A Review on Drilling Printed Circuit Boards

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Key word: Drilling; PCB; Review

Abstract: Drilling is one of the most complicated machining process, and it becomes much more complicated when the workpiece is printed circuit board (PCB) which is composite material with anisotropy. Only a small defect may cause great losses. Numerous studies have been conducted on both the drilling process and PCB structure design, but the investigations into the drilling processes of PCB are not systematic. The present review article addressed the report about tool materials and geometrics, force, temperature and radial run-out occured in drilling processes and damages in drilling. And as a conclusion, some of these critical issues are proposed to meet the challenges in analysis and optimization for drilling PCB.

1 Introduction

In recent years, the production of printed circuit boards (PCBs) has not only increased in quantity but also improved in quality. The high packaging density of PCBs is required to be improved and miniaturized. For instance, from the point of view of the public, the downsizing of televisions and telephones has made it possible to change these from stationary to portable devices. Thus, high-quality micro-machining is necessary for PCBs.

The basic materials forming a board are an epoxy glass mix, made by impregnating rolls of woven glass cloth with resin, and sheets of copper foil which are used to make the electrical connections [1]. A typical board may have multiple alternate layers of epoxy glass and copper foil, manufactured by squeezing in a large hydraulic press. The board will not become a circuit until connections are made between the different copper layers and when the discrete electrical components are soldered or welded in place. Thus, through hole drilling is one of the fundamental processes required in the manufacture to produce an electrical connection between the circuits on the board.

Drilling is one of the most complicated machining processes, and it becomes much more complicated when the workpiece is printed circuit board (PCB) which is composite material with anisotropy. Tool trends to wear and break. The accuracy of hole location, the presence of entry and exit burrs, smear of resin on the sides of holes and delamination and so on may affect the integrity of the connections made by plating the drilled holes. Only a small one of these defects may cause great losses. In order to overcome these problems, numerous studies have been conducted on both the drilling process and PCB structure design, but the investigations into the drilling process of PCB are not systematic. The present review article addressed the report about tool materials and geometrics, force, temperature and radial run-out occured in drilling process and damages in drilling. And as a conclusion, some of these critical issues are proposed to meet the challenges in analysis and optimization for drilling PCB.

2 Tool materials and geometrics

2.1 Tool materials

High speed steel (HSS) and tungsten carbide (WC)are mostly used as tool materials for the drilling of composites, while polycrystalline diamond (PCD) is less frequently tested [2]. Carbide tools yield good results in terms of tool wear and tool life during the machining of GFRP [3].

Carbide drills are manufactured using powdered metallurgy technology [4,5]. Micro-fine (less than one micrometer) tungsten-carbide and cobalt powders are formed into blank and sintered. In this process the blanks are subjected to extremely high pressures and temperatures. The sintering temperature is high enough to melt or flow the cobalt in the powdered mix which acts as the binder for the tungsten-carbide base material. Bit geometry is formed on automated grinding machines. The coblat content of small diameter drills, less than 0.50mm, is generally increased from 6 percent to 12 percent for improved toughness. In smaller diameters, micro-fine powders with particle sizes less than one micron are used to improve wear resistance.

2.2 Tool geometrics

Tool geometrics is a relevant aspect to be considered in drilling PCBs, particularly when the quality of the machined hole is critical. Figure 1 [6] is a drawing of a typical solid carbide bit used in printed circuit board drilling. Various aspects of bit geometris are noted in the figure. Several features of the geometrics are unique to printed cricuit board bit design. PCB drills generally have a point angle of approximately 130°. The helix angle is generally 30° to 35°. Two relief angles are commonly used on the back side of the lip or cutting edge. The diameter of the bit is usually relieved behind the margin. The diameter of most bit are back tapered to reduce side wall friction during drilling. A spade design is commonly used for larger diameters to reduce side wall friction. The diameter of the bit is sharply reduced a short distance from the tip forming a spade head. Most drills taper out from the base of the flute end to a shank approximately 3.18mm in diameter.

The diagram of the microdrill and its characteristics are shown in Fig. 2 [7]. The cutting plane (also called first facet or lip relief plane) is consisted of four edges, of which the cutting lip and chisel edge are two important cutting edges on the first facet. The centering point is the first contact point of a microdrill with the material surface, and cutting lips are the major cutting edges for material removal. Chisel edges are comprised of two intersecting planes that define two primary cutting edges of the microdrill. They remove the material by extrusion and cut at a highly negative rake angle.

Cemented carbide drills which is generally shaped by grinding are commonly applied in PCB drilling. At present, drills with diameters down to 0.1mm and less are commercially available but their reliability in the computer numerically controlled (CNC) machines used for PCB drilling decreases significantly as the size reduces from 0.25 to 0.1 mm [1]. Since 1984, Kosmowski , Kang, Ehmann and Chyan, etc. have done systematic researches on microdrill. Kosmowski [8] indicated that the reduction in diameter increases drill flexibility and reduces the strength of the bit. Small diameter bits are used in dense packaging formats where accuracy is critical. As the drill diameter is reduced, it approaches the size of inhomogeneities in the stack causing significant bit wander in deep holes.Kang [9] established a mathematical models for the planar microdrill point

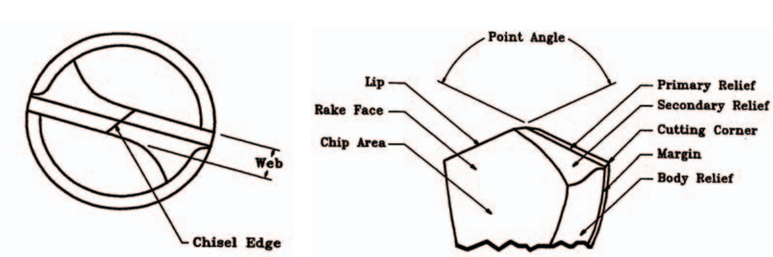

Figure 1 Drill bit terminology [6]

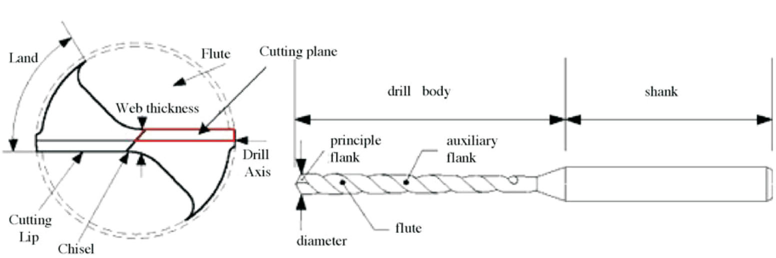

Fig.2. Schematic diagram of a microdrill [7]

and developed its grinding method. Chyan [10-12] designed a curved helical microdrill point and established its mathematical models and grinding systems in computer. It's found that curved helical microdrill is much better than planar microdrill in grinding and cutting characteristic. Zhou [13] established a mathematical model of the helical flute of microdrill and developed a CAD system of helical flute (0.4mm in diameter). Xiang [14] proposed a regrinding method for microdrill (diameter: 0.3~0.5mm).

3 Drilling process

3.1 Methods of drilling

Drilling is one of the basic, most frequently performed, machining processes. Several methods are used for producing micro-holes including conventional punches and dies, electrical discharge machining (EDM), vibration drilling, laser machining, etc. [15-18].

Electrical discharge machining can be used for graphite-epoxy laminates since the graphite fibers are electrically conductive. Note that high currents and high temperatures are produced which can cause severe melting of the composite surface, thermal expansion of the graphite fibers in the lateral direction and debonding between fibers and the matrix. The production rate of an electrical discharge machine is slow [19].

Vibration drilling is a branch of vibration cutting, which is fundamentally different from conventional drilling. The conventional drilling is a continuous cutting process, while the vibration-assisted drilling is a pulsed intermittent cutting process by piezoelectric crystal oscillator. Vibration thrust and torque are smaller than conventional values by 20-30% under the same drilling condition [18,20]. Although vibration drilling [16-18] can avoid burr and improve cutting stability, there are still a lot of problems to conquer.

Laser machining is a process that no contact between the tool and the workpiece, and it eliminates the delamination. Laser drilling [21, 22] is being developed as a solution for smaller hole sizes, but there are also problems associated with the process. A PCB is made up of three materials-copper, glass fibres and resin, which have very different material and optical properties. This makes it difficult for a laser beam with particular characteristics to cut cleanly and efficiently through the board. The hole produced by a laser in a standard PCB is sometimes tapered. Also, very small holes produced by laser have been limited to a depth equivalent to the diameter. The main use of lasers is seen to be for small blind and buried vias.

In order to produce through-holes in MPCBs, the main area of interest in the present research, only mechanical drilling is favorable as hole depth increases, because of the need for high accuracy low temperatures and deformation forces in order to produce high quality holes on a glass-epoxy composite board known as the FR-4 board [23,24].

3.2 Thrust force and Torque

In a drilling process, the drill and workpiece have a relative motion along with the axis of the hole so that the surplus material is removed. To generate and maintain the relative motion, a thrust force and torque are applied to the drill.

In early work, Boston and Gilbert [25] examined the forces on a drill, end-load and torque, depend on cutting conditions. Then, many authors [26-28] have subsequently investigated how forces depend on drill geometry. A general conclusion is that end-load largely depends on the chisel edge, while most of the torque contribution comes from the cutting action of the two main cutting edges. Man Sheel Cheong [29] indicated that when drilling holes with a large aspect ratio, the cutting forces acting on the drill bit increase as the drill penetrates the workpiece. The chip produced during cutting is the primary cause of this increase, since it increases friction between the flute and the cut surface of the workpiece. Hinds [1] indicated that drill forces, comprising an end-load and a torque, depend upon the process conditions and the composition of the material being cut. Force trends associated with wear, glass content, chip-load and aspect ratio are presented together with an indication of the contribution from the copper layers. Yang [30] built a real-time monitoring system of micro-hole drilling force based on neural network.

3.3 Bit temperature

When drilling, temperatures usually exceed the glass transition temperature of adhesive matrix in the laminate base material[6]. Drilling temperature usually increases with wear of the bit. Gross defects such as land tear out are common at high drilling temperatures. Lands are small copper rings in conductive planes that surround plated holes and provide the connection between the holes and circuit traces that radiate from the holes. Prior researches [31-33] have shown that drilling significantly affects the quality and reliability of plated hole connections. Many defects in plated holes are related to the thermally sensitive nature of the lamina used in modern circuit boards. Di Ilio [34], Jain S [35] and Chen W S [36] considered that problems occur if temperatures in the work material are allowed to rise to too high a level. The difference in the coefficients of linear expansion between the resin and fibres gives rise to residual stresses which makes it more difficult to attain high dimensional accuracy, with drilled holes showing a smaller diameter than the drill used. Bolton Robert William[6] developed a suitable on-line measurement system with an infrared pyrometer, documented sensor responses and evaluated the sensitivity of temperature while drilling printed circuit board stacks.

3.4 Radial run-out at the drill tip

Ultrahigh rotational spindles have been developed for higher precision and productivity drilling with smaller microdrills. PCB manufacturers can use commercial spindles rotating as high as $3x10^5$ min^{-1} or more. However, high rotational speed might cause a radial run-out at the drill tip.

Hidehito Watanabe [37] observed the drilling behavior at contact with a work surface using a high-speed video camera (drill diameter is 0.1mm, rotational speed is $3x10^5$ min^{-1}). He concluded that: (1) Orbital revolving drills with the radial run-out substantially move toward the centripetal direction, just after starting contact with a work surface. (2) The entry sheet effectively intensifies the centripetal action. (3) The radial run-out is insensitive to drill wear as well as hole quality, because of the centripetal action. A radial run-out at the drill tip might deteriorate hole quality, such as hole location accuracy or surface roughness on a hole wall.

4 Damage of drilling

4.1 Tool wear

The high packaging density of PCBs requires smaller size drills to be produced. But the smaller size drills are inherently more prone to wear severely and its life and reliability are decreasing sharply. Shorter life and tool change more frequently have become a bottleneck of PCB industries.

A worn-out microdrill damages the quality of the surface finish and the dimensions of the drilled hole. Tool wear not only reduces the part geometry accuracy directly but also increases the cutting forces drastically. While a drill begins to wear, the cutting forces increases and the temperature of the drill raises, which speeds up the physical and chemical reactions associated with drill wear, and causes rapid deterioration of the drill quality [38].

Ross conducted a Taguchi multi-factorial experiment to identify the influential factors on drill life [39]. Treanor and Hinds [40] considered that it is possible to maintain good drill condition and consequently a longer drill life if correct values are used for the influential parameters. In particular, drills survive better when cutting the minimum number of layers of copper with thinner foil, the use of an entry material is set aside, the holes have a lower aspect ratio and with minimal penetration into the back-up material. Hinds [1] concluded that the copper content used in a board should be held to a minimum by using the thinnest copper foil possible and having a small number of layers. The aspect ratio to be drilled should be kept to a minimum in order to reduce drill wear. The maximum chip-load that should be used is dependent on the drill diameter. Su [7] developed an automated flank wear measurement scheme using vision-aided system for a microdrill and proved the feasibility of measuring frank wear with the hole-drilling tests on a 10-layered PCB. Teti [3] reviewed the effectiveness of the tool materials for various machining processes of composites and indicated that tool wear mechanisms are primarily related to the physical and mechanical characteristics of the different fiber matrix systems. Glass fibers show a strongly abrasive behavior because they are extremely abrasive by nature.

4.2 Tool breakage

Small diameter drills used in drilling PCB appear to be bad rigidity and prone to break . Hinds [41] used finite element methods to analyse the stresses occurring in microdrills. Gong [42] developed a computer program for the calculation of the variations of the critical speeds and of the buckling loads, and analyzed the effects of drill geometry, boundary condition, rotational speed, and crosssectional area on the buckling loads and the critical speeds. Yang [43] developed the on-line monitoring to prevent microdrills from breaking and to increase microdrill availability. Yan [44] built a 3D drill model by simulating the grinding process of flute and flank by using UG. The various ratios of the web thickness to the diameter, the flute length and the helix are calculated by ANSYS, in order to analysis the torsional, twisty and pressural rigidity. Fu [45] established A 3D model of a microdrill bit via CAD softwareis and this enables the construction of an accurate drill bit mode. Hidehito Watanabe [37] indicated that rotational speed is significantly effective on breakage life.

4.3 Surface integrity

The drilled hole quality is a key factor determining plating quality and the quality of the finished MPCB [46,47]. The quality of holes can be judged in terms of accuracy of hole location, the presence of entry and exit burrs, smear of resin on the sides of holes and delamination, all of which are features which may affect the integrity of the connections made by plating the drilled holes [1].

Coombs [48] presented a comprehensive list of quality issues and their probable causes and solutions. For example, the smear problem can derive from a poor back-up or entry material, an uncured laminate, a worn drill bit or from having too high a surface speed at the drill. Burrs occur again with poor back-up or entry materials, when feeds are too high or when there are circumstances that result in loose stacking of boards. Su [7] proposed that in PCB manufacturing, a worn-out microdrill damages the quality of the surface finish and the dimensions of the drilled hole. Eiichi Aoyama [49] demonstrated that the reduction of fibre bundle thickness is effective to decrease the internal damage of drilled hole. Lu Xiaoping [50] experimentally discovered that the factors influencing the hole roughness might be different when the drill diameter range from 0.3mm to 1.0mm by drilling 6 layer PCBs. Hidehito Watanabe [37] consider that radial run-out at the drill tip , which might deteriorate hole quality, such as hole location accuracy or surface roughness on a hole wall. Some researchers proposed vibration drilling [17,18,51] to avoid burr and improve cutting stability.

5 Concluding remarks

The following conclusions can be drawn with regard to the drilling of printed circuit boards:

(1) Cemented carbide drills which is generally shaped by grinding are commonly applied in PCB drilling. As the diameter of drills is reduces, the drill flexibility increases and the strength

of the bit reduces. Thus, researches have been done to establish the drill model and grinding system. But these researches mostly relate to general metal machining. Drills specially used in drilling PCBs need to be improved.

(2) Although there are lots of methods of drilling such as electrical discharge machining (EDM), vibration drilling, laser machining and so on, mechanical drilling is avorable as hole depth increases, because of the need for high accuracy low temperatures and deformation forces in order to produce high quality holes in PCBs.

(3) It was indicated that thrust force and torque depends on the cutting condition, drill geometry, the composition of the material being cut. The chip produced during cutting is the primary cause of this increase, since it increases friction between the flute and the cut surface of the workpiece. when drilling holes with a large aspect ratio, the cutting forces acting on the drill bit increase as the drill penetrates the workpiece. Copper layers also contribute to the force increase.

(4) As the drill wear, the drilling temperature increases.When the temperature rise to too high a level, defects occur to reduce dimensional accuracy and drill holes show a smaller diameter than the drill used.

(5) Although ultrahigh rotational speed drilling can developed higher precision and productivity using smaller microdrills, it might cause a radial run-out at the drill tip. A radial run-out at the drill tip might deteriorate hole quality, such as hole location accuracy or surface roughness on a hole wall.

(6) Tool wear mechanisms are primarily related to the physical and mechanical characteristics of the different fiber matrix systems. Reducing the number of layers of copper with thinner foil and the aspect ratio to be drilled can decrease drill wear.

(7) The quality of holes can be judged in terms of accuracy of hole location, the presence of entry and exit burrs, smear of resin on the sides of holes and delamination, all of which are features which may affect the integrity of the connections made by plating the drilled holes. Drill wear, drilling methods, radial run-out at the drill bit, materials of entry or back-up and fiber bundle thickness are all associated with the hole quality.

Acknowledgements

This project was supported by the Key Program of NSFC-Guangdong Joint Fund, China(Grant No. U0734007).

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