Micro Drill Bit Design on the Basis of the Combination of Theoretical Analysis, Numerical Simulation and Experimental Verification

Lianyu Fu, Zhenchao Yu and Jianguo Qu
Shenzhen Jinzhou Precision Technology Corp

Abstract

To improve the design efficiency of a micro drill bit, a method on the basis of the combination of theoretical analysis, numerical simulation and experimental verifications is presented. As examples, the theoretical analyses of drill bit stress and rigidity conditions are investigated with emphasis. To perform such analyses, the finite element analysis (FEA) is recommended. To examine the accuracy of the theoretical analysis result and the performance of designed micro drill bit, experimental verification is conducted. Two design examples using the presented design method, namely one design of micro drill bit for flexible PCB (FP type) and the other for high Tg PCB (HT type) are discussed.

1. Introduction

With the rapid developments of printed circuit board (PCB) and packaging technology, PCB mechanical hole drilling has to face more challenges, such as too small drill bit diameter and the rapid appearances of new type of PCB. Therefore, micro drill bit suppliers must employ the state-of-the-art design techniques to ensure the performance and lead time of products.

Generally, the micro drill-bit is designed on the basis of experiment, rather than theoretical study. The reason is the micro drill-bit is a cutting tool with complex shapes. It is difficult to accurately obtain the mathematical model of it, and find the solution of this model. The finite element (FEM) analysis is a powerful tool used to accurately simulate engineering problems. Thus, the FEM analysis of micro drill-bit is applied as a theoretical analysis tool in this study to obtain the relationship of drill bit performances and drill bit key parameters.

In this paper, a design method based on the combination of theoretical analysis, numerical simulation and the experimental verifications is presented. The objective of this paper is to provide the designers of micro drill bit a useful tool to improve the product design efficiency and ensure the drill bit performances.

2．Drill Bit Design Procedures

A new kind of drill bit (the key parameters of drill bit) is/are initially designed based on the properties of printed board being processed, the material of drill bit, the conditions of CNC machine tool and drilling parameters being used and other experiences during drill bit design. After the determination of initial drill bit parameters, numerical simulation is conducted to get the 3-D model of drill bit. The numerical simulation is performed on a platform of specially designed software. The main purpose of numerical simulation is to provide an accurate 3-D drill bit model for theoretical analysis. Another purpose of numerical simulation is to provide the information of wheel position and wheel shape to guide drill bit manufacturing.

After obtaining 3-D model of micro drill bit, the theoretical analysis can be conducted. In this part of study, the finite element analysis (FEA) is employed considering the following advantages of it:

1) The deformation of the micro drill-bit can be simulated.
2) The stress conditions of the micro drill-bit can be inspected, and reveal the drill bit's respective strength.
3) The micro drill-bit's rigidity can be studied; thus the hole registration accuracy can be predicted.

4) Finally, the influential mechanism of the micro drill-bit's parameters—in terms of strength and rigidity can be easily determined, providing useful information to drill bit designers.

After the theoretical analysis, the obtained results are verified by experiments. If the experimental results are consistent with the theoretical analysis result, the presented FEA method is confirmed. If there are conflictions with the experimental results, the theoretical analysis method should be modified and improved. The above mentioned design process can be concluded in Figure 1.

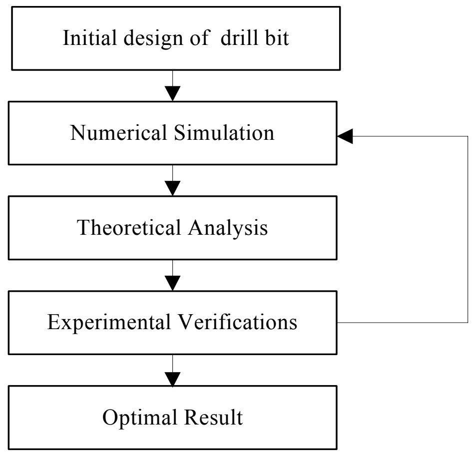


Figure 1 - Design procedures of a micro drill bit

3. Theoretical Analyses and Numerical Simulation

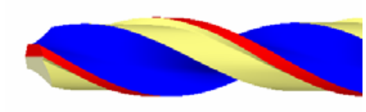
The key parameters of micro drill bit including helix angle, front web thickness, rear end thickness, relief angle and helix groove shape are considered in this paper. The influences of these parameters on the drill performance are listed in Table 1. Although the designers are familiar with the overall influences of these parameters on the drill performances, but it is somehow difficult to learn the details of the influential mechanisms. Therefore, it is worthy of conducting the theoretical/FEA investigation of a micro drill bit.

3.1 Model establishment

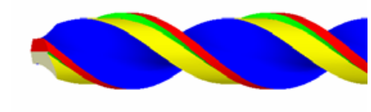
To conduct FEA of micro drill bit, the solid model of drill bit should be established first. There are several typical solid model established methods, such as the mathematical model method, the characteristics point method. In this research, the numerical simulation result is employed to construct the 3-D model of drill bit. The established schematic models with different helix angles, different front web thickness, different rear web thickness, different relief angles and different helix groove shapes are shown in Figure 2.

Table 1 - Influences of drill parameters on drill performances

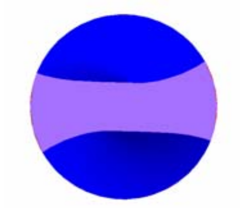
	Hole registration	Chip evacuation	Hole wall roughness	Drill life	Drill breakage
Helix angle	●	●	●	●	
Front web thickness *KF*	●			●	●
Rear web thickness *KR*	●	●	●	●	●
Relief angle		●	●	●	
Shape of helix groove	●	●	●	●	●



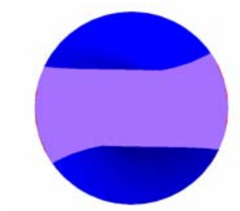
Small helix angle



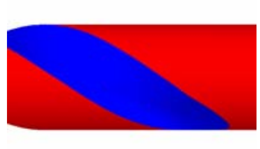
Big helix angle



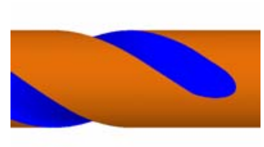
Small front web thickness



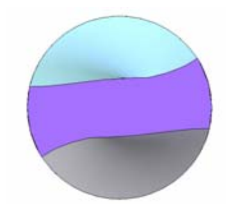
Big front web thickness



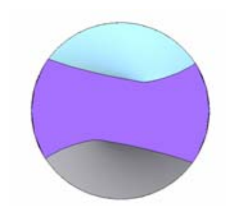
Small rear web thickness



Big rear web thickness



Groove shape with large chip evacuation space



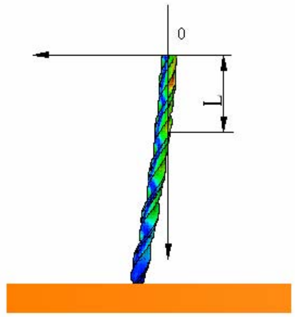
Groove shape with high strength

Figure 2 - Models with different parameters

3.2 Influences of Helix angle on drill performances

As mentioned above, the helix angle influences hole registration accuracy, hole wall roughness, drill bit life and chip evacuation force. The FEM analyses results on hole registration accuracy are shown in Figure 3 and Figure 4. It can be observed that the hole registration varies in a small ranges when the helix angle varies from 25 degree to 45 degree.

The hole wall roughness is closely related with the chip evacuation conditions. If the chip evacuation becomes difficult, the hole wall roughness gets worse correspondingly. A big helix angle is beneficial to improve the chip evacuation force, but the chip evacuation path becomes longer. In our research, the chip evacuation capability becomes better if a large helix angle is applied when the helix angle varies between 25 degree to 45 degree. If the helix angle increases further, the chip evacuation becomes worse.



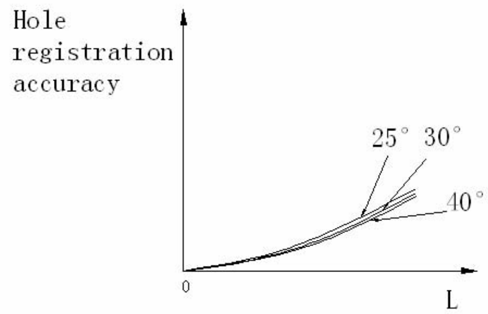


Figure 3 - Deflection of drill bit Figure 4 Influences of helix angle on hole registration accuracy

3.3 Influences of web thickness on drill performances

The front web thickness influence the hole registration accuracy, drill life, drill breakage, while the rear web thickness influences the hole registration accuracy, hole wall roughness, drill life, drill breakage. In front web thickness design, too small front web thickness should be avoided. If the front web thickness is too small, the primary face becomes narrow and the wear performance becomes worse, the drill bit tends to be broken (See Figure 5 and 6).

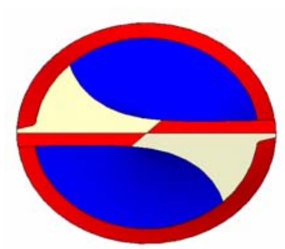


Figure 5 - Model with a small front web thickness

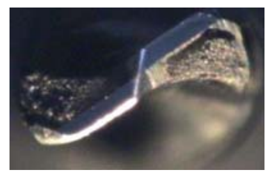


Figure 6 - Wear of drill bit with too small front web thickness

It can be found by the FEA of drill bit that a big rear web thickness is beneficial to a better hole registration accuracy. Also the rear web thickness influences the drill bit life and drill breakage rate, as the rear web thickness influences the drill bit strength. The FEA results show that if the rear web thickness is too small, the drill bit tends to be broken during the drill process. And even worse, the drill bit will be broken at the very beginning of the drilling process. Furthermore, the rear web thickness influences the hole wall roughness as the rear web thickness influences the chip evacuation space.

3.4 Influences of relief angle on drill performances

Relief angle influences the hole wall roughness and drill bit life. As shown in Figure 7, changes of relief angles lead to variations of angle between the rake face and the relief face, changes of sharpness and strength of drill bit. On the other hand, the relief angle influences the friction between the relief face and the PCB, and a large relief angle will reduce this friction force and the temperature of drilling area.

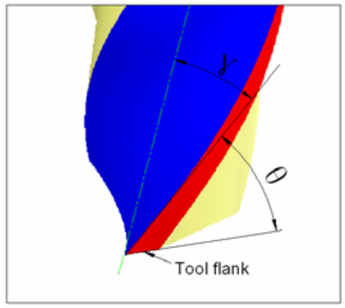
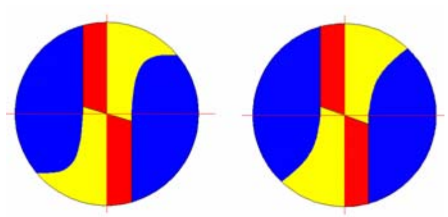


Figure 7 Influences of relief angle drill performance

3.5 Influences of helix groove shape on drill performances

The helix groove shape plays a critical role in the drill bit design process. The hole registration accuracy, the chip evacuation capability, drill bit life and drill breakage rate are all influenced by the helix groove shape. To investigate the influences of helix groove shape on drill bit rigidity and hole registration accuracy, two kinds of drill bits with different helix grooves are designed, as shown in Figure 8. By utilizing the FEM analysis, it is easy to get the hole registration accuracy differences between these two designs. The results show that the hole registration accuracy of drill bit with helix groove shape (a) is better than that with helix groove shape (b). Furthermore, a big cross section inertia moment should be employed if good hole registration accuracy is required. Of course, the designed helix groove must ensure adequate chip evacuation space and reasonable strength.



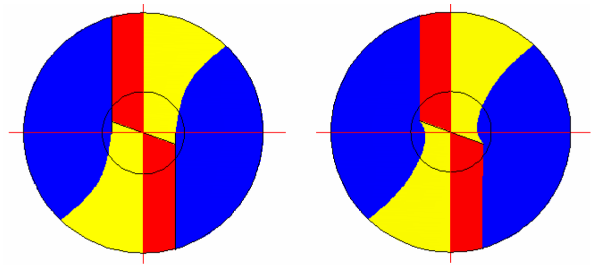
(a) (b)

Figure 8 - Different helix groove shapes

The drill breakage rate is mainly determined by the strength (bending and torsion strength) of drill bit. It is very convenient to study the drill bit strength via FEA. As an example, the FEA of two designs with different helix groove shapes (shown in Figure 9) is conducted. The calculation results show that the strength of drill bit with shape (a) is much better than that with shape (b) due to the small helix groove shape differences. Therefore, it is critical to control the helix groove shape of drill bit during its design and manufacturing processes.

3.6 Multi-factor analyses

To compare the influences of drill bit parameters on the drill bit performances, an orthogonal experiment analysis using FEA can be conducted. To do this, the following orthogonal table is used and the influential mechanism of drill parameter on drill performance can be revealed.



(a) (b)

Figure 9 - Different helix groove shapes

Table 2 - the orthogonal table for FEA

Factors	**Helix angle**	**Front web thickness**	**Rear web thickness**	**Relief angle**	**Helix groove shape**
Levels	$\square_1$	KF_1	KR_1	$\square_1$	H_1
	$\square_{\square}$	KF_2	KR_2	$\square_{\square}$	H_2
	$\square_{\square}$	KF_3	KR_3	$\square_{\square}$	H_3
	$\square_{\square}$	KF_4	KR_4	$\square_{\square}$	H_4

4. Experimental Verifications and Design Examples

In the above discussions, the influences of several key parameters, namely the helix angle, front web thickness, rear web thickness, relief angle and helix groove shapes on the drill performances are investigated theoretically. Meanwhile the above results must be confirmed by the experiments. Here the experimental verification is described combined with two design examples, drill bits for flexible PCB (FP type) and high Tg PCB (HT type). The basic ideas to design these two drill bits are illustrated in Table 3.

To examine the performance of designed micro drill bit, the experimental verifications are conducted on a HITACHI 6-spindle CNC drilling machine. The drill wear conditions are observed via a digital microscope, the hole registration accuracy are measured via a hole AOI machine and the hole wall roughness is measured through the metallographic microscope. The experimental results are listed in Table 4. From the results, it can be found that the FP type and HT type drill bits have excellent performances including wear conditions, hole registration accuracy, hole wall roughness and drill breakage rate. The designs of these two kinds of drill bits are successful.

5. Concluding Remarks

The presented micro drill bit design method on the basis of combination of theoretical analysis, numerical simulation and experimental verification is demonstrated an applicable way to improve the drill bit design efficiency. To investigate the influences of drill bit key parameters on the drill performances, the FEA can be conducted. The helix angle and the helix groove shape are critical to the drill bit performances and these two parameters should be considered carefully during design process. Different design ideas should be implemented for different printed circuit boards. The experimental verifications confirm that the presented two design examples, FP type drill bit and HT type drill bit, are successful.

Table 3 - Basic ideas to design FP and HT type drill bits

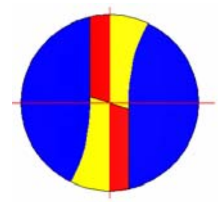
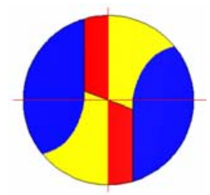
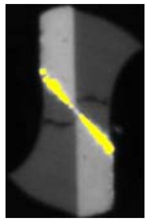
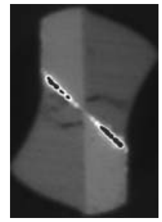
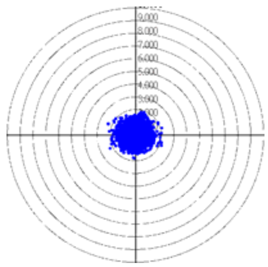
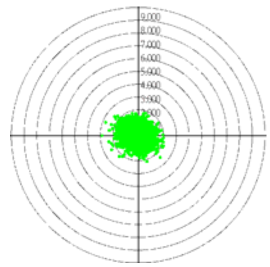
Drill bit	Helix angle	Relief angle	Front web thickness	Rear web thickness	Shape of helix groove
FP type	Big value. Reasons: Soft material, chip can not be evacuated easily. small drill wear	Big value. Reasons: to reduce the drill friction and improve the hole wall roughness	Small value. Reasons: improve the chip evacuation capability	Small value. Reasons: to improve the chip evacuation capability	
HT type	Small value. Reasons: Hard material, chip can be evacuated easily. Serious drill wear	Small value. Reasons: a big relief angle will reduce the strength of cutting edge	Big value. Reasons: improve the wear performance	Big value. Reasons: to improve the drill bit strength	

Table 4 - Typical experimental results for two designed drill bits

Items	FP type	HT type
Wear conditions		
Hole registration accuracy		
Hole wall roughness	<19um	<18um
Drill breakage rate	0	0

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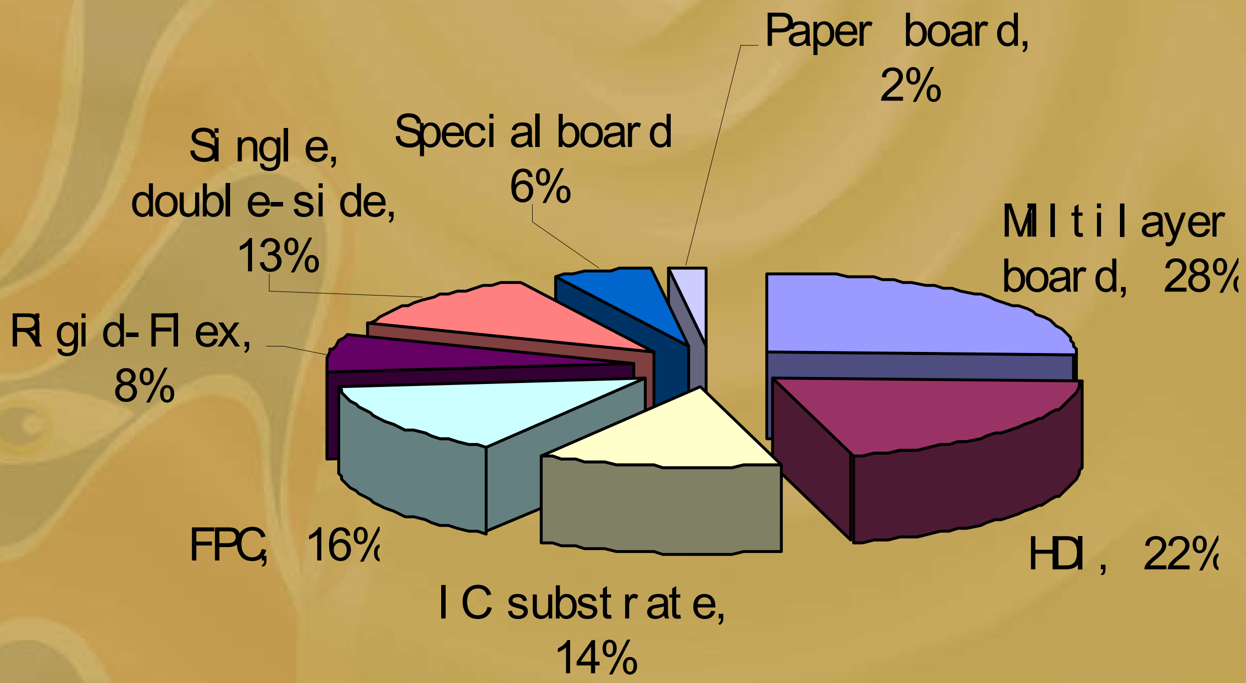
Micro Drill Bit Design Based on the Combination of Theoretical Analysis, Numerical Simulation and Experimental Verification

Presented by: Dr Fu Lianyu

Outline

- Introduction
- Drill bit design procedures
- Theoretical analyses and numerical simulation
- Experimental verifications and design examples
- Concluding remarks



PCBs by types (source: CPCA)

Worldwide PCB market (2005~2010, Prismark):

Year-on-year growth rate≈6%, in China, 14%

Three stars: HDI, IC substrate & FPC

Lead-free and Halogen-free

RoHS (Restriction of Hazardous Substances)

WEEE (Waste Electrical and Electronics Equipments)

High Tg PCBs

Fillers: SiO_2, Al_2O_3, $Al(OH)_3$,…

Points in drill bit for high Tg PCB:

※Drill wear

※Drill bit strength

Challenges of micro drilling

① Small drill bit diameter (HDI, IC substrate & FPC) ,difficulty to prevent drill breakage.
② Increasing requirements to improve the drill bit performance.
③ Increasing appearance rate of new types of PCB materials.

Mechanical and Laser Drilling

① Laser drilling is suitable for micro via drilling in HDI or IC substrate manufacturing due to its high efficiency and micro hole machining capability.

② Limitations of laser drilling: difficulty in Cu machining of CO_2 laser, reduced machining efficiency of UV laser, restriction of aspect ratio, cost of drilling machine.

③ Rapid development of mechanical drilling:

※ Minimum diameter 0.015mm drill bit is reported.

※ High spindle speed (300K or 350K rpm) drilling machine.

※ Excellent hole quality.

④ Mechanical drilling will still dominate the PCB hole drilling techniques.

Traditional drill bit design

Flow:

A design idea→ sample manufacturing→ experimental verifications→ optimize the original design→ a new product

Reason:

Difficulty in obtaining the accurate model & solution of micro drill bit.

Limitation:

Design efficiency & cost

Main design procedures

Theoretical Analysis

+

Numerical Simulation

+

Experimental Verification

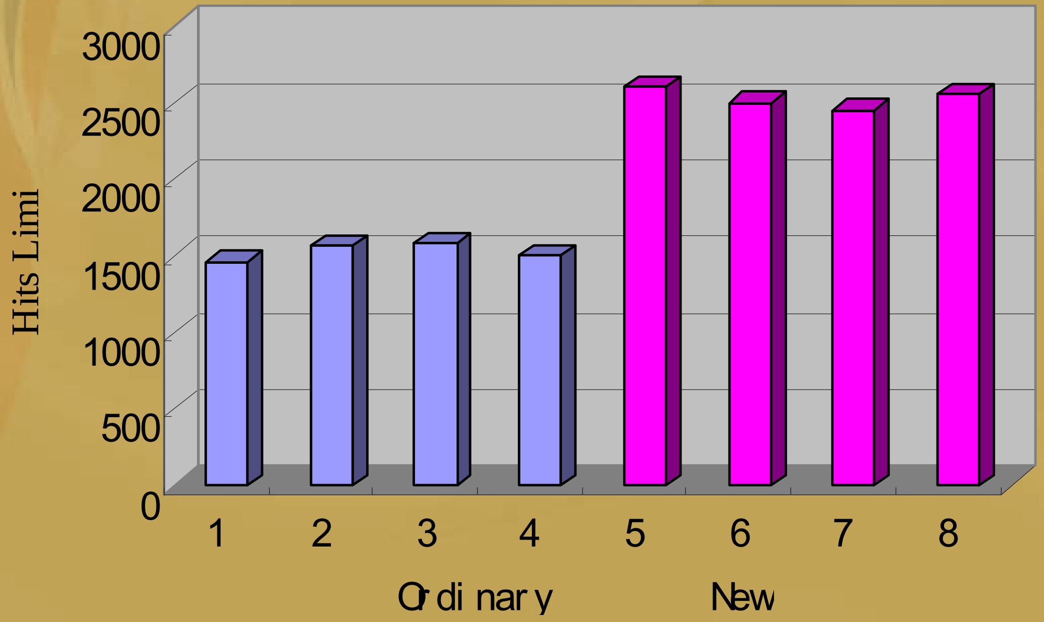
Bases of initial design

※Properties of printed board being processed.
※Material of drill bit.
※Conditions of CNC machine tool.
※Drilling parameters being used.
※Other experiences during drill bit design.

Novel drill bit design method

Drill bit material:

Drill bit material is especially important for the developments of ultra small (diameter<0.1 mm) drill bit.



Coating Techniques

※Coating technique employs chemical vapour deposition (CVD) or physics vapour deposition (PVD) to obtain ultra hard composite and consolidated material surface.

※ Coating materials: carbide, nitride, carbonitride, oxide, boride, silicide, diamond and composite materials

※There is still a long way for the successful utilization of coating techniques in micro drill bit.

FEM analysis

※ The deformation of the micro drill-bit can be simulated.

※ The stress conditions of the micro drill-bit can be inspected, and reveal the drill bit's respective strength.

※ The micro drill-bit's rigidity can be studied, the hole registration accuracy can be predicted.

※ The influential mechanism of the micro drill-bit's parameters—in terms of strength and rigidity can be easily determined, providing useful information to drill bit designers.

Influential mechanism of key drill bit parameters on its performances

	Hole registration	Chip evacuation	Hole wall roughness	Drill life	Drill breakage
Helix angle γ	●	●	●	●	
Front web thickness *KF*	●			●	●
Rear web thickness *KR*	●	●	●	●	●
Relief angle α		●	●	●	
Shape of helix groove	●	●	●	●	●

Establishment of 3-D micro drill bit model

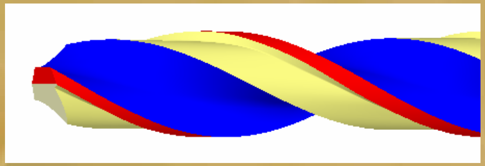
Typical solid model established methods:

※Mathematical model method.

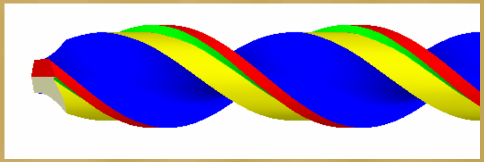
※Characteristics point method.

Here, the numerical simulation result is employed to construct the 3-D model of drill bit.

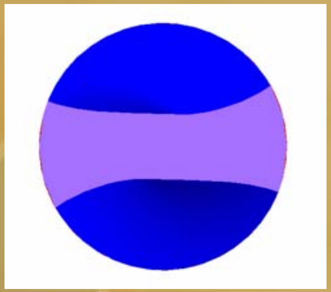
Models of micro drill bits with different design



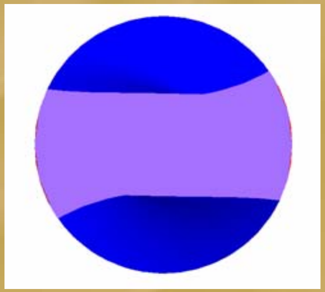
Small helix angle



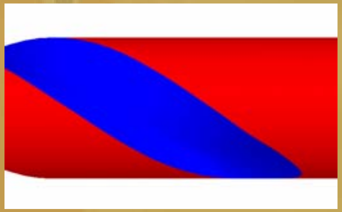
Big helix angle



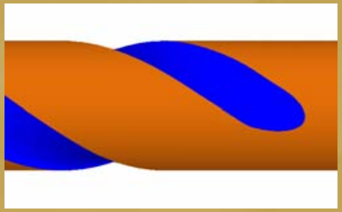
Small front web thickness



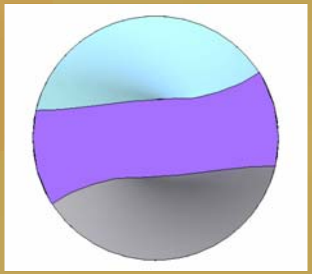
Big front web thickness



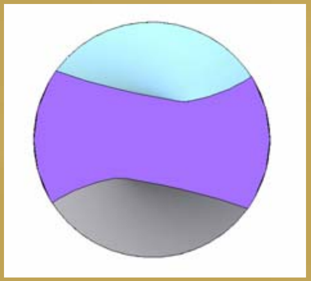
Small rear web thickness



Big rear web thickness

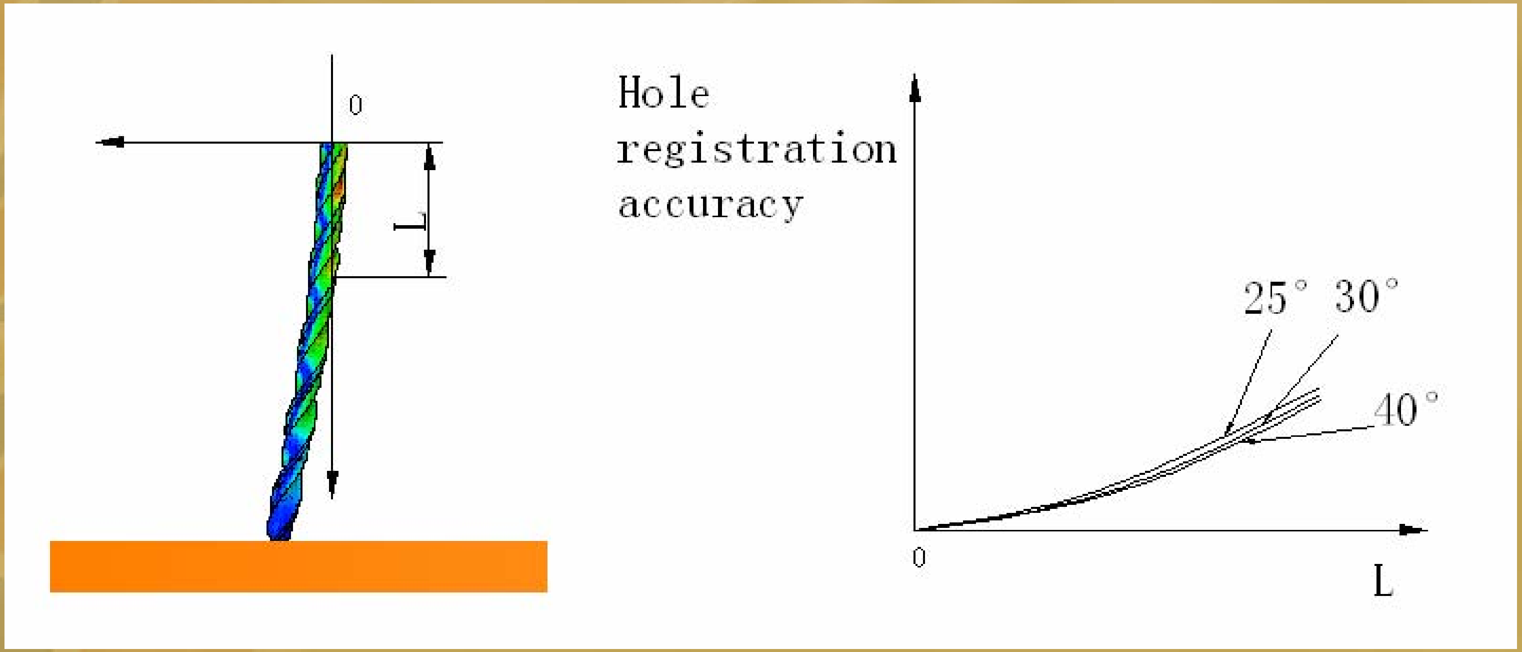


Groove shape with large chip evacuation space



Groove shape with high strength

Influences of helix angle



Chip evacuation capability:

In our research, the chip evacuation capability becomes better if a large helix angle is applied when the helix angle varies between 25 degree to 45 degree.

Influences of web thickness

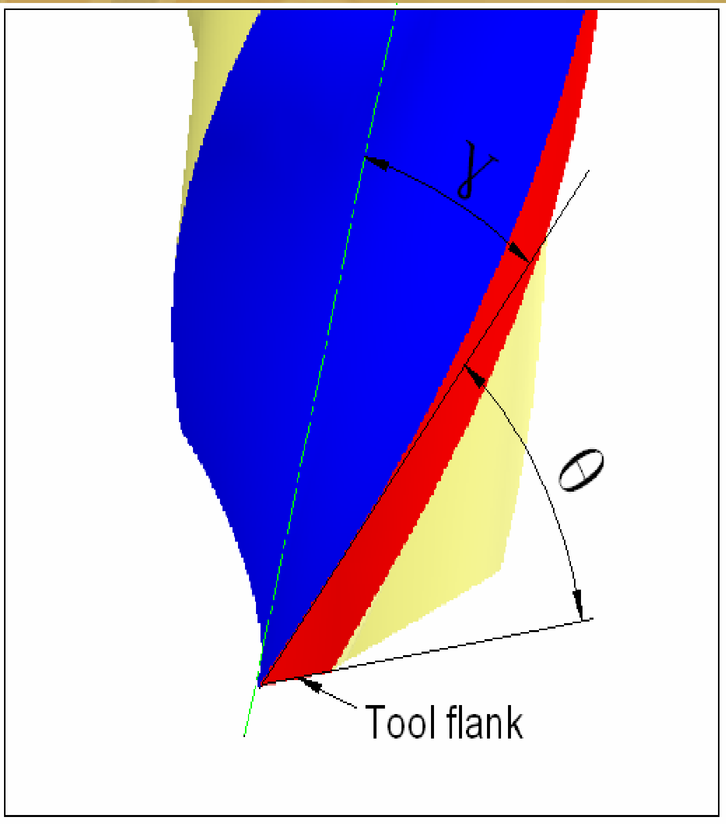
① In front web thickness design, too small front web thickness should be avoided.

② A small front web thickness leads to a narrow primary face, the wear performance becomes worse, the drill bit tends to be broken.

③ The FEA results show that if the rear web thickness is too small, the drill bit tends to be broken during the drill process. And even worse, the drill bit will be broken at the very beginning of the drilling process.

④ The rear web thickness influences the hole wall roughness as the rear web thickness influences the chip evacuation space.

Influences of relief angle

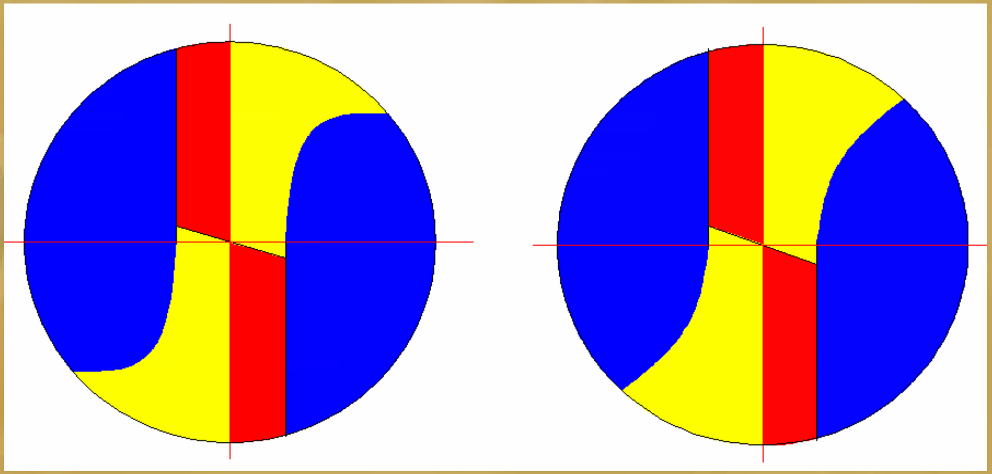


※Changes of relief angles lead to variations of angle between the rake face and the relief face, sharpness and strength of drill bit.

※The relief angle influences the friction between the relief face and the PCB.

※A large relief angle will reduce the friction force and the temperature of drilling area.

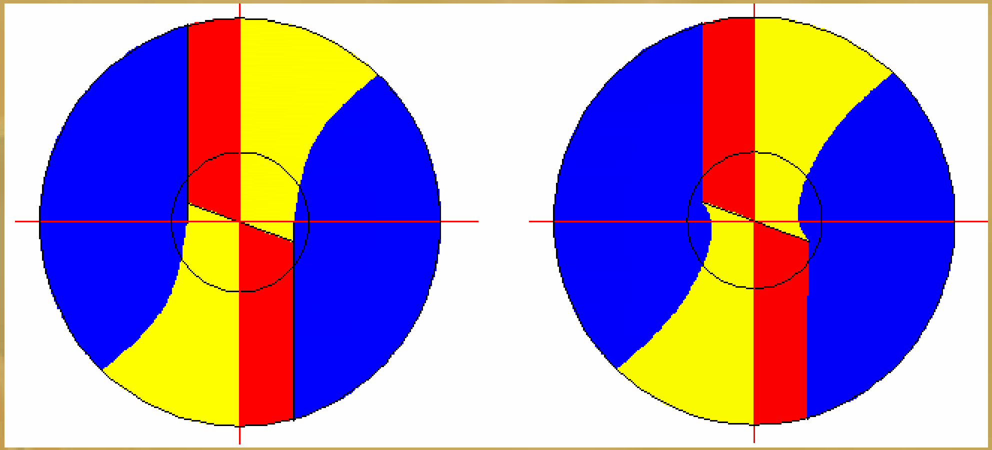
Influences of helix groove shape on drill performances



(a) (b)

※The hole registration accuracy of drill bit with helix groove shape (a) is better than that with helix groove shape (b).
※A big cross section inertia moment should be employed if good hole registration accuracy is required.
※The designed helix groove must ensure adequate chip evacuation space and reasonable strength.

Influences of helix groove shape on drill performances



(a) (b)

※The drill breakage rate is mainly determined by the strength (bending and torsion strength) of drill bit.

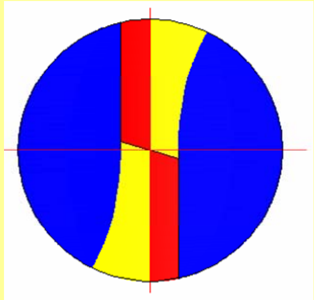
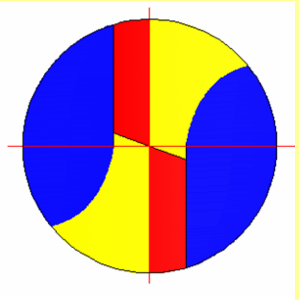
※The strength of drill bit with shape (a) is much better than that with shape (b).

※It is critical to control the helix groove shape of drill bit during its design and manufacturing processes.

Orthogonal analyses

Factors	Helix angle	Front web thickness	Rear web thickness	Relief angle	Helix groove shape
Levels	γ_1	KF_1	KR_1	α_1	H_1
	γ_2	KF_2	KR_2	α_2	H_2
	γ_3	KF_3	KR_3	α_3	H_3
	γ_4	KF_4	KR_4	α_4	H_4

Two design examples

Drill bit	Helix angle	Relief angle	Front web thickness	Rear web thickness	Shape of helix groove
FP type	Big value. Reasons: Soft material, chip can not be evacuated easily. small drill wear	Big value. Reasons: to reduce the drill friction and improve the hole wall roughness	Small value. Reasons: improve the chip evacuation capability	Small value. Reasons: to improve the chip evacuation capability	
HT type	Small value. Reasons: hard material, chip can be evacuated easily. Serious drill wear	Small value. Reasons: a big relief angle will reduce the strength of cutting edge	Big value. Reasons: improve the wear performance	Big value. Reasons: to improve the drill bit strength	

Points of testing

① Drilling is conducted on a Hitachi CNC drilling Machine (160K rpm, 6-axis).

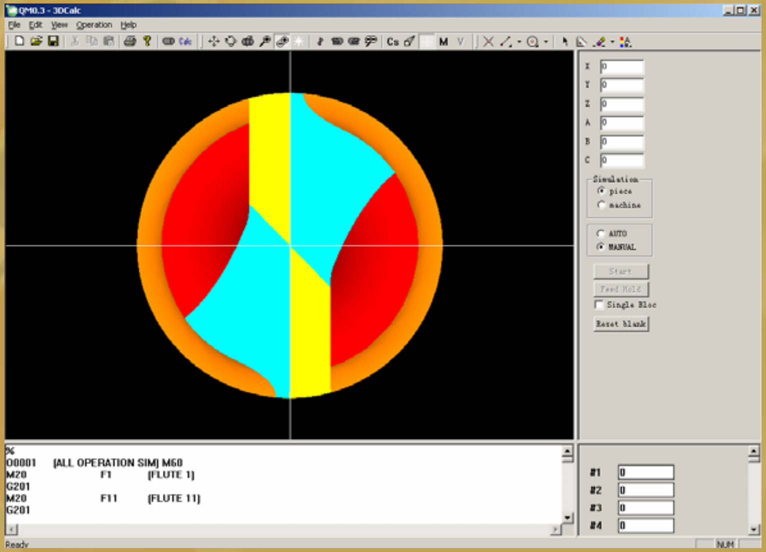
② Reliability (Fast) testing parameters are recommended.

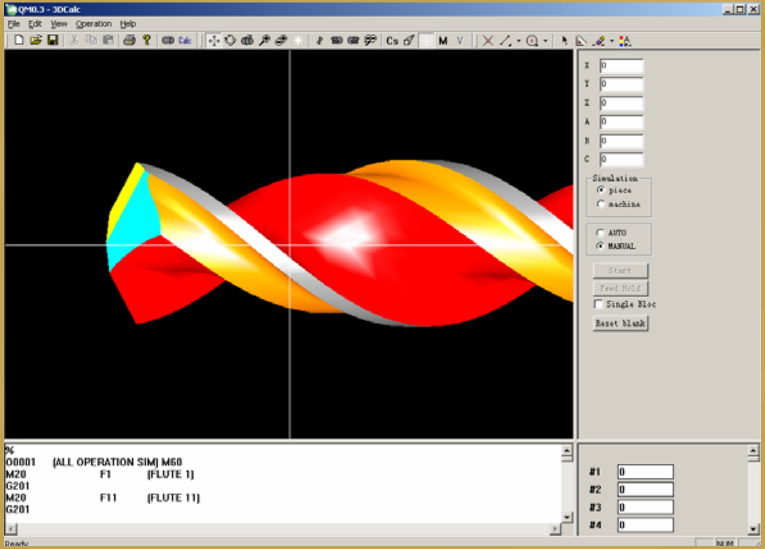
③ Hole AOI to obtain the drill registration accuracy.

④ Hole section view to get the hole wall roughness.

⑤ Drill bit AOI to get the drill wear condition.

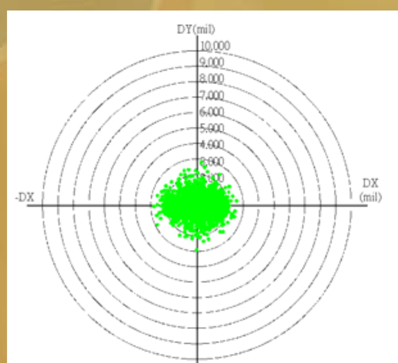
Drill bit simulation for High Tg PCBs

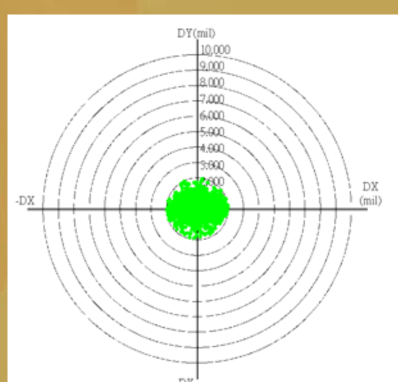




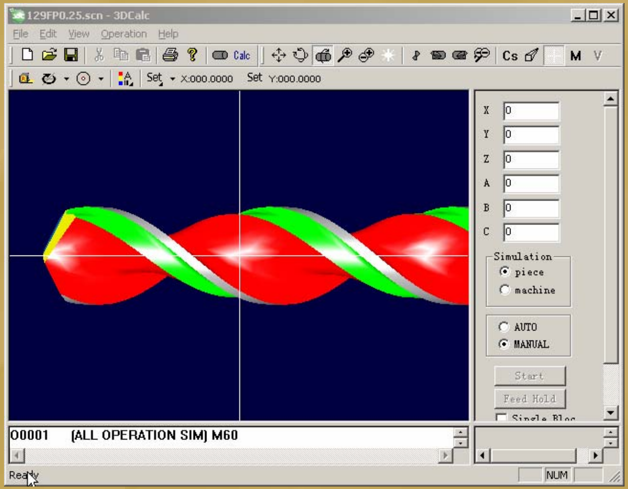
ϕ0.25-4.5

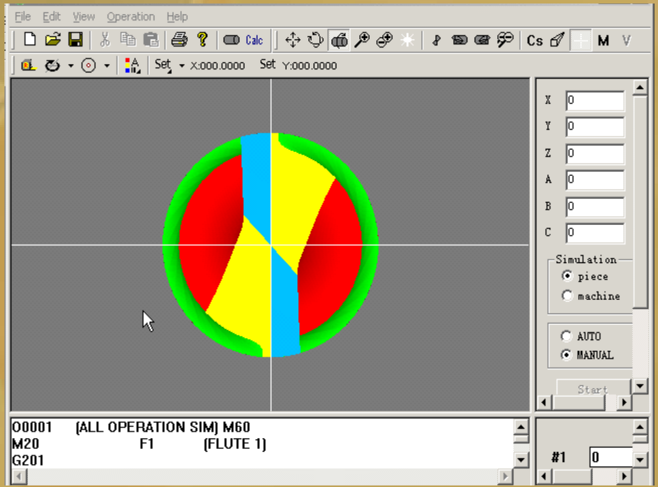
PCB: High Tg, halogen free board, ten layers, t1.6×2
Feed rate: F=45mm/s
Hits limit : 2500+2200
Spindle speed: 148K rpm

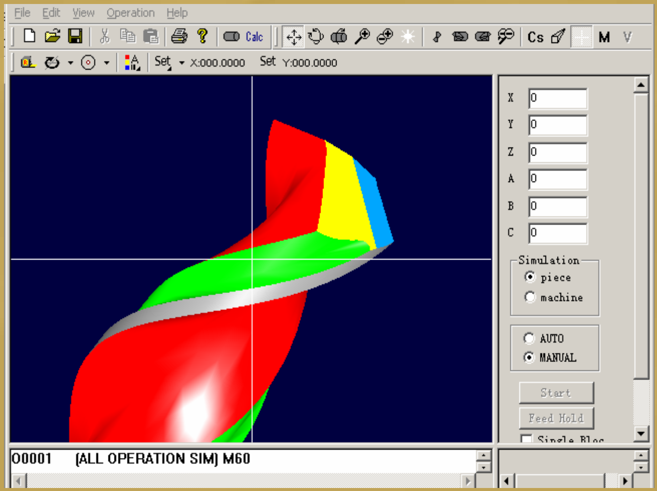




Drill bit simulation for FPCB





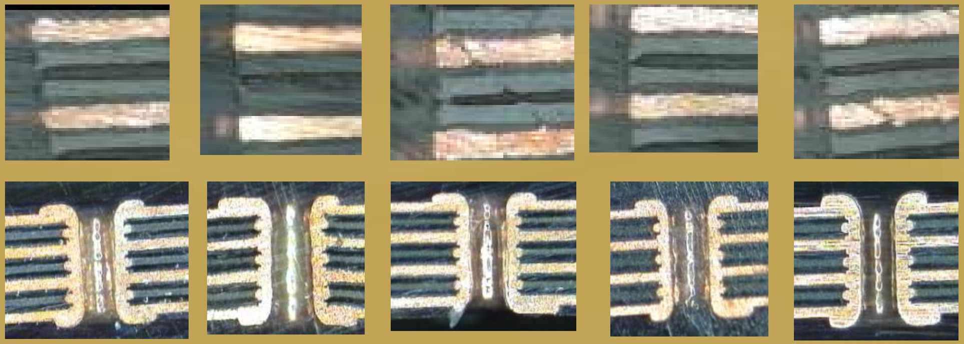


Design Examples

ϕ0.20×3.5

PCB: FPC, 4 layers, t0.32×2
Feed rate: F = 30mm/s
Hits limit：2200+2000
Spindle speed: 160K rpm

Drill after 2200hits



Concluding remarks

① The rapid development of PCB industry requires the rapid development of new type of micro drill bit. A novel high efficiency drill bit design method is desired to meet this challenge.

② The presented micro drill bit design method is demonstrated an applicable way to design a new drill with high efficiency.

③ To investigate the influences of drill bit key parameters on the drill performances, the FEA can be conducted.