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Microdrilling for printed circuit boards (PCBs)—Influence of radial run-out of microdrills on hole quality

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ABSTRACT

This paper represents the drilling of dense printed circuit boards (PCBs) using microdrills. Although ultra-high rotational drilling is known as empirically effective to improve tool breakage, it causes microdrills' radial run-out as it has some disadvantages. Hence, the correlation between the radial run-out of drills and the hole quality was examined experimentally using 0.1-mm diameter drills at a rotational speed of 3×10^5 min^{-1}. The drilling behavior at contact with a work surface was dynamically observed using a high-speed video camera. It was 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.

1. Introduction

Now days, many printed circuit boards (PCBs) are applied to compact electronic appliances which require high efficiency and high functional performance. PCB demands an increase in number of wiring layers, the density of printed circuit and the miniaturizing of through holes. Currently, microdrills of 0.1–0.3 mm in diameter are commonly used in production lines and drills of diameter 0.05–0.075 mm are tentatively used in aggressive lines [1]. The stack height of PCB is increasing more and more in order to improve the productivity in drilling. As the result, microdrills with a long body are demanded and concern for drills with aspect ratio of 15 or more is also increasing [2].

PCB is laminated composite material consisting of copper foils, resin and glass fiber cloth. So it is difficult to drill deeper holes at high productivity and high precision. For instance, microdrills are easy to break during drilling. Therefore, it is serious for PCB manufacturing that more conservative drilling conditions chosen for safety bring lower productivity and higher cost.

To comply with this current tendency, 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 3×10^5 min^{-1} or more.

However, high rotational speed might generate an excessive centrifugal force around a drill. It might also cause the increase of collet chuck looseness, drill chucking misalignment, imbalance of the collet and/or imbalance of a microdrill. These factors bring to increase radial run-out at the drill tip [3], which might deteriorate hole quality, such as hole location accuracy or surface roughness on a hole wall. However, there are only a few studies about the influence of radial run-out on hole quality [4–8], especially about the hole quality in ultrahigh rotational drilling with microdrills [9,10].

The purpose of this paper is to improve the breakage life and the productivity, which are controversial problems regard as microdrills. The influence of radial run-out on hole quality such as hole location accuracy, enlargement error of hole diameter, burr height and hole wall roughness is investigated using 0.1-mm diameter drills at 3×10^5 min^{-1} rotational speed.

2. Experimental method and conditions

2.1. Experimental setup

The experimental setup is schematically shown in Fig. 1. A NC drilling machine (Hitachi Via Mechanics, ND-1V212) for PCB is used. It has an air-bearing spindle driven by an AC motor of maximum rotational speed 3×10^5 min^{-1}. A high-speed camera (Nac Image

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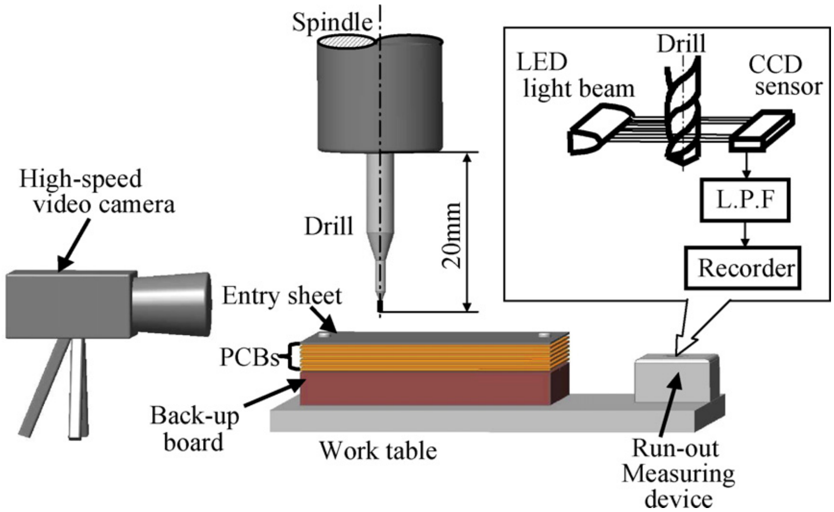

Fig. 1. Experimental setup for microdrilling tests.

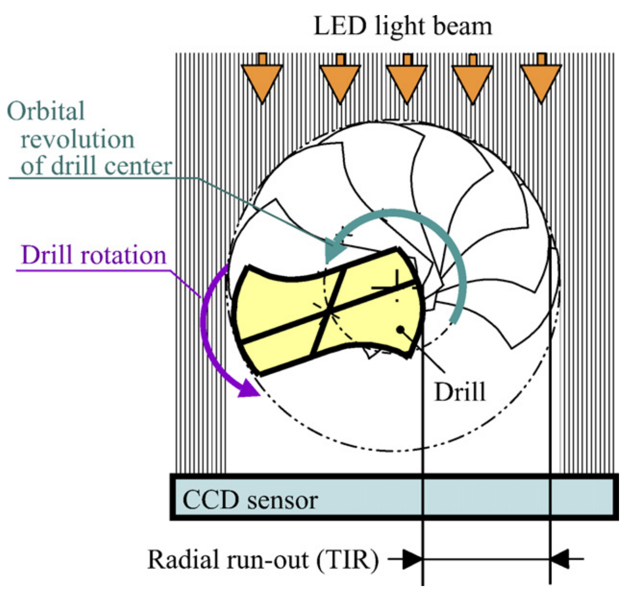

Fig. 2. Measuring method of radial run-out during rotating.

Technologies, Memrecam fx-K4) is set to observe the behavior in a side view of a drill during drilling. Maximum frame rate of the camera is 6×10^4 fps (12 frames per rotation at 3×10^5 min^{-1} rotational speed). Radial run-out is measured by a run-out measuring device (Union Tool Co., TP-FA). Fig. 2 shows the schematic measuring principle of radial run-out. Radial run-out is estimated as the maximum total indicator readout (TIR) under orbital revolutions of a drill during air cut. LED light beam is 2 μm in thickness. Radial run-out signals are affected by two helical flutes of drill. Therefore, it is necessary to detect radial run-out signals through a half lead [11]. In this study, radial run-out is defined as the maximum of radial run-out signals detected through a half lead from the drill shoulder. The run-out measuring device TP-FA is set on the worktable to measure radial run-out interruptedly through drilling tests according to NC control in the drilling machine.

2.2. Drilling conditions

Table 1 shows the specifications of drills used for drilling tests. The drill is a twist drill with 0.1 mm in diameter, 1.5 mm in body length and 2.0-mm diameter shank. It is made of ultra-fine tungsten carbide. The specifications of ultra-fine tungsten carbide are shown in Table 2. The lateral stiffness at drill tip is as low as 1.85×10^{-3} N μm^{-1} in 0.1-mm diameter drills tested. A PCB is 0.1 mm in thickness, laminated by glass fiber cloth and polyimide. Both sides are clad with a copper layer of 6-μm thick. The workpiece consists of an entry sheet, four-stacked PCBs and a back-up board placed orderly, fixed by stud pins at the both ends of the workpiece on the work table.

Table 1
Specifications of drill

Drill diameter (mm)	0.1
Flute length (mm)	1.5
Helix angle (°)	45
Point angle (°)	120
Web thickness (mm)	0.04
Overall length (mm)	31.8

Table 2
Specifications of tungsten carbide

Cobalt (wt%)	8
Hardness (HRA)	93.0
Mean grain size (μm)	0.6
Young's modulus (GPa)	570

For PCB, the entry sheet was used to improve the initial hole location accuracy and lubrication-related. Also, this is effective in reducing burrs on hole shoulders. Especially, aluminum clad with resin was used as an entry sheet for the microdrilling tests. The principal ingredient of the resin is polyethylene glycol, which is 1.1 in specific gravity. This entry sheet is most popularly used in microdrilling production lines. Back-up board is a paper phenol laminated board.

Table 3 shows drilling conditions.

Drills are voluntarily set up in the range from 0 μmTIR to 100 μmTIR in radial run-out under different chucking conditions on a collet. Although it might be in the nature of things, the radial run-out revolves synchronizing with the spindle rotation. And its direction is in accordance with the rotating direction of drills.

Table 3
Drilling conditions

Rotational speed: *N*	3×10^5 min^{-1}
Feed rate: *F*	1500 mm/min
PCB	Glass fiber cloth base copper clad laminate (Mitsubishi: HL832HS)
Stack heights	t0.1 mm/panel × 4 panels
Tool durations	4000 hits
Drilling pitch	0.25 mm
Radial run-out	0–100 μmTIR
Entry sheet	Aluminum clad with resin: aluminum (t0.07 mm); polyethylene glycol (t0.04 mm)
Back-up board	Bakelite (t1.5 mm)

2.3. Evaluation of hole quality

Hole quality: hole location accuracy, enlargement error of hole diameter, burr height and hole wall roughness, are evaluated as below:

(1) *Hole location accuracy*:
Hole location accuracy is measured on the top side of 1st PCB and the bottom sides of 4th PCB using a position analyzer (Hitachi Via Mechanics, HT-1AM), which consists of CCD camera and image processor. Measurement accuracy is ±5 μm. It is measured as the deviation of hole location from ideal drilling coordinates, and the average values are plotted. Here, pitch errors peculiar to the drilling machine were compensated prior to the estimation [12].

(2) *Enlargement error of hole diameter*:
The enlargement error of hole diameter is the difference between the diameter of a brand-new drill and drilled hole diameters, defined as ΔD. It was measured by a digital microscope (Keyence: VHX-200), and then hole diameter on the top side of 1st PCB was calculated from optional three points on the hole circumference.

(3) *Burr height and hole wall roughness*:

As shown in Fig. 3, cross-sections through the hole center axis were observed. The maximum burr height of the top copper foil on hole shoulders of the work surface is estimated as the burr height H_b. Using the cross-sections with copper plating treatment, the maximum dent on plated hole wall was defined as hole wall roughness R_z.

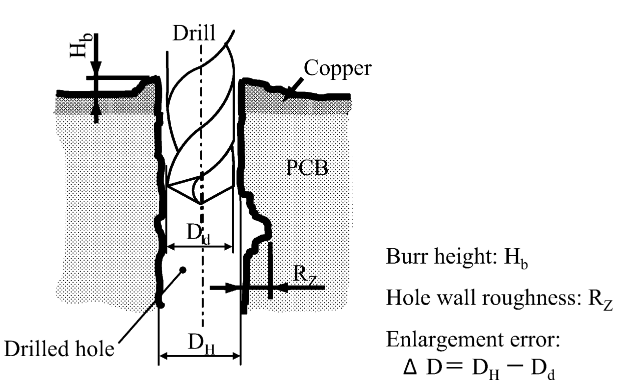

Fig. 3. Definition of factors estimating hole quality.

3. Experimental results and discussions

3.1. Effect of rotational speed on breakage life

If specific drilling energy for unit chip volume is assumed to be constant for PCB, the drilling torque is proportional to feed rate, and inversely proportional to rotational speed. Therefore, the drilling torque, which is dominant in drill breakage [10], would be independent on rotational speed. However, the torque depends on "chip load", which is defined as "feed per drill rotation".

Fig. 4 shows an example of the influence of rotational speed upon breakage life and drilling hit rate, in drilling tests using 0.1-mm diameter drills under a chip load of 5 μm/rev. Breakage life at a constant chip load is extended as rotational speed increases with higher productivity. This improvement of breakage life as well as productivity is a significant benefit at a higher rotational speed. However, the experimental result shows that specific drilling energy decreases substantially with the increase of rotational speed against the above-mentioned prediction. It can be presumed that the intensity of work would be decreased by a rise of cutting temperature under higher rotational speed of microdrills. However, the exact theory has not been defined yet.

The following will be discussed on the base of the fact that rotational speed is significantly effective on breakage life.

3.2. Influence of radial run-out on hole quality

Influence of radial run-out on hole location accuracy, enlargement error of hole diameter ΔD, burr height H_b and hole wall roughness R_z is discussed at a rotational speed of 3×10^5 min^{-1} as below.

Fig. 5 shows the influence of radial run-out on the hole location accuracy. It can be recognized in the figure that the hole location accuracy has not any correlation with radial run-out on the top side of the 1st PCB or on the bottom side of the 4th PCB. The correlation between radial run-out and enlargement error of hole diameter ΔD on top side of 1st PCB is shown in Fig. 6. In the figure, it can be recognized that the enlargement error of hole diameter ΔD increases slightly with the increase of radial run-out. Fig. 7 shows the influence of radial run-out on burr height H_b. The burr height H_b slightly grows in the increase of radial run-out.

However, the influence of radial run-out on the enlargement error of hole diameter ΔD and on the burr height H_b varies scarcely within certain micrometers even when radial run-out reaches to

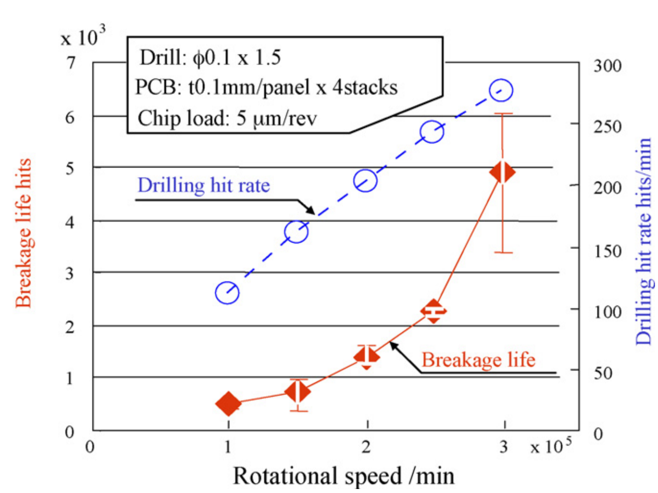

Fig. 4. Influence of rotational speed on breakage life and drilling hit rate.

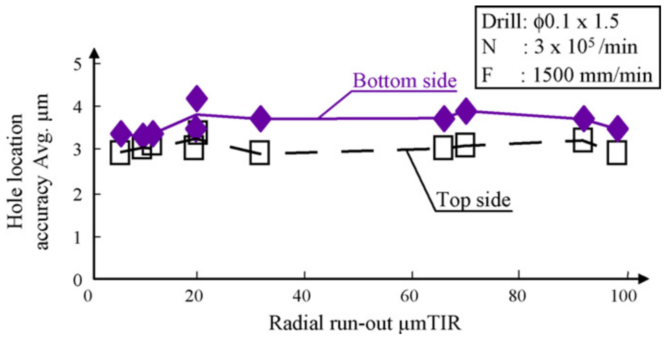

Fig. 5. Relationship between radial run-out and hole location accuracy.

100 μmTIR. Fig. 8 shows hole wall roughness R_z of four stacked panels drilled at 10 μmTIR and 98 μmTIR in radial run-out. The hole wall roughness is measured at the phase of 45° against the yarn in the glass fiber cloth. Each figure is plotted as the average on cross-sectional profiles of 10 holes. The variation in the hole wall roughness R_z cannot be confirmed by both radial run-out.

It is concluded that the radial run-out hardly influences on hole quality within these experimental conditions. Therefore, it is presumed that large radial run-out during air cut almost reduces to the normal drilling after the contact with a work surface in the drilling of PCB.

3.3. Centripetal behavior

Fig. 9 shows the photographs of drilling behavior taken by a high-speed camera when the drill starts contacting with an entry sheet. The four photographs were taken in very short time: (a) a photo taken during air cut, (b) one at 0.1 ms (0.5 rev of drill) after (a), (c) one just after contact with an entry sheet, and (d) one at 0.1 ms (0.5 rev of drill) after (c), respectively. In the figure, it is observed that the rotating drill fluctuates left and right parallel along the drill axis during air cut. While penetrating the entry sheet, the drill tip is located near the center of the deviation, although the deviation is kept at the end part of drill body. Hence, it can be presumed that the drill body is deflected laterally along the axis of drill body and the radial run-out is dumped at the drill tip. Therefore, the drill deflects elastically in the modal shape which has the drill tip as a node and the other end of drill body as an anti-node.

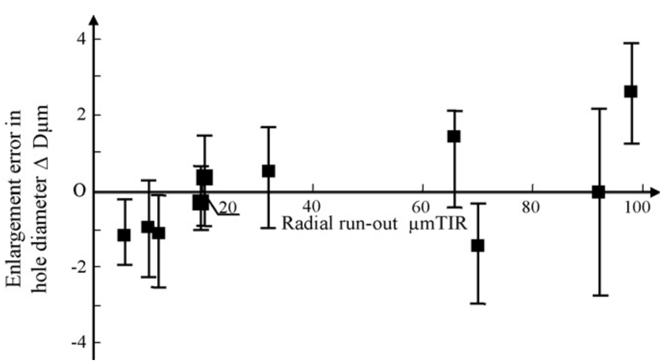

Fig. 6. Enlargement error of hole diameter on top side.

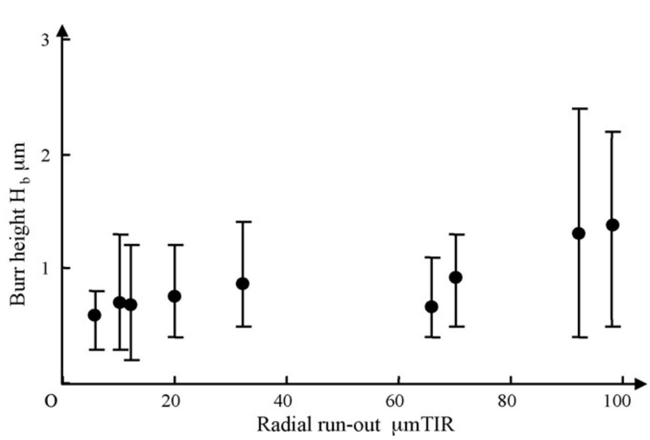

Fig. 7. Influence of run-out on burr height.

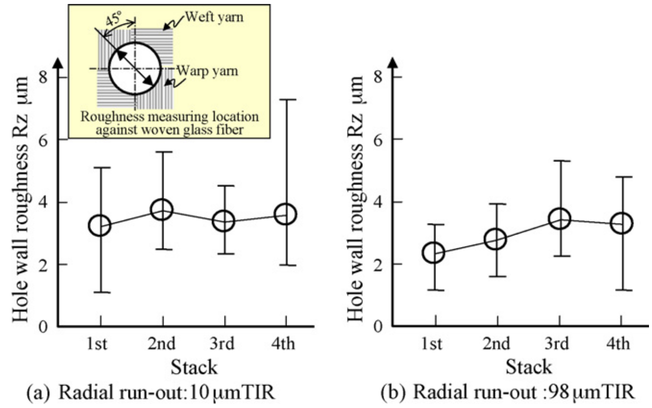

Fig. 8. Influence of radial run-out on hole wall roughness.

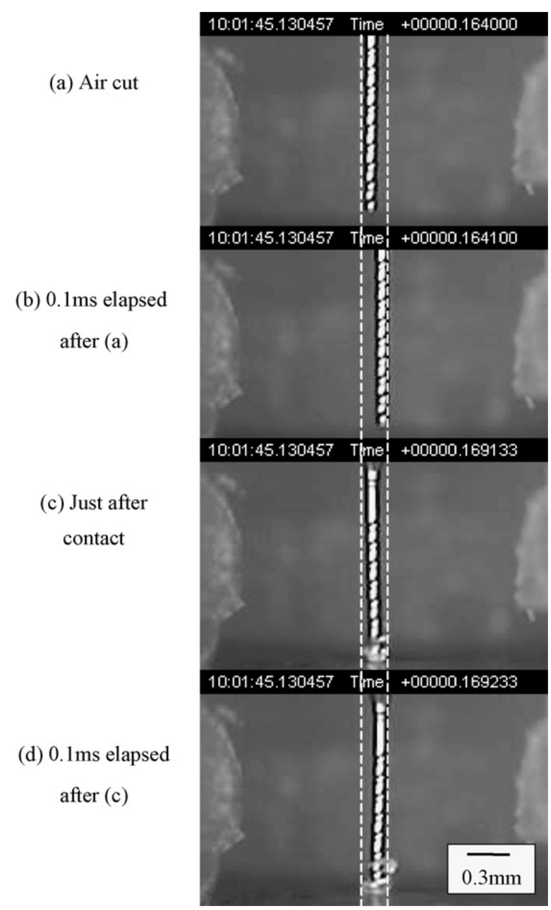

Fig. 9. Photos of deviating behavior of drill body at a moment of contact with a work surface.

Fig. 10 shows eight continuous photographs taken at interval of 0.3 ms (every 1.5 rev of drill), when the drill starts contacting with an entry sheet. From the comparison among the serial photographs, it is recognized that:

1. The deviation at the drill tip suddenly decreases toward the rotating center of the spindle with drilling deeper, although it is significantly large before the contact with an entry sheet.
2. After contacting the drill tip with the entry sheet, it takes only about 1.5 ms (7.5 rev of drill) until the radial run-out at the drill tip is dumped. The drill is fed 37.5 μm for drilling 1.5 ms, which is moderately deeper than the length from the drill tip to its shoulder, which is 23.9 μm.

According to the above-mentioned results of hole location accuracy and the modal shape around the drill body, it can be concluded that centripetal action substantially occurs on the contact area between a drill and an entry sheet. Radial run-out of the drill tip gets to be dumped soon after the initial contact with the entry sheet, and radial run-out converges to the center of rotating spindle by the centripetal action in very short time. Hence, it is presumed that vibration-free drilling of PCBs is realized after penetrating through the entry sheet.

3.4. Effect of entry sheet on centripetal action

The effect of an entry sheet can be testified in comparison of drilling tests with and without an entry sheet. The influence of radial run-out on hole location accuracy is shown in Fig. 11, when drilling tests were done without an entry sheet. It indicates that hole location accuracy becomes worse in proportion to radial run-out. Especially, it depends more significantly upon radial run-out at the bottom side of 4th PCB than one at the top side of 1st PCB. Therefore, we can say that the radial run-out scarcely converge to the center of rotating spindle, and drill bodies are bent in PCBs. Centripetal action is active, however, even without an entry sheet because of weak correlation between radial run-out and hole location accuracy.

For instance, the drill tip starts contacting with a work surface at a location of 40 μm deviated from the center of rotating spindle, when radial run-out is 80 μmTIR. Therefore, the hole location error might result in 40 μm. According to Fig. 11, however, hole location accuracy on the top side of 1st PCB is about 12 μm even though radial run-out is 80 μmTIR. The hole location error is restricted to 30% of the deviation 40 μm. The centripetal action works to reduce 70% of the deviation in the copper clad layer and/or glass cloth resin.

It is concluded that the centripetal action primarily acts on the drill tip from an revolving orbital to the center of rotating spindle, and an entry sheet effectively enhances the centripetal action to reduce the deviation of hole location, even when there is radial run-out beyond 80 μmTIR or more.

3.5. Influence of radial run-out on drill wear

The top views of drill after drilling 4000 hits at radial run-out of 6 μmTIR and 98 μmTIR are shown in Fig. 12. In each photograph of the figures, a dotted circle indicates the circle circumscribed outer corners of a brand-new drill before drilling test. In the figure, each photograph shows normal wear as the flank at outer corner cutting edges is remarkably worn. That is, any abnormal wear triggered by radial run-out cannot be recognized.

Fig. 13 shows an example of the diameter decrease along the drill body after a 4000 hit drilling test. The drilling test in the figure is correspondent with the tests in Fig. 12. They are measured with the drill diameter measuring device. Here, drill diameter decrease

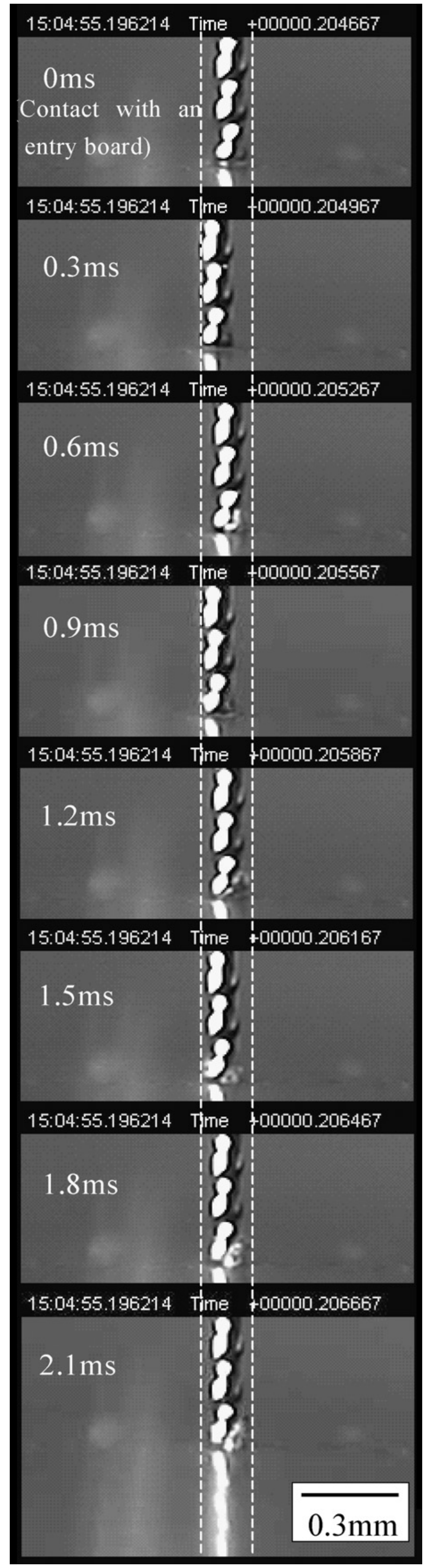

Fig. 10. Serial photographs of microdrilling.

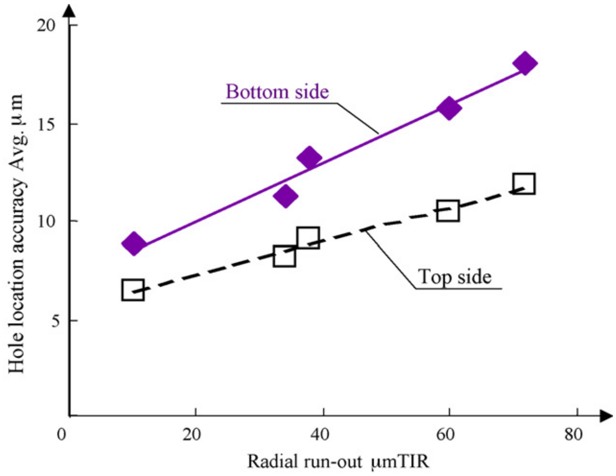

Fig. 11. Dependence of hole location accuracy on radial run-out in drilling without entry sheet.

Δ_d stands for the difference between drill diameters before and after 4000 hit drilling test. In the figure, the profile of a worn drill is plotted as drill diameter decrease from the drill tip to 0.3 mm toward drill body. The distance from the drill tip, the abscissa, is plotted on the brand-new drill. In the figure, there is not significant difference in drill diameter decrease between worn drills with a small radial run-out and a large radial run-out. That is, radial run-out hardly affects the drill wear.

In general, it is well known that the surface quality has a strong correlation with tool wear. Hence, the wear of a chisel edge and outer corner edges seem to be lead to reduce cutting ability and to deteriorate hole location accuracy. The burr on hole shoulders would become higher by dulled outer corner edges. The more heat generation and the worse chip removal caused by dulled cutting edges also seem to deteriorate hole wall roughness. However, any abnormal wear was not observed even drilling with large radial run-out herein and any radial run-out hardly affected hole quality either.

It results that any radial run-out hardly affects the drilling behavior, resulting in drill wear or hole quality either.

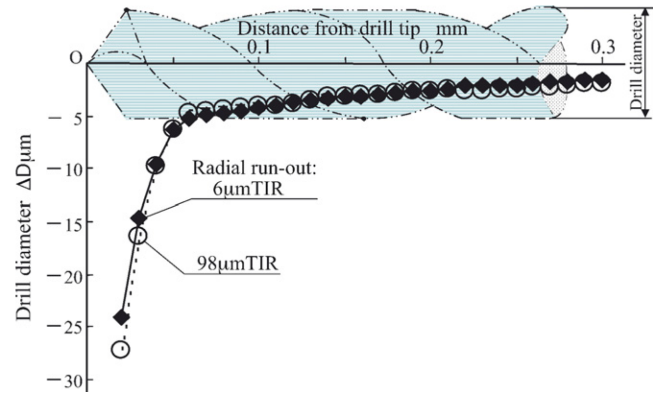

Fig. 13. Distribution of drill diameter decrease after drilling 4000 hits.

3.6. *Influence of drill wear on centripetal action*

Fig. 14 shows the dependence of radial run-out on accumulative hits. Radial run-out is detected during initial air cut and interrupted air cut at the interval of 500 hits until 2000 hits. Three drilling tests start initially at radial run-out 56 µmTIR, 80 µmTIR, and 98 µmTIR, respectively. In the figure, radial run-out is almost independent

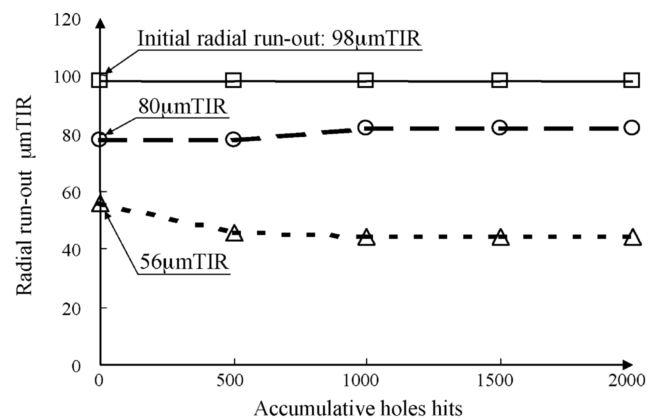

Fig. 14. Dependence of radial run-out on drilling time.

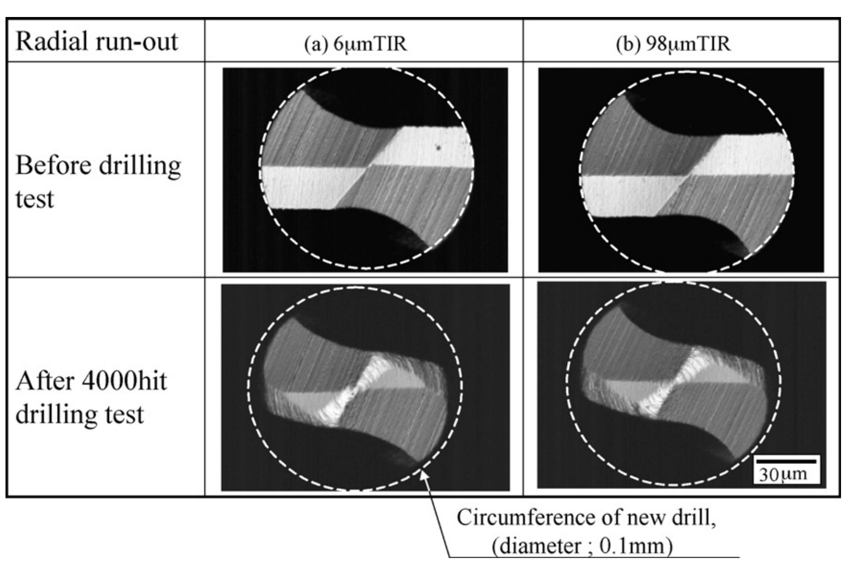

Fig. 12. Comparison of wear on top of drill at different radial run-outs.

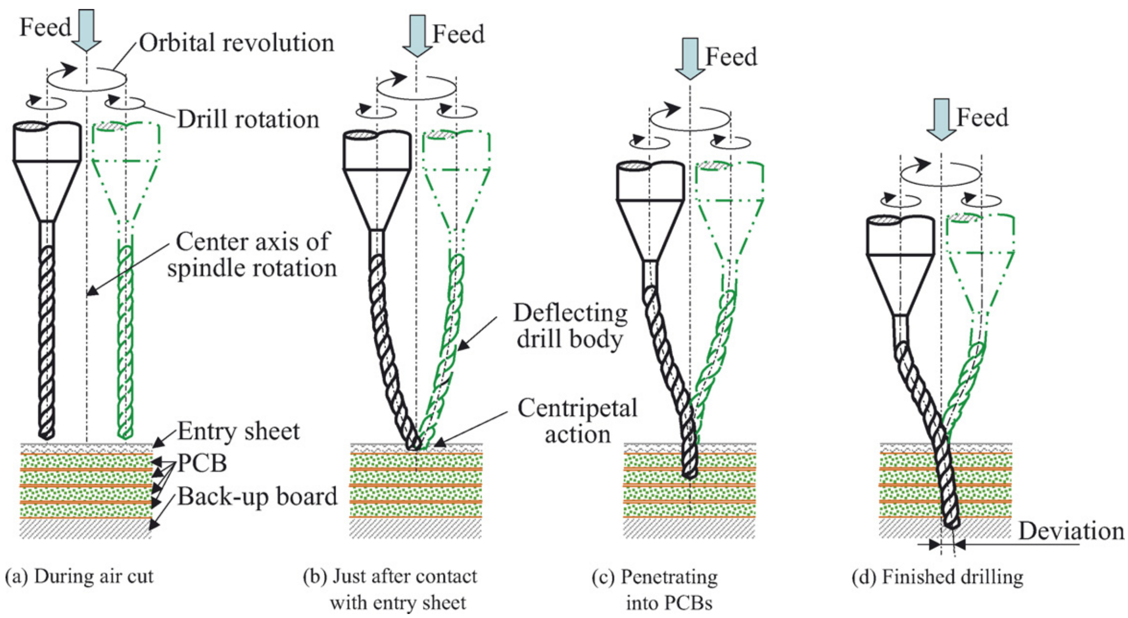

Fig. 15. Centering model of microdrill for PCB.

of accumulative hits, although inevitable drill wear is gradually increasing.

It should be noted that the centripetal action is maintained during drilling, and radial run-out is not significantly influential in hole quality nor drill wear for microdrilling by the use of optimal entry sheets. The independence of radial run-out is brought for the reason that microdrills have low stiffness and then the drill tip is easily centered by the centripetal action.

According to the above-mentioned discussion, centering model of microdrills with some radial run-out is proposed for PCB drilling, as shown in Fig. 15.

However, generating mechanism of centripetal action has not revealed yet. It will be reported in detail in near future.

4. Conclusions

In order to improve the productivity and breakage life which are controversial in microdrilling for PCB, this paper deals with the correlation between radial run-out and the hole quality in drilling tests using 0.1-mm diameter drills at a rotational speed of 3×10^5 min^{-1}. The conclusions obtained within the experimental conditions are as follows:

1. The radial run-out which is below 100 μm hardly affects the hole quality.
2. Orbital revolving drills primarily move toward the centripetal direction just after contact with a work surface. An entry sheet effectively enhances the centripetal action.
3. The radial run-out is hardly influential on drill wear, because of the centripetal action under low bending stiffness in 0.1-mm diameter drills.
4. The centripetal action makes drill wear insensitive to the radial run-out.
5. Centering model is proposed in consideration of centripetal action with a microdrill for PCB drilling.

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