS molecules. This physically adsorbed \( \gamma \)-GPS layer is prevent the interaction between the chemically adsorbed \( \gamma \)-GPS layer and composite laminates, resulting in sharply decease of the tensile load with high concentration of \( \gamma \)-GPS solution as similar to Ref. [26]. At 2 wt\% \( \gamma \)-GPS concentration, the silane pretreatment guarantees an increase of adhesion properties and delamination resistance of the FMLs due to the resistance of the silane–metal interface to hydrolysis phenomena as described in Ref. 27.

After determining the silane concentration (2 wt\% \( \gamma \)-GPS), tensile tests were performed to evaluate the effects of different circular hole perforations on interlaminar bonding between Al sheets and composite laminates. Figure 6 shows typical load-% strain curves of drilled FMLs with the 2 wt\% \( \gamma \)-GPS concentration. In general from Fig. 6, the interlaminar strength of FMLs were improved with all circular hole perforations according to undrilled FMLs with the 2 wt\% \( \gamma \)-GPS concentration (Fig. 5b). It was determined that more shear energy was required for deforming the FMLs. Also it can be seen that strain values were increased with increase in the number of circular holes in the FMLs (Fig. 6a–d). The load-% strain curves were demonstrated that circular hole perforations improved the ductility and also toughness of FMLs. Compared to undrilled (Fig. 5b) and drilled with array type A and B FMLs (Fig. 6a–d), for a given strain value the maximum loads of the drilled with array type A and B FMLs were higher.

Compared to two array types, A and B, it was observed that the interlaminar strength of FMLs drilled with array type A was better than array type B (Fig. 6a and b, Fig. 6c and d). Conversely, load-% strain curves give information about the damage mechanisms occurred in the FMLs during tensile tests. For array type B, except a lower slope of load-% strain curves that is caused by the stress concentration of notch, a platform of load-%
strain curve was observed around 95% critical failure load until the final fracture. This is associated with the occurrence of damage initiation such as fiber breakage, splitting, and delamination at hole edges as similar to Ref. 5 (Fig. 6b). Bearing failure was observed at each FML with A or B array type circular hole perforations. From Fig. 6a, the bearing specimen show a linear response up to approximately 7,500 N. At this point, the stiffness begins to decrease and keeps decreasing until a maximum stress of approximately 10,500 N is reached as similar to Ref. 28. This stiffness reduction indicates the onset and growth of damage. In line with the general viewpoint of bearing failure is a noncatastrophic failure mode. Finally, the load-% strain curves for the net-
tension failure are shown in Fig. 6a and c. The specimens suddenly rupture by a crack growing from the hole edge and the metal-composite laminate joint is unable to sustain any further tensile loading. Net-tension failure is a catastrophic loss in the joint’s load-carrying capacity.

Figure 7 shows the comparison of maximum load values of undrilled and drilled FMLs as related to circular hole perforations and hole diameters. In general from Fig. 7, the adhesive bonding strength of each FMLs with different circular hole perforations are increased according to undrilled FMLs. In addition, for both circular hole perforations, increasing the number of circular holes in FMLs are reduced the adhesive bonding strength between Al sheets and composite laminates. If the circular hole diameters are compared, adhesive bonding strength of the FMLs with φ 5 mm circular holes are approximately 5% higher than FMLs with φ 3 mm circular holes. At higher circular hole diameters, it is thought that the strength of the materials shall reduce due to greater notch effect. But strength of the materials is improved due to higher mechanical interlocking between the Al sheets and composite laminates. It can be seen that adhesive bonding strengths of the FMLs with the circular hole formation, A array type, are better than array type B. Array type A circular hole formation resembles hexagon. It is supposed that the load capacity of the FMLs increases and balances with the hexagonal structure. For the other circular hole formation, array type B, more notch effect occurs due to the circular holes at the bottom and top. Net-tension failure involves a fracture across the width of the joint and normally occurs when the width to
The hole diameter (w/d) ratio is small. It is found that w/d values as low as 2 were necessary to promote net-tension failures in GLARE two joints [28]. It is predicted that the adhesive strength of the drilled with array type B FMLs is decreased due to small w/d ratio depend on the circular holes at the bottom and top. Adhesive strength of the drilled with array type A-3 and A-4 FMLs is the highest compared to other array types. Average maximum loads for array type A-3 and A-4 FMLs 10,440 N and 10,929 N, respectively. Beside this, the lowest adhesive strength of the drilled FMLs is observed at array type B-1 and B-2. For array type B-1 and B-2, average maximum loads are 8,519 N and 8,918 N, respectively (Fig. 7a and b).

After failure, FMLs with two different circular hole perforations (φ3 and φ5 mm) were examined optically with a digital camera to elucidate the failure modes during tensile loading. In this study, only macrostructural damage evolution images of two different circular hole perforations (φ5 mm) are given. Because of similar damage evolution was observed for FMLs with φ3 mm circular holes, Macrostructural damage evolution images of tested specimens were not added. Macrostructural damage evolution images of two different circular hole perforations (φ5 mm) taken by digital camera are shown in Fig. 8. It is evident from the Fig. 8 that dominant damage mechanisms are determined as delamination of composite laminates and Al sheets, fiber breakage, splitting of composite laminates as similar to Ref. 5. The first damage mechanism is the fiber breakage and splitting in upper or bottom composite laminates layers which were bonded Al sheets adhesively occurred at a range of 30°–45° to the direction of tensile loading. It is easily observed that the angle of splitting of composite laminates was increased with decreasing the THA/CA ratio (Fig. 8b and d). Fracture in all of the plain Al alloys occurred in failing at approximately 65° to the applied load [29]. A closer examination of the fracture surface revealed significant amounts of fiber breakage within composite laminates suggesting that the fibers have played an important role in the failure process. In addition, composite laminates show evidence of localized deformation and a typical angle failure commonly. This behavior resulted from the influence of the glass fiber-reinforced composite when subjected uniaxial loading conditions promoted localized stretching and plastic deformation in the Al layers as similar to Ref. 19. Conversely, Al sheets fractured at approximately 90° to the direction of applied loading due to circular hole perforations. The presence of circular holes at the Al sheets affected the damage characteristic of Al sheets and composite laminates. The bearing and net-tension failures which were occurred in Al sheets due to the circular holes affected the angle of composite laminates as similar to Ref. 19.
laminates splitting and fracture of Al sheets (Fig. 8a). Beside this, typical damage characteristics of drilled FMLs did not change with the array types (A or B).

Figure 9 shows the damage surfaces of FMLs with the different circular hole perforations (ϕ5 mm) with OM. It is determined that PPS matrix + glass mat fibers columns were formed between Al sheets and composite laminates (Fig. 9a–c). Besides the adhesive bonding between metallic layers and composite laminates, mechanical interlocking was constituted with PPS matrix + glass mat fibers columns which were improved the ILSS of the FMLs. During tensile tests, more shear loading was recommended to generate the shear failure of each column at the bottom circular holes. By this way, some of the shear energy was absorbed from PPS matrix + glass mat fibers columns. This behavior supports the tensile test results of drilled FMLs. It is determined that the main damage mechanism at hole regions is bearing failure (Fig. 9a–c). Bearing failure is defined as local crushing of the material adjacent to the hole and normally occurs when the edge distance to hole diameter (e/d) and width to hole diameter (w/d) ratios are large [28]. It is appointed that the composite laminates and Al sheets are quite stiff so that high shear loads which are needed to obtain ultimate failure at circular holes will cause bearing failure. So the load capacity of drilled FMLs is higher than undrilled FMLs. In addition, net-tension failure also was observed at all drilled FMLs (Fig. 9). Net-tension failure is associated with Al sheets and composite laminates tension failure due to stress concentrations at the circular holes.

CONCLUSIONS

In this study, a novel FML based on a glass mat reinforced thermoplastic and Al alloy is manufactured by using hot press. Surface treatments processes of Al sheets and compression moulding process of a novel FML were determined. It is determined that the best adhesive bonding between Al sheets and composite laminates could be achieved by pretreatment of the Al sheets with 2 wt% concentration of γ-GPS solution. After determining the optimum silane concentration, tensile tests were performed to investigate the effect of different circular hole perforations on ILSS properties of FMLs. It was found that the interlaminar strength of FMLs were improved with all circular hole perforations. For both circular hole perforations, increasing the number of circular holes in FMLs were reduced the adhesive bonding strength between Al sheets and composite laminates. If the circular hole diameters were compared, adhesive bonding strength of the FML with ϕ5 mm circular holes was approximately 5% higher than FML with ϕ3 mm circular holes. Also it was found that adhesive bonding strengths of the FMLs with the circular hole formation, array type of A are better than array type B.

OM was used to determine the failure modes and damage characterisation of FMLs. It is determined that PPS matrix + glass mat fibers columns were formed between Al sheets and composite laminates. Besides the adhesive bonding between metallic layers and composite laminates, mechanical interlocking was constituted with PPS matrix + glass mat fibers columns which were improved the ILSS of the FMLs. It is determined that the main damage mechanism at hole regions is bearing failure. In addition, net-tension failure was also observed at all drilled FMLs.

REFERENCES