Laser Drilling of a 7-layer Flexible Printed Circuit Board using a Pulsed Ytterbium Fiber Laser System

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Abstract: Recently, laser-processing industry is becoming increasingly popular because of its advantages of low cost, fast and good energy efficiency. The electric circuit board manufacturers also began to import related laser processing technology to improve the productivity. This paper presents the laser drilling process and quality analysis of the 7-layer flexible printed circuit (FPCB). A laser drilling system pulsed Ytterbium fiber laser, expander device, focal lens, galvanometric scanner and XY-axis manual stage was used to perform the hole cutting of the multilayer-layer FPCB. This study succeeded in establishing a comparing procedure, which enabled the characteristic comparison between the various experimental conditions. We believe that this study provides a useful database for FPCB drilling technology.

1 INTRODUCTION

Laser is a kind of modern light source, which emits light when a driving voltage is applied. The light is amplified by a process of the stimulated emission of electromagnetic radiation. The optical properties of laser are monochromatic, coherent, collimated and polarizable. In recent years, laser industry becomes increasingly popular because of the demand of high manufacturing efficiency for various products. Due to the advantage of high power intensity, long lifetime, low power consumption, good luminous efficiency, faster switching and small size, the laser technology has gradually replaced the traditional optical lighting and mechanical processing. Nowadays, laser has been widely used in optical measurement, precision machining, bio-treatment, image projection and versatile sample excitation applications (Malcolm, 2000) (Winco, 2000) (Han-Chao, 2015) (Surmann, 2003) (Seokbae, 2002). Among them, the most popular is precision machining. Due to the high collimation of the laser, the focused spot can be very small. In other words, the energy dose is quite high. The melting and vaporization processing can be carried out in a small area of the sample. It means that the resolution of laser processing is very high. The laser processing material is not limited to metal, and can be glass, wood, ceramics, plastic and paper. For the cutting, engraving or welding application, the typical lasers are CO2 laser, Nd:YAG laser, semiconductor laser and fiber laser etc. Recently, due to the rise of mobile devices, the demand for laser-processing the small circuit boards is rapidly growing. Therefore, the electric circuit board manufacturers also began to import related laser processing technology.

For the printed circuit board manufacturing industry, laser direct cutting and drilling is the most popular (Ching-Ching, 2017) (Hsin-Yi, 2016) (Kestenbaum, 1990) (Avanish, 2008) (Winco, 2007) (Reinhart, 2010) (Owen, 1998). Because the novel printed circuit board has high conductive wiring density, small holes and contacts, the resolution of the traditional mechanical processing is obviously insufficient. Also, mechanical cutting is also easy to damage the printed circuit board. The most common samples recently are soft-matter printed circuit board and high density inter-connect (HDI) printed circuit board. In order to improve the processing accuracy and stability, laser ablation gradually replaced the mechanical processing. Laser ablation has the advantages of simple, high-resolution and rapid. It cannot only accurately control the ablation depth and the size, but also prevent overheat and maintain the results quality. The type of laser light source can determine the ablation characteristic. For example, because the power of CO2 laser is very high, the action of laser ablation is rapid. However, its long wavelength leads to low resolution. Therefore, this

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kind of light source is only suitable for the processing with a resolution greater than 100 µm. On the contrary, although the UV laser has very high resolution and low energy consumption, the light source and related devices are extremely expensive. Even if the resolution can be better than 50 µm, it is a big burden for the manufacturer. For common laser ablation, YAG laser is the relatively suitable light source that well balance the resolution and instrument cost. Through the appropriate optical lens, the ablation resolution of the laser can achieve between 40 to 100 µm. All the pattern formation is performed by the galvanometer mirrors, so the ablation speed is very fast. Various materials and combinations of printed circuit boards have individual laser processing parameters, so the optimization procedure is very important. The printed circuit board manufacturers have to master the related know-how for the laser processing to maintain the competitiveness of production.

This paper presents the pulsed laser drilling process and quality analysis of the multi-layer flexible printed circuit (FPCB). A scanning laser drilling system composed of a pulsed Ytterbium fiber laser, optical expander, galvanometric scanner and XY-axis motorized stage was used to perform the blind-hole cutting for the multi-layer FPCB. The sample is a FPCB cross-stacked with black-oxide copper, cupper and epoxy coated glass fabric. The machining target is a perfect blind hole that has two layers depth. This study succeeded in establishing a comparing procedure of processing parameters, which enabled the characteristic comparison between the profiles of the drilled hole in various conditions. The morphology of the laser-drilled holes was measured by an optical microscope with 20X objective lens. By numerical analysis, the proposed amendment to the laser drilling process is able to achieve an optimal balance between process efficiency and hole quality. The laser drilling system was used to perform the hole cutting with hundreds of processing parameters. With the optical observation of experimental results, the morphology and profile of each laser-drilled holes would exhibit their individual characteristics. Following the numerical analysis, the amendment to the laser drilling process could be proposed to achieve a good shape that has minimal carbonization and thermal influence. We believe that this study provides a useful database for FPCB drilling technology.

2 EXPERIMENTAL SETUP AND SAMPLE PREPARTION

Figure 1 shows the experimental setup of the scanning laser drilling system for the laser drilling of multi-layer flexible printed circuit board. The system composed of a pulsed Ytterbium fiber laser, expander device, focal lens, galvanometric scanner and XY-axis manual stage. The wavelength and maximum power of the laser source are 1064 nm and 30 W, respectively. The working distance of the lens is 152.6 mm and the scanning range is 80 × 80 mm2. All optical and electronic components were precisely positioned through the designed metal mechanisms. The photodiode and power meter were used to measure the average power of laser with various parameters before conducting the drilling process. The estimated value of spot size is about 81 µm, and the depth of field is about 4,256 µm. The effective laser processing area could be directly defined by the graph inputted into the software. A laptop connected with the control circuit board was used to interactively drive the laser to perform the hole cutting of the samples.

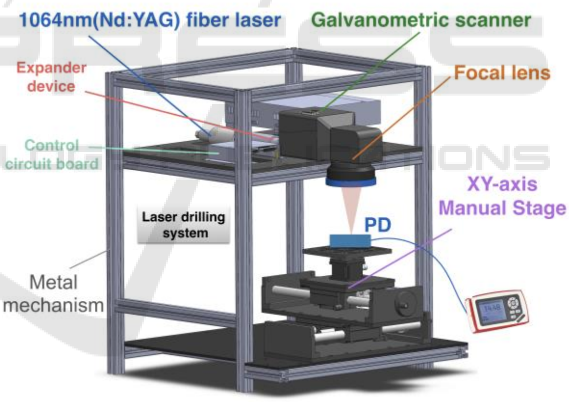

Figure 1: Experimental setup of the laser drilling system.

Figure 2 shows the relationship between the pulse frequency and relative peak power of the laser source. The values of peak power were calculated by dividing the pulse frequency and time duration from measured average power. The various duty cycles for laser driving are represented by the various color curves. From the figure we can see that the maximum peak powers of the laser occur at the pulse frequency of 90 KHz. The peak power is rapidly attenuated from 90 to 1000 KHz, and the difference is small after 1000 KHz. Also, the light intensity is relatively unstable at pulsed frequency below 60 KHz. Therefore, the suitable parameters for laser drilling are between 60 ~ 1000 KHz.

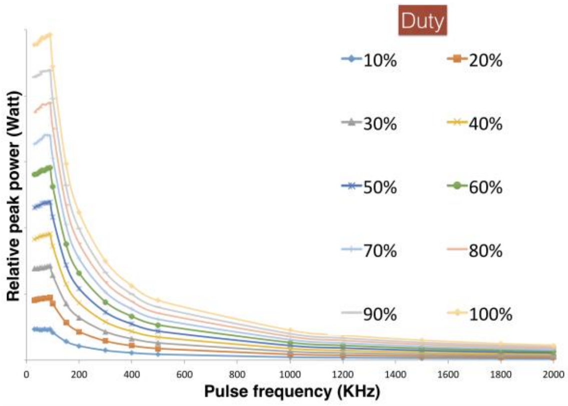

Figure 2: The relationship between the pulse frequency and relative peak power of the laser source.

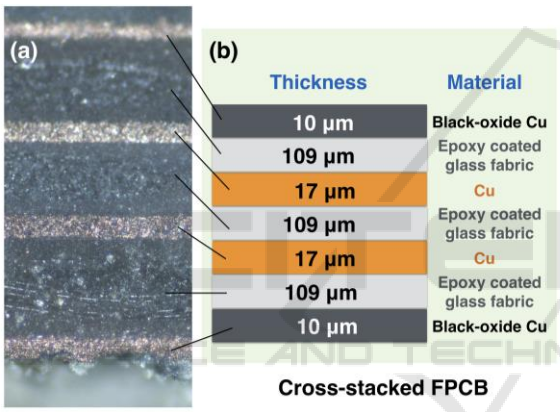

Figure 3: (a) The cross-sectional image and (b) Structural diagram of the cross-stacked FPCB.

The sample for laser drilling was a FPCB cross-stacked with black-oxide copper, copper and epoxy coated glass fabric, as shown in figure 3. Figure 3(a) is the cross-sectional image of the sample measured by the optical microscopy. The thickness and the material of the cross-stacked FPCB are shown in figure 3 (b). The top and bottom layer are 10 μm thick black-oxide copper. The dielectric layers are 109 μm thick epoxy coated glass fabrics. The inner conductive layers between dielectric layers are 17 μm thick coppers. The cross section of the sample is formed by the cutting of a diamond knife, therefore the softer copper layer will be pulled and cause it to look thicker in figure 3 (a). Also, the transverse direction glass fabric can be seen at the bottom layer of the dielectric layer. Before the laser processing, the surface of the sample should be cleaned carefully with alcohol. The particles on the sample surface can lead to laser processing errors. As the sample is softer, it is easy to warp and deformation. A mount was made to effectively hold the sample and maintain that the sample surface accurately located on the focal plane of the laser. The stability of the laser processing has been verified before the start of the experiment.

3 RESULTS AND DISCUSSION

The parameters for laser drilling are very diverse, including the duty cycle, pulse frequency, the number of shots, the delay time and trepanning speed, and so on. Each parameter will have an impact on the machining process. Before starting laser drilling, the laser focal plane must be positioned on the surface of the FPCB to maximize the efficiency of laser ablation. The adjustment of the focal plane (z-axis) was achieved by the beam expander in the system, rather than the use of a mechanical movement stages. As the focal spot of the laser is relatively small, so to achieve 100 μm drilling must use the trepanning method. Before that, we must first understand the relationship between the size of the hole and the machining parameters when the FPCB is directly drilled without trepanning. Figure 4 shows the optical images of the laser-drilled results. In order to achieve thru-holes, the higher peak power of laser must be used. The duty cycle of laser is 50%, the pulse frequency is 50-110 KHz, and the number of shots is 1000 shots. The green words indicate the aperture size of the thru- hole, and the black words represent the surface ranges of the FPCB affected by the heat damage. Although the spot size of the laser is about 81um, only the central part of the higher energy area can effectively ablate the FPCB materials. It can be found from Figure 3 that the laser processing energy is highest at the frequency of 90 kHz. Corresponding to Figure 4, the hole is relatively larger and the diameter is about 41um. The farther the pulse frequency from 90 KHz, the smaller the hole. It can be estimated that the minimum thru-hole size drilled by the system is about 20 μm. The processing quality around the circumference of the hole also needs to be concerned. If the heat damages are too large, it will often cause the unpredictable problems while the FPCB was used. After comparing the contours of each hole, it could be found that the better thru-hole which has balance ratio of inner and outer diameter occur at the pulse frequency of 90 KHz. Although the smaller holes have better resolution, the heat-affected regions did not correspondingly become smaller.

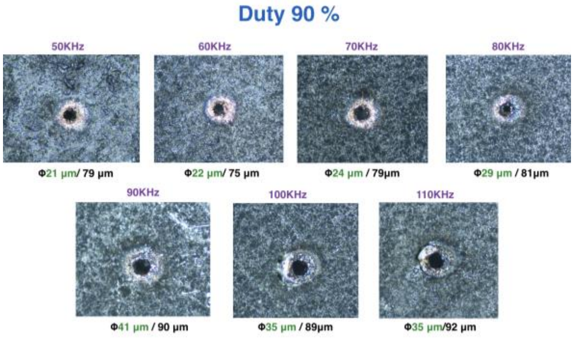

Figure 4: Optical images of the holes by directly laser ablation without trepanning.

In order to perform a 100 μm aperture laser drilling, the trepanning procedure is required. The correct trepanning method can effectively make the hole size increase and maintain the circle shape. We must first understand that whether the various trepanning methods will have impact on the shape of the hole. Figure 5 shows processing results using five kinds of trepanning mode, including two-way, one-way, lateral and vertical progressive scanning and snail-like trepanning. In the software, the input hole size images are 50 μm, 80 μm and 100 μm. Because the actual drilled hole size is always greater than the settings size, the input hole size images should be less than 100 μm to achieve a just 100 μm size hole. In order to achieve thru-hole, the higher peak power of laser was used. The duty cycle of laser is 80%, the pulse frequency is 90 KHz, and the number of shots is 1000 shots. From the figure you can see the holes are not perfect round. The reason is that the surface of the black-oxide copper of the FPCB is quite rough, and the glass fabric weaving in dielectric layer is randomly distributed, so the uniformity of laser processing cannot be perfect. In figure 5, it could be found that the 50 μm hole size image will form an actual hole with about 78 um diameter, which is enlarged by 1.56 times. The 80 μm hole size image will form an actual hole with about 100 μm diameter, which is enlarged by 1.25 times. That is also the hole size what we expect. The 100 μm hole size image will form an actual hole with about 116 μm diameter, which is enlarged by 1.16 times. In other words, the larger the hole size setting image will generate a hole which is closer to the actual drilling hole size. This phenomenon may come from the effect of the resolution of the laser spot. In addition, the use of 50 μm hole size image setting will generate a diamond-like shape. This problem may come from the resolution limit of the galvanometer mirrors. Therefore, using a larger hole size image for laser drilling setting may easily achieve a perfect round hole. However, the current processing results only like a relatively round pentagon.

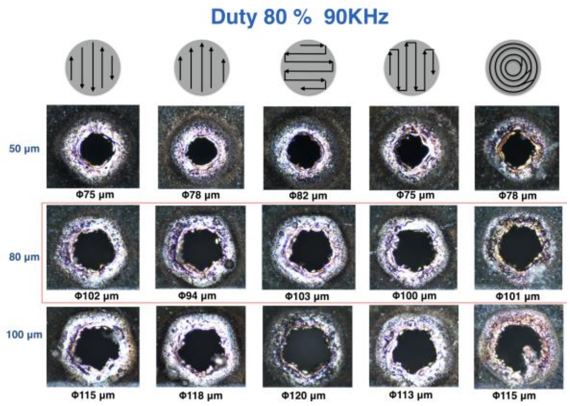

Figure 5: Optical images of the holes drilled by various trepanning modes and setting hole sizes.

Theoretically, the higher the peak power will be easier to penetrate through the FPCB. But in fact it needs to match the trepanning speed and other conditions. In order to quickly understand the drilling results with using various peak power and pulse frequency, a laser-drilling array method was used to quickly help us to find the appropriate range of parameters. Figure 6(a) shows the array pattern with various parameters for image setting in the system. The trepanning mode is snail-like and the hole size is 80 μm. The vertical axis is the pulse frequency from 10 to 2000 KHz, and the horizontal axis is the duty cycle from 10 to 100%. Figure 6(b) shows the actual hole array after laser machining. In order to confirm whether the parameters can achieve the thru-holes, in uniform white light was used to illuminate the sample from the back. As long as the FPCB has been penetrated, a light spot would be observed. It can be found that the higher pulse frequency part will cause serious thermal effect around the holes. The external qualities of the holes are totally bad. The formation of thru-holes falls in areas of high peak power. Some holes have particularly large light spot may not because the hole size is larger. Because the sidewalls of the hole have less scattering impurities (such as glass fabric residues) will also increase the amount of transmission light. The actual hole still needs a high magnification microscope to directly observe and qualify.

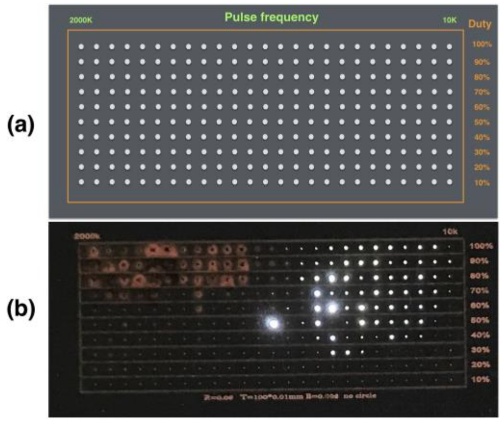

Figure 6: Set pattern and actual hole array after laser machining with various duty cycle and pulse frequency.

After selecting the hole size image of 80 µm for setting, an actual hole size of about 100 µm can be successfully formed. It is necessary to understand the processing parameters that can form a thru-hole or blind-hole, and whether the holes size will change correspondingly after drilling. Figure 7 shows the laser drilling results of FPCB using the previously optimized parameters: snail trepanning with 80 µm hole size image setting. The variables are the laser duty cycle and pulse frequency. In order to easily observe the actual peak power difference of the laser, figure 3 is narrowed down and embedded to the top of the Figure 7. The corresponding pulse frequencies are marked by dotted lines. The actual peak powers of the laser with 10% duty cycle are labeled as A-1, A-2, A-3 and A-4 at pulse frequency of 80, 200, 400 and 1000 kHz. The actual peak powers of the laser with 40% duty cycle are labeled as B-1, B-2, B-3 and B-4 at pulse frequency of 80, 200, 400 and 1000 kHz. The results show that the drilled hole size can be controlled in the vicinity of 100 µm regardless of the value of the laser duty cycle and pulse frequency. Due to the uncertainty of the measurement and the non-uniformity of the FPCB material, the deviation of about 10 µm should be accepted. The peak power below the B-1 level can ablated the surface of the black-oxide copper of the FPCB, However, it cannot effectively achieve broken copper of the first layer. Due to the effect of the snail trepanning, the edge of the hole will have a dark ring. It indicates that the areas were ablated slightly. Although A-1 and B-3, A-2 and B-4 have similar peak power, however the qualities of the holes are totally different. The reason is that the different pulse frequencies would cause different drilling overlapping under a fixed trepanning speed.

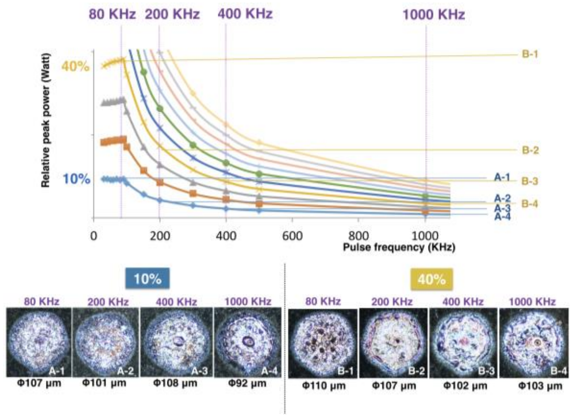

Figure 7: Laser drilling results using 10% and 40% duty cycle at pulse frequency of 80, 200, 400 and 1000 kHz.

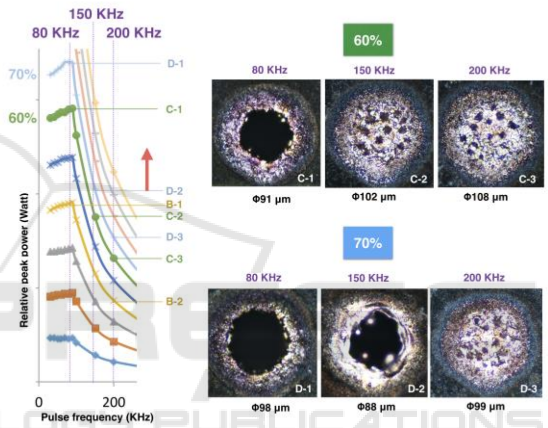

Figure 8: Laser drilling results using 60% and 70% duty cycle at pulse frequency of 80, 150 and 200 kHz.

Under the same drilling parameters, figure 8 shows the drilling results with higher duty cycle. Since the pulse frequency above 400 KHz cannot provide an enough peak power for thru-hole generation, the pulse frequency parameters are changed to be 80, 150, 200 kHz. The duty cycles are raised to be 60% and 70%. Figure 3 is narrowed down and embedded to the left of the Figure 7 and the corresponding pulse frequencies are also marked by dotted lines. The actual peak powers of the laser with 60% duty cycle are labeled as C-1, C-2 and C-3 at pulse frequency of 80, 150, 200 KHz. The actual peak powers of the laser with 70% duty cycle are labeled as D-1, D-2 and D-3 at pulse frequency of 80, 150, 200 KHz. The results still demonstrate that the drilled hole size can be controlled in the vicinity of 100 µm regardless of the value of the laser duty cycle and pulse frequency. With the validation of microscopic images and backlighting observation, 100 µm thru-hole will generate when the laser peak power is higher than D-2 (red arrow). A lot of tiny pores were gradually formed on the hole surface if the laser peak power is between B-1 and C-3. The depths of these holes are about 1 to 2 μm only. It means that only the surface of the black-oxide copper is ablated away. The result also indicates that using the laser with peak power higher than D-2 level and reducing the number of shots could achieve the various blind holes. The laser with peak power lower than B-1 cannot form the blind holes even if the number of laser shots is increased.

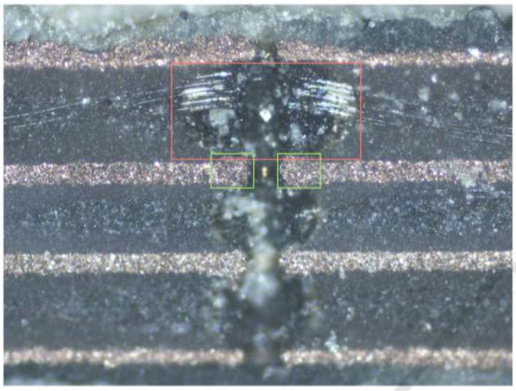

Figure 9: The cross-sectional image of the drilled thru-hole measured by an optical microscope.

Figure 9 shows the cross-sectional image of the drilled thru-hole measured by the optical microscope. The laser drilling parameters are: duty cycle of laser is 80%, the pulse frequency is 90 KHz, and the hole size image for setting is 80 μm. By optical alignment using a digital microscope, the diamond round knife can be precisely positioned on the hole middle for cutting the hole in half. As the mechanical cutting will pull copper layer, it will cause hole shrinking in metal layers, as shown in the green square area. Although the use of grinding method can achieve a smoother cross-section of FPCB, the time cost and failure rate are too high. Figure 9 shows that the laser-drilled thru-hole has a shape like a calabash. Because of the trepanning processing, a lot of shots and the focal plane of laser located on the surface of the FPCB, the heat will concentrate on the first and second layer around the hole region. The copper has better thermal conductivity, therefore the glass fabric layer will occur expanded ablation, as shown in the red square area. The laser-drilled hole can be control as a 100 um size, however, the exit need to rapidly discharge the scraps. The hole at the other side will burst and form a larger hole. The size is about 1.6 to 2 times of original hole. We believe that the quality of hole sidewall can be further improved by turning the better processing parameters. A better way should be a gradual trepanning down process that can maintain the hole size even in the different depth. For further experiments, we will work in this direction.

4 CONCLUSIONS

This study succeeded in developing a simple, rapid and relative accurate method for the quality analysis of the laser-drilled hole on flexible printed circuit. An laser drilling system system equipped with 1064 nm pulsed Ytterbium fiber laser, optical expander, galvanometric scanner and XY-axis motorized stage was used to perform the hole cutting with many kinds of processing parameters. With the optical observation of experimental results, the size and shape of each laser-drilled holes would exhibit their individual characteristics. Both the through and blind holes can be successfully formed. Following the numerical analysis, the amendment to the laser drilling process could be proposed to achieve a ideal hole shape, minimal carbonization and thermal influence. This system is compatible with most laser-drilling experiment and can be used for multi-layer FPC. This study provides a useful database for FPCB drilling technology.

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