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CO₂ LASER DRILLING OF MICRO-VIA WITHOUT CONFORMAL MASK IN PCB MANUFACTURE

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Abstract

In order to ensure that the laser remains at the forefront of micro-via forming in the future, many new laser technologies are being investigated by PCB manufacturers for high-density interconnect (HDI) printed circuit boards. As there were limitations of etching small micro-via size and registration in conformal masked laser drilling method, copper direct drilling by laser irradiation has been developed as an alternative. This research work was studied on the difference between several surface treatment processes for enhancing the laser absorptivity of copper, and reducing the thickness of the copper layer by chemical means in laser drilling technology. Also, the effect of critical laser drilling parameters and dielectric material properties were studied in this paper. It was shown that unreinforced and pure resin epoxy material was better in laser ablated microvia manufacturing. The laser absorptivity of copper and copper thickness were very critical factors for implementing copper direct laser drilling technology successfully in printed circuit board industry. By using same laser energy, better hole size and shape was achieved by oxide replacement process (Multibond) which showed higher surface roughness Ra, 0.5606 μm and grain structure among the oxide surface treatments in this study. It was found that 5-7 μm copper thickness was more suitable and achievable for controlling micro-via hole size and shape in CO₂ copper direct laser drilling.

1. Introduction

Micro-via drilling using laser technology has become more and more important for manufacturing high-density interconnect (HDI) printed circuit boards. It is necessary to develop and apply another CO₂ laser drilling technique without etching via patterns in advance, in which it eliminates the registration of imaging process and limited etching capability in conformal mask drilling. Drilling the copper layer by direct laser irradiation is a promising alternative. However, absorption of laser energy in the thick copper layer on conventional PCBs is poor due to the high reflection of copper at 9.4 μm wavelength of CO₂ laser. Therefore, research work has to be carried out on different surface treatment processes to improve the surface topography of copper, and reducing the thickness of copper layer by chemical means for enhancing the

laser absorption of copper. In this research project, the copper direct laser drilling technology will be studied with regard to different aspects such as dielectric materials used, laser absorptivity on copper surfaces, as well as critical characteristics of laser drilling technology. The study concentrated on copper direct drilling by CO₂ laser only because UV-YAG or other lasers have already been proven to have good performance and to have the capability to drill copper directly in PCB micro-via manufacturing. However, as the CO₂ laser drills holes in resin materials four to five times faster than the UV/YAG laser, it is worth investigating CO₂ laser drilling for drilling both resin and copper, due to its higher speed and lower cost.

2. Experimental Method

A Mitsubishi CO₂ laser drilling machine (ML605GTXII) was used in the experiments. The maximum rated power and maximum pulse peak power of the laser is 100W and 10KW, respectively. The frequency varies from 10 to 1000Hz. The pulse width is ranging from 1 to 15 μs . This model of CO₂ laser drilling machine has a high productivity and wide application range in the PCB micro-via industry. The principal processing configuration (Figure 1) is that the beam oscillates from the CO₂ laser. It is then propagated through different collimation lenses and bending mirrors, which are located in the image transferring the optical system to the galvano section. At the galvano section, the lens is guided to the f θ lens by two mirrors. A mask is used to control the beam diameter for the processing point.

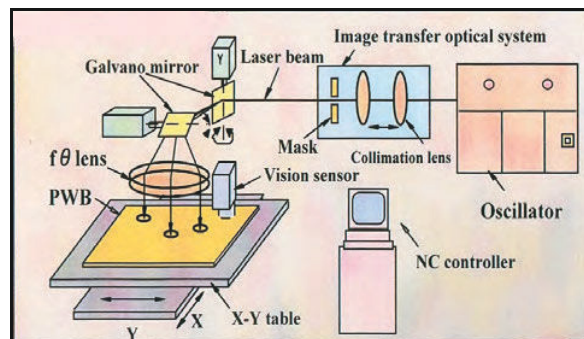


Figure 1 Configuration of CO₂ laser drilling machine (Mitsubishi ML605GTX II-5100U)

In this study, it was divided into three parts of experiments. The purpose of the first part of the experiment was to evaluate different dielectric materials by CO₂ laser ablation in terms of hole qualities which included hole shape, resin residue inside the hole, and the roughness of the hole walls. The testing materials included normal 1080 FR-4 prepreg, non-glass reinforcement laser drillable prepreg 1078, resin-coated copper foil with 65µm resin thickness, as well as Speedboard™ C prepreg (1.5mils thickness). The experiment would indicate which type of material would be more suitable for the rest of the research work. All the materials were drilled by the conformal mask method. The conformal mask method was used for this part of the experiment because the influence of copper thickness would be eliminated. The testing details were summarized in Table 2.

Table 2 First experiment summary (Comparison of laser ablation on different dielectric resin materials)

Testing Materials:	Normal FR-4, Non glass-reinforcement, Resin-coated copper (RCC), Speedboard C
Pulse width / Pulse energy	7µs / 12mj, 15µs / 25mj
Number of shots	1 - 3 shots
Micro-via diameter	3mils, 4mils, 5mils, and 6mils
Sample size	3 samples per test run
Holes per sample	20 x 20 holes per sample

The second experiment was conducted to study the effect of the surface pre-treatment process for enhancing the laser absorbance of copper surfaces. Black oxide and oxide replacement treatments from two chemistry suppliers were investigated for this study of copper direct drilling. The testing materials used for this part of experiment were resin-coated copper, MicroThin M-type and S-type with ultra-thin copper thickness, 3 micron. Therefore, the thickness and uniformity of copper over the dielectric materials would not affect the experimental results. The different oxide surface pre-treatments were performed on the copper surfaces of MicroThin S-type and compared with MicroThin M-type without any surface pre-treatment for CO₂ laser direct ablation. In order to simplifying the experiment conditions and to limiting the scope of experiment, only the pulse width and number of shots were varied and studied in this part of experiment. Since the energy per pulse of laser (E) is equal to the product of peak power (P) and pulse width (τ) (i.e., E=P τ), the pulse width was varied with pulse energy at a fixed peak power for this part of experiment. The laser absorbance of treated copper surfaces and the surface topography was evaluated. The critical processing parameters affecting the quality and reliability of the oxide coating were also analysed. The testing summary was shown in Table 3.

Table 3 Second experiment summary (Comparison of laser ablation on different oxide treatments)

Testing Materials:	Resin-coated copper (3µm Cu; 65µm Resin)
Surface treatment	Black oxide (MacDermid) Oxide replacement (MacDermid) Black oxide (Shipley) Oxide replacement (Shipley) No treatment (MicroThin M-type)
Pulse width / Pulse energy	6µs / 10.54mj ; 7µs / 12.14mj; 8µs / 13.75mj; 9µs / 15.36mj; 10µs / 16.96mj
Number of shots	1 shot, 2 shots
Micro-via diameter	3mils, 4mils, 5mils, and 6mils
Sample size	3 samples per test run
Holes per sample	20 x 20 holes per sample

Lastly, the critical and optimized processing parameters found in the last two parts were studied regarding to different copper thickness. Resin-coated copper (RCC) with 12µm Cu and 65µm resin thickness was used as the testing materials. In order to achieving the thickness, Surface Uniform Etching Process (SUEP) was applied to reduce the copper thickness of testing specimens and then processed by Multibond oxide replacement. The testing plan was summarised in Table 4.

Table 4 Third experiment summary (Comparison of laser ablation on different copper thickness)

Testing Material	Resin coated copper (12µm Cu; 65µm Resin)				
Surface treatment	Oxide replacement (Multibond)				
Micro-via size	4mils				
Sample size	1000holes per test run				
Test no.	Copper thickness (um)	1st Shot (mj)	2nd Shot (mj)	3rd Shot (mj)	Total Energy (mj)
1	5	6	2	2	10
2		8	2	2	12
3		10	2	2	14
4	6	10	2	2	14
5		12	2	2	16
6		15	2	2	19
7	7	19	2	0	21
8		21	2	0	23
9		23	2	0	25

3. Experiment Result and Discussion

3.1 Comparison Of Laser Ablation On Different Dielectric Resin Materials

In this part of the experiment, it was found that only one shot of drilling was not enough to drill the micro-via holes completely onto the inner copper pad for all the testing materials. For normal FR-4 prepreg (1080) and non-glass reinforcement laser drillable prepreg (1078), even though the pulse width and energy per pulse were doubled, the depth of the drill only increased slightly and some of the holes were still under-drilled. However, the increase of pulse width and pulse energy showed great improvement on the drilling the micro-via holes onto the inner copper pad for Speedboard C prepreg and resin-coated copper foil materials. All of the holes could be drilled completely onto the inner copper pad surface and had good tapered hole shapes.

According to the experimental results, it showed the depth of drill increased accordingly in general as the number of shots was increased to two shots. It was necessary to increase the number of shots in order to make sure all the resin was removed from the holes. It is also noted that too much energy delivered by the laser can yield a barrel shape, which is difficult in the electroplating process. It was found that only two shots of drilling provided enough energy to drill the holes completely for resin-coated copper (RCC) material while other materials needed more energy to do so. The result indicates that the energy control of laser ablation regarding to different resin materials is very important for micro-via drilling. Thus, different drilling processing parameters should be applied to the corresponding materials on a case by case basis.

In order to quantify the results of the experiment, entrance diameter, bottom diameter and taper angles of micro-via holes in different processing conditions were measured by Lecia microscope. The diameter ratio between the entrance and bottom diameters was defined to measure the shape of the hole. The ideal range of diameter ratio is 0.75 to 1.00. If the ratio is greater than 1, the shape of the hole may be that of a barrel or inverted-taper. The mean diameter ratios under different laser drilling conditions for corresponding materials were summarized in Figures 5 – 8. It was found that the mean diameter ratio of normal FR-4 prepreg was lower than that of other testing materials in all cases. It was indicated that the normal glass fabric epoxy FR4 prepreg has poor laser drillable ability due to material non-uniformity over the prepreg. The properties of glass are different from those of resin in the temperature of decomposition and the conductivity of heat. Also, it appears likely that both non-glass reinforcement prepreg and resin-coated copper have less variation of mean diameter ratio among all drilling conditions. The results proved that such dielectric materials would be more suitable as the testing materials for the other parts of experiment in this research project. In fact, resin-coated copper has been selected as the main testing materials for

the remainder of the experiments in this research due to its availability and extensive application in the market for the PCB industry.

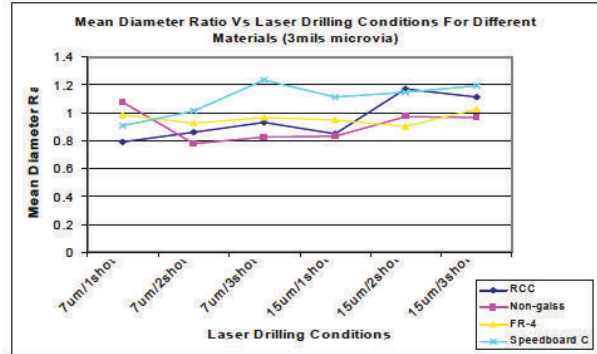


Figure 5 Mean diameter ratio vs. laser drilling conditions materials (3mils micro-via)

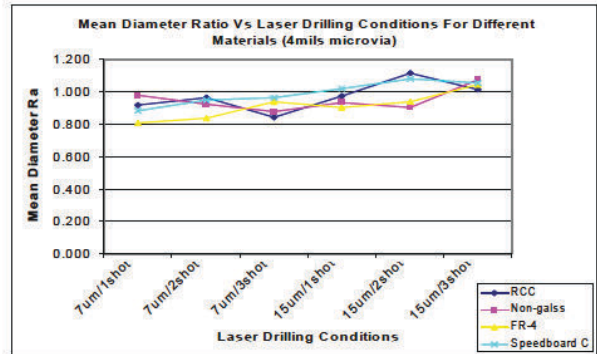


Figure 6 Mean diameter ratio vs. laser drilling conditions materials (4mils micro-via)

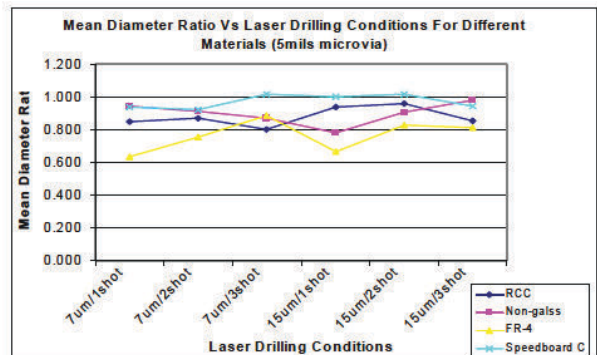


Figure 7 Mean diameter ratio vs. laser drilling conditions materials (5mils micro-via)

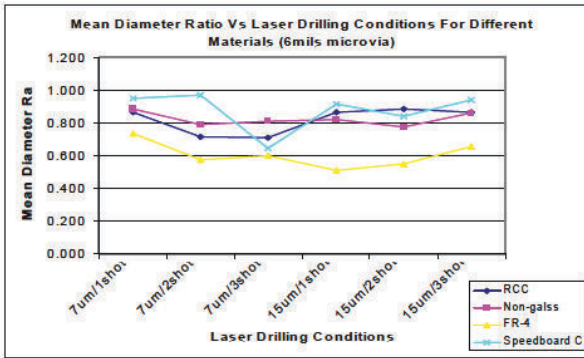


Figure 8 Mean diameter ratio vs. laser drilling conditions materials (6mils micro-via)

3.2 Comparison Of Laser Ablation On Different Oxide Treatments

It was found that the colours of the four oxide treatments under investigation are different in degree of darkness. As there was no suitable quantifying measurement of colour, the treated specimens were only be compared directly by visual observation (Table 9). It was noted that the colour of MacDermid black oxide process without post-dip treatment was in very dark black colour. The degree of darkness for other testing oxide treatments was also different in some extents individually. In general, the colour of black oxide treatment was darker in colour than that of oxide replacement due to the different process flow and different chemistry compositions. As the surface oxide treatments used in this research work were performed only for enhancing the laser absorbance on copper, the bonding reliabilities of treatments such as peel strength, for enhancing the adhesion between the prepreg and copper in the PCB lamination process were not be taken into detail consideration. The post-dip treatment was being skipped in black oxide process of MacDermid in order to increase the dark colour of treated surface for evaluation.

The surface roughness Ra of different oxide treatments were measured by the Form Talysurf surface texture contact-type measuring system. A diamond stylus was used to measure the surface roughness that travels along a straight line over the measured surface. As all the testing oxide treated surfaces are not reflective, the laser or optical interference measurement of surface roughness can not be performed on them. The measurements of surface roughness for different oxide treatments were summarized in Table 10. In fact, surface roughness can also be directly observed through scanning electron microscope (SEM). It was found that the surface roughness of oxide replacement, Multibond has the greatest value of Ra, 0.5606 μm among the oxide surface treatments in this research. All other oxide surface treatments in this study have nearly the same degree of surface roughness, Ra in the range of 0.2465-0.2523 μm . Only the black oxide treatment of Shipley showed lower surface roughness of Ra, 0.2106. According to the SEM photographs, it was observed that the grain structures of

different oxide treated surfaces also agreed with the surface roughness measurement results. Oxide replacement treatment, Multibond has larger grain size on the rough surface, whereas Shipley black oxide treatment has coarse and fine grain structure on the treated surface (Figure 11).

Table 9 Colour photos of different oxide treatments

Surface Oxide Treatment	Colour Photos
Black oxide (Shipley)	
Black oxide with post-dip (MacDermid)	
Black oxide without post-dip (MacDermid)	
Oxide replacement (Circubond) (Shipley)	
Oxide replacement (Multibond) (MacDermid)	
Without treatment (MicroThin M)	

Table 10 Surface roughness Ra of different oxide treatments

Surface Oxide Treatment	Ra (μm)
Black oxide (Shipley)	0.2106
Black oxide with post-dip (MacDermid)	0.2523
Black oxide without post-dip (MacDermid)	0.2519
Oxide replacement (Circubond) (Shipley)	0.2465
Oxide replacement (Multibond) (MacDermid)	0.5606
Without treatment (MicroThin M)	0.2232

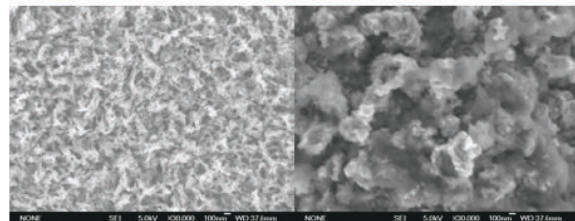


Figure 11 SEM photographs
Black oxide, Shipley (Left)
Oxide replacement, Multibond (Right)

By analysing the hole qualities after laser ablation, it was found that the CO₂ laser was not capable to drill through the copper surface of MicroThin M-type without oxide surface pre-treatment in the drilling of 6mils micro-via. It was indicated that oxide surface treatment had to be applied on the copper surface for enhancing the laser absorbance in copper direct drilling. It was also found that some of micro-vias in 5mils and 6mils hole sizes with different kinds of oxide surface treatments in this study have the under-drilled problem by using shorter pulse width and lower pulse energy laser conditions. According to the mean diameter ratios between the entrance and bottom diameter (shown in Figures 12 -15), oxide replacement process, Multibond has better result with value very close to 1.00. It means that CO₂ laser ablation on ultra-thin copper surface treated with more aggressive and higher topography oxide coating was possible and effective for micro-via drilling. In fact, the hole sizes, hole shape as well as hole wall quality drilled by CO₂ laser is a function of many factors such as pulse energy, pulse width, material properties.

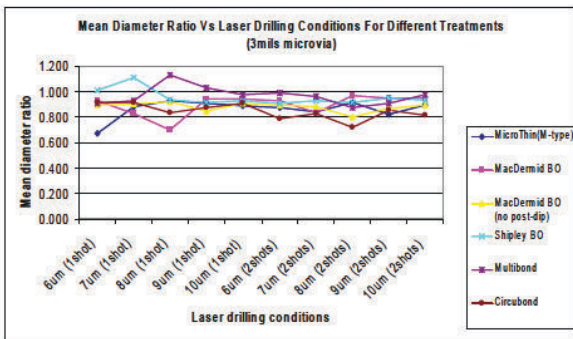


Figure 12 Mean diameter ratio vs. laser drilling conditions materials (3mils micro-via)

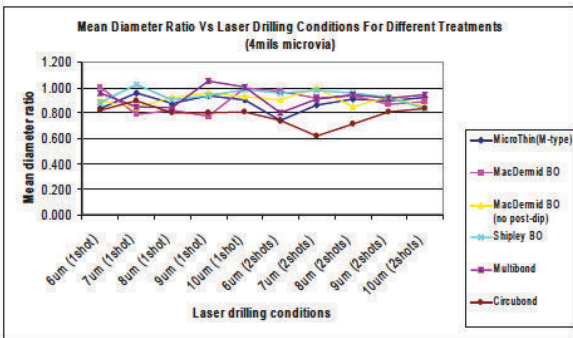


Figure 13 Mean diameter ratio vs. laser drilling conditions materials (4mils micro-via)

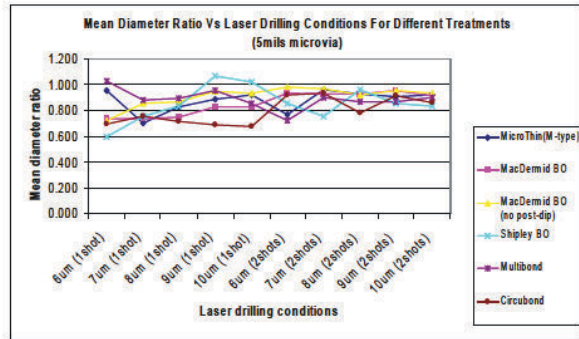


Figure 14 Mean diameter ratio vs. laser drilling conditions materials (5mils micro-via)

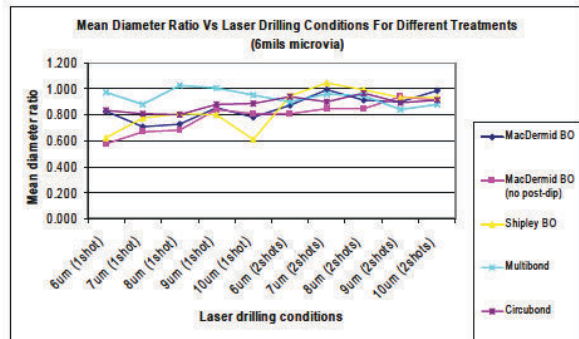


Figure 15 Mean diameter ratio vs. laser drilling conditions materials (6mils micro-via)

3.3 Comparison Of Laser Ablation On Different Copper Thickness

According to the experimental results for copper thickness 5 μ m, it was found the larger the energy of first shot, more burned copper burr around the hole onto the surface (Figure 16). However, if the energy was not large enough, the target diameter could not be achieved. In fact, the first shot was very important for burning off the thin copper layer and pre-forming the dielectric slightly. The second shot was used to form the hole shape and the required hole diameter. The third and last shot has to fine tune the hole wall and shape as well as to remove the resin residue on the inner copper pad. By increasing the laser energy of first shot for higher copper thickness, 7 μ m and 9 μ m, the experimental results showed that the energy required was not directly proportional to the thickness. Most of the holes were under-drilled by the laser ablation. The laser energy was not enough to remove the resin completely. Compared with the results for 5 μ m and 7 μ m copper thickness, under-cut of dielectric was found underneath of copper layer (Figure 17). It meant that the energy was not large enough to burn off the copper for achieving the 4mils diameter, but such energy was too large for drilling the resin dielectric. It was very difficult to control the hole shape and size in drilling 9 μ m the copper thickness by laser ablation. In fact, total energy, numbers of shot, energy per shot are very critical for the copper direct laser drilling. More detailed studies and experiments have to be performed to

find out optimum drilling conditions for the relative copper thickness.

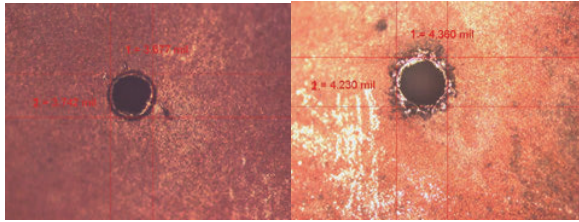


Figure 16 Holes by laser ablation 6+2+2mj (left); 10+2+2mj (right)

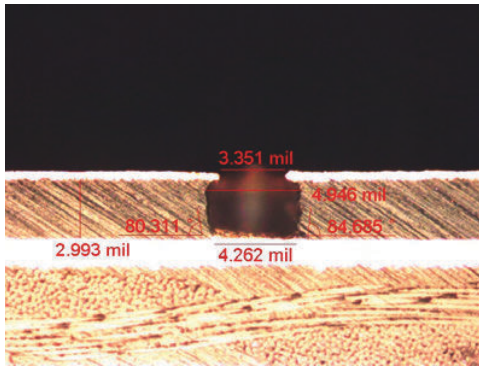


Figure 17 Cross-section of holes (9 μ m copper thickness) by laser ablation, 23+2+2mj

4. Conclusions

From the above experiments and analysis, the following conclusions can be obtained:

1. Unreinforced and pure resin epoxy materials such as resin coated copper (RCC) and laser drillable prepreg were better in laser ablated microvia manufacturing for PCB.
2. Surface oxide treatments available in PCB fabrication were proved the capabilities for enhancing the laser absorbance on copper. The degree of darkness for the oxide treatment has no influence on the laser absorbance of copper surface.
3. Amongst the different oxide treatments tested in the above experiment, Multibond of MacDermid showed better performance in laser direct drilling in term of hole quality and hole shape. It was mainly due to the more aggressive and higher topography oxide treated surface for enhancing the laser absorbance.
4. Ultra thin copper thickness ranging from 5-7 μ m was more suitable and achievable for controlling micro-via hole size and shape in CO₂ copper direct laser drilling. Total energy, numbers of shot, energy per shot are very critical factors and have to be optimized for successful micro-via forming by laser ablation.

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