Blind Via Hole in Multi-layer AFRP Printed Wiring Boards by Build-Up Process*
(Quality of Hole Drilled by Small Power Laser)

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In the printed wiring board manufacturing sector, methods have been developed to improve the circuit packaging density. The multi-layer printed wiring board manufacturing process is receiving particular attention. In the current manufacture of these boards, the method frequently used is to laminate the core with insulating resin, namely a build-up process. Etching is generally used to form the holes connecting the circuits of these boards. However, a problem has emerged in that the strength of the substrate decreases due to the insulating resin part as the multi-layers are progressively formed. Thus, it becomes necessary to use FRP for the insulation layer part. Since it is very difficult to etch composites, lasers have been proposed for a new way to drill holes in such materials. By appropriate adjustment of the laser penetration energy, the holes are drilled only in the insulation part, and a technique is proposed to stop the holes using the copper foil forming the circuit. AFRP has been considered a suitable FRP for such laser processing. In the present study, attempts were made to experimentally produce multi-layer boards using AFRP and GFRP for the build-up insulation layer, and the characteristics of blind via holes drilling with a small power laser were investigated.

_**Key Words:** FRP, AFRP, GFRP, Printed Wiring Boards, Laser, Drilling, Damage, Copper Plating, Blind Via Hole, Insulation Layer_

1. Introduction

One requirement has been that the packaging density of printed wiring board be improved to achieve downsizing and multi-function of electric devices. Therefore, flexible PWBs, and multi-layer PWBs have been developed to meet this requirement.

In the past, a circuit pattern was formed on only one PWB surface, or the circuit patterns were formed on both PWB surfaces. Next, the traditional multi-layer PWB appeared, which included the circuit patterns in each layer. This type of multi-layer PWB was manufactured by the press molding after circuit patterns were formed on each insulation layer. Therefore, many through-holes, on which electric plating was performed, were needed to connect the circuit patterns among layers. However, a problem has emerged in that many through-holes prevent the flexible designing of the line spaces to improve the packaging density. Recently, to overcome this problem, the build-up process is receiving particular attention10. Thus, the traditional multi-layer PWB is considered as a core material. The insulation layers are pressed on the core material as a build-up process.
Blind via holes are drilled in the insulation layers. Copper plating is carried out to connect the circuit between the insulation layers. Finally, circuit patterns are made by etching to remove the copper at unneeded locations. As a result, the circuit patterns can be flexibly designed because there are few through-holes by means of this process.

At the present time, there are two methods to form blind via holes; (photo or chemical) etching and laser drilling. However, in adopting the etching processes, a problem has emerged in that the strength of the substrate decreases due to the insulating resin layer as the multi-layers are progressively formed. On the other hand, in adopting the laser drilling process, blind via holes can be also formed in the FRP insulation layer. Among FRPs, AFRP has been considered a suitable FRP for such laser processing. Additionally, it is considered that a little energy must be used to drill the blind via holes because of the thin insulation layer and small diameter holes. Thus, in the present report, we deal with the characteristics of blind via holes formed in the AFRP insulation build-up layer by means of small power CO₂ laser.

### 2. Experimental Equipment and Method

#### 2.1 Build-up process

The manufacturing processes (for example, 4-circuit layers) in this study are indicated in Fig. 1. First, circuit patterns are formed on the traditional multi-layer PWB, namely the core material. Second, AFRP layers as insulation layers are pressed on the core material. This is called the build-up process. Third, blind via holes are drilled in the AFRP layers by lasers. Fourth, through-holes are drilled by means of a drill tool. Fifth, cleaning and plating are done. Finally, circuit patterns on both sides are formed by etching the plated copper.

![Fig. 1 Multi-layer PWB production processes](image)

#### 2.2 Experimental materials

GFRPs are frequently used for traditional PWBs. Therefore, the core material was the copper clad laminate GFRP (glass woven cloth/epoxy composites) which was thickness 0.8 mm and was with thickness 18 μm copper foil. The core had a glass content of 60% mass. The build-up layer consisted of AFRP (non-woven aramid fiber, namely Technora by Teijin Co., Ltd.) / epoxy composites). The build-up layer had an aramid content of 50% mass, and was 0.1 – 0.3 mm thick. In addition, the GFRP was also used as the build-up layer in order to compare the AFRP layer. These materials were made by Shin-Kobe Electric Machinery Co., Ltd.

#### 2.3 Experimental equipments for laser machining and plating

The laser beam machine (type 48-5-28W, Synrad Co., Ltd.) was used with output of 25 – 50 W. The wavelength was 10.6 μm. A laser beam was single mode, and light convergence was achieved by means of a ZnSe lens. The beam was focused on the upper surface of the workpiece, with a beam diameter of about 0.3 mm at the time. N₂ is used as the assisting gas in drilling. In plating process to form the circuit the electrolytic plating was done after chemical plating on PWBs.

### 3. Laser Drilling Process

#### 3.1 Conditions for forming blind via hole

The FRPs including the epoxy resin are generally good absorbent materials for a CO₂ laser beam. On the other hand, the copper foil tends to strongly reflect a beam below the ablation threshold of copper. To obtain the blind via holes in the third process in Fig. 1, the laser drilling can remove the build-up layer, and must stop at the copper foil on the core. Figure 2 shows three kinds of holes formed, depending on the amount of energy input. The incomplete holes are obtained with less laser energy, as indicated in Fig. 2 Δ. The complete blind via holes are formed with appropriate laser energy in Fig. 2 ○. The hole is drilled through the copper foil with much laser energy in Fig. 2 □.

Considering the severe conditions of small diameter drilling of FRP, we must investigate the laser

![Fig. 2 Types of formed holes](image)
machining of the epoxy resin, the aramid fiber and the glass fiber, respectively. Here, as is known, the maximum temperature \( T_{\text{max}} \) on the surface is indicated by Eq. (1), when the laser beam of an energy density irradiates the workpiece:

\[
T_{\text{max}}(t) = e \times 0.48 \times (P/W)(k/t)^{0.5}
\]

(1)

Here, \( e \): absorption coefficient; \( P = W/(\pi r^2) \); \( W \): laser energy (W); \( r_0 \): spot radius (m); \( k \): thermal diffusivity (m²/s) and \( K \): thermal conduction rate (W/mK); \( t \): irradiation time (s)

\[
= (\text{thermal conduction rate}) / [(\text{specific heat}) \times (\text{density})]
\]

The irradiation time was calculated to reach the decomposing temperature of the epoxy resin, aramid, and glass by means of Eq. (1). The vaporized temperatures are 775, 1,075 K, and 3,075 K. Thermal conduction rates are 0.3, 2.5, and 1.03 (W/mK). Thermal diffusivities are 0.14 × 10⁻⁶, 1.4 × 10⁻⁴, and 0.47 × 10⁻⁴ (m²/s), respectively. The absorption coefficient \( e \) is 0.9.

The calculated results are 0.08 \( \mu \)s for the epoxy resin, 1.5 \( \mu \)s for the aramid fiber, and 6 \( \mu \)s for the glass fiber when irradiating with a laser energy of 50 W. Provided the small power laser is also used, it is clear that it takes a very short time to reach the vaporized temperature. Sufficient machining of these materials can be done by a small power laser.

Compared to epoxy resin, an organic material, much energy is required to decompose an inorganic material such as glass. On the other hand, there is little difference between the aramid and epoxy resin because aramid is also an organic material.

Figure 3 shows the hole types of AFRP layer, arranged according to the irradiation time and frequency. The symbols in Fig. 3 are the same as shown in Fig. 2. The time interval is 1 s between the irradiation pulses. First, note the horizontal axis of one pulse. When the irradiation time is shorter than 1 s, incomplete holes appear due to less input energy. When the irradiation time becomes 2 - 4 ms, blind via holes are obtained. When the irradiation time becomes long, a laser beam drills through the copper foil.

The absorption coefficient is considered to be 2 - 4% for the surface of a copper material. The temperature \( T_a \) of copper foil is investigated in laser irradiation. When it is assumed that the foil in a spot diameter is heated in laser irradiation, \( T_a \) is indicated by Eq. (2)

\[
T_a = e \times W \times t / (\pi \rho C t_a x r^2)
\]

(2)

Here, \( \rho \): density (8,680 kg/m³); \( C \): specific heat (0.447 kJ/kgK); and \( t_a \): thickness of foil (m).

Figure 4 shows the relationship between irradiation time with laser power 50 W and copper foil temperature. The copper melting temperature (1,357 K) is also shown in Fig. 4. The absorption coefficient is low for a CO₂ laser beam. However, the copper is also thin. Therefore, the temperature reaches the melting point during an irradiation time 2 - 4 ms for the copper foil. To prevent drilling through the copper foil, the irradiation time for copper foil must be kept less than 2 ms. The above calculated result is in good agreement with the time when complete blind via holes are formed by one pulse in Fig. 3.

As for the vertical axis in Fig. 3, when the blind via hole has been finished and the irradiation is then repeated, the copper foil is drilled through. It is considered that the copper foil gradually suffers damage because the foil on the surface is slightly melted by every irradiation.

Figure 5 shows the hole types when the output power decreases to 25 W. The irradiation time of 3 ms is required to form the blind via hole by one pulse. Two pulses are required in an irradiation time of 2 ms/pulse. However, a great many conditions can be seen to form the complete blind via holes.

Figure 6 shows the hole types when drilling in the GFRP layer. Note the horizontal axis of one pulse. An irradiation time of 3 - 5 ms is required to form a blind via hole by one pulse. As for the vertical axis,
three pulses are required in an irradiation time of 1 ms/pulse. More input energy is required to machine the glass than the aramid according to the calculated results by Eq. (1). Thus, it takes longer to drill the GFRP layer than the AFRP one.

3.2 Black damage around hole

The laser drilling applied to FRP, resulted in a dark heat-damaged area on the hole surface as shown in Fig. 7. The reason for the black damage on the hole wall is the resin pyrolysis carbon material adhering to the rough wall surface caused by the difference in the fiber and resin thermal decomposition temperatures. Therefore, we examine the black damage width in this section. Figure 8 shows the relationship between the black damage width and irradiation time after drilling for AFRP and GFRP. The damage widths decrease as the irradiation time decreases. These damages cannot be seen in less than an irradiation time of 2 ms. Thus, the black carbon adhering to the wall surface can be reduced by shortening the laser irradiation time sufficiently. However, the roughened surface resulting from the difference in fiber and resin decomposition temperature remains on the wall of the drilled hole.

As a result, the blind via holes without black damage can be formed for the AFRP layer by means of a 50 W laser beam. On the other hand, these holes cannot be formed for a GFRP layer. Nor can these holes be formed for an AFRP layer by means of a 25 W laser beam.

3.3 Hole surface

Figure 9(a) and (b) show the SEM photographs of the cross section after drilling the AFRP layer. The complete blind via hole can be visually confirmed in Fig. 9(a). A tapered hole wall can be seen as a difference from drilling holes with a conventional drill tool. From Fig. 9(b), the hole surface is found to be good quality because only very short fiber can be seen only on the wall. On other hand, it is considered that the melting phenomenon cannot be seen because the aramid fiber has a lower decomposing temperature than the melting one. However, the melting part in tip of fiber can be seen. Thus, this phenomenon occurs because the temperature rises immediately in laser drilling.

Figure 10 shows the SEM photograph of the hole after drilling the GFRP layer. The long fiber can be seen to project in the hole. In addition, the glass fibers protruding become spherical in shape under the surface tension.
Fig. 9 Cross section of drilled holes (Irradiation 2 ms × 1 pulse, laser power 50 W, AFRP 0.3 mm)

Fig. 10 Entrance to drilled holes (Irradiation 2 ms × 1 pulse, laser power 50 W, GFRP 0.3 mm)

Fig. 11 Cross section of drilled hole (Irradiation 2 ms × 8 pulse, laser power 25 W, GFRP 0.3 mm)

Fig. 12 Definition of taper angle

(a) Hole diameter

(b) Taper angle

Fig. 13 Relation between irradiation and formed holes

Figure 11 shows the SEM photograph of the cross section after drilling GFRP layer, with 8 pulses (pulse duration 2 ms, laser power 25 W). We can see the large difference between the glass cloth and epoxy resin in Fig. 11. The fiber bundle becomes spherical due to melting of the glass fiber tip. As a result, the roughened surface remains on the wall of the drilled hole.

3.4 Shape of drilled hole

The diameter at the hole entrance, the diameter at the hole bottom and the taper angle on the hole wall are defined as shown in Fig. 12. Figure 13 (a) and (b) show the relationship between laser irradiation time and the hole shape after drilling AFRP layer. The increasing tendency of the bottom diameter can be seen as the irradiation time increases. On the other hand, the entrance diameter maintains approximately
constant. As a result, the taper angle reduces as the irradiation time increases. With a laser power of 25 W, the diameters of the hole bottom and entrance show smaller diameters (than at 50 W). The taper angles roughly tend to be the same values.

From the above results, it is confirmed that the small power laser with 50 W makes it feasible to form the blind via hole in an AFRP layer 0.3 mm thick, which is considered the maximum thickness in PWB fields practically. On the other hand, it is difficult to obtain proper hole quality due to the fiber projection and the black damage when drilling the GFRP layer.

4. Hole Quality after Copper Plating for Electric Circuit

4.1 Hole conditions after plating

Figure 14(a) and (b) show cross-sectional photographs of the AFRP layer after copper plating for the circuit connection between layers. The connection between the inner and the outer circuit can be seen in Fig. 14(a). However, it is confirmed from Fig. 14(b) that thin plating takes place at the hole wall near the bottom where there is poor flow of the plating liquid. On the other hand, adequate plating can be obtained because there is little fiber projection, which can be seen between the fiber-rich part and resin-rich part shown in Fig. 14(b).

Figure 15(a) and (b) show cross-sectional photographs of the GFRP layer after copper plating. Some part on the under side of the fiber projection remains unplated because the plating fluid flow is so poor at this part in Fig. 15(a). An undercut also appears around the hole bottom wall. This is why a reflected laser beam from the copper foil surface affects the resin around the bottom. The hole diameter tends to be smaller at the woven glass cloth in Fig. 15(b). This tendency is considered as characteristic when drilling the GFRP layer. Thus, the large diameter hole is drilled because the GFRP layer near the surface consists of resin with a low vaporized temperature, and the smaller diameter hole is drilled in the glass reinforcement part with a high vaporized temperature. Therefore, the hole shape of the GFRP layer indicates a large taper angle due to different diameters at the hole entrance and bottom.

4.2 Surface roughness on the hole wall

The surface roughness on the hole wall is considered an important factor to estimate the reliability of the circuit connection between layers, because its increase causes uneven plating and the blow holes.

Fig. 14 Cross section of drilled hole after plating (Irradiation 1 ms×2 pulses, Laser power 50 W, AFRP 0.3 mm)

Fig. 15 Cross section of drilled hole after plating (Laser power 50 W, GFRP 0.3 mm)
The surface roughness at the hole entrance and the bottom are measured from the sectional photograph after plating. Figure 16(a) and (b) present the results. From Fig. 16(a), the irradiation time has little influence on the surface roughness. From Fig. 16(b), however, the irradiation frequency affects it. The maximum surface roughness is greater than the fiber diameter (13 μm). However, it is confirmed in Fig. 16(b) that repeated irradiation makes it possible to reduce the surface roughness at the hole entrance to about half the fiber diameter. As a result, it is difficult to maintain the constant thickness of plating around the hole bottom, because the hole diameter decreases and the surface roughness increases.

4.3 Influence of build-up layer thickness

Figure 17 shows a cross-sectional photograph after copper plating of the drilled hole in a build-up layer with a thickness of 0.1 mm. Comparing the plating thickness of hole entrance with that of the hole bottom, there is no difference between them. Adequate plating is seen at the hole wall from the entrance to the bottom, because the plating fluid flow in the hole is improved due to decreasing the hole depth. The different plating thickness between the entrance and the bottom, which is shown in Fig. 14(b), cannot be seen in Fig. 17. Therefore, we draw attention to the diameter $D_2$ at the hole bottom, and investigate the relationship between the aspect ratio $t_2/D_2$ and the plating thickness ratio $t_2/(plating$ $thickness$ $at$ $the$ $entrance$). Figure 18 indicates the results. Provided the $t_2/D_2$ is less than 0.5, the plating thickness ratio indicates about 1. The plating thickness remains approximately constant from the entrance to the bottom. Provided the $t_2/D_2$ is about 1, the plating thickness decreases to about 0.5. It is confirmed that the metallization of the build-up layer for blind holes depends on the aspect ratio between the layer thickness $t_2$ and the hole bottom diameter $D_2$.

5. Conclusions

(1) Complete blind via holes can be formed with appropriate laser energy, which can remove the build-up layer and be reflected by the copper foil. It is confirmed that the small power laser with 50 W makes it feasible to form blind via holes for the practical thickness of an AFRP layer.

(2) Blind via holes without black damage around
the hole wall can be obtained for the AFRP build-up layer by means of a 50 W laser beam.

3) Plating is difficult on the laser drilled hole wall at the bottom, because the laser drilling causes an decrease in the hole diameter and an increase in surface roughness at the bottom.

4) The uniformity of plating blind via holes can be predicted by the aspect ratio between the layer thickness and the hole bottom diameter.

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