621.59

Paper No. 214-24

Positional Accuracy of Hole in Drilling* (Effect of Rigidity and Point Geometry of Drill)

By Keizo SAKUMA** , Hiroshi KIYOTA**
and Hidenori MORITA***

Hole positional accuracy, which is important in drilling operations with automated machine tools, e.g. NC machining-centers, is examined by a special runout device.

Positional deviation of a drilled hole from the spindle rotating axis is mostly determined at the beginning of penetration. This deviation is caused by the deflection of tool rotating axis around a certain point on chisel edge. The experimental results indicate the drill overhang length has a significant influence on the hole positional accuracy. A fine feed in start of drilling and a spiral type of drill point grinding are effective to reduce such deviation. Stub tooling system, which gives a strong bending rigidity of tool, is a desirable technique to improve the positional accuracy in drilling operations.

Key Words: Drilling, Hole positional accuracy,
Tool behavior, Mechanism of deflection,
Drill overhang length, Point geometry

1. Introduction

Twist drills are widely used in factories. Positional accuracy of holes is one of the most important factors in drilling operations with automated machine tools, e.g. NC machining-centers.

Other workers reported a variety of papers on drilling accuracy. But they almost used a relatively small size of drilling machine with low rigidity, which has a significant influence on the hole accuracy(1)-(3). The tool and machine spindle tend to deflect in such drilling operations. Little is known about the deflecting behavior of the tool itself, which drifts away from the spindle rotating axis during cutting.

An experimental study was conducted using an NC vertical milling machine with high rigidity in its spindle system. The deflecting mechanism of the conventional point drill is clarified by observing the tool behavior at the beginning of

penetration and by measuring the positional accuracy of drilled hole with a special runout measuring instrument. Furthermore, several kinds of twist drills of long and stub length with a variety of point shapes (conventional point, split point, spiral point, and "three-rake" point) were prepared to examine the influence of tool rigidity and point geometry on the positional accuracy of drilled holes.

2. Experimental Procedure

6mm diameter straight shank drills (material AISI M2 HSS) of two different lengths were mainly used in this experiment. Their dimensions and rigidities are shown in Table 1. DIN338 standard drills (J: jobber series) have lengths close to those of JIS B4301 standard drills (E), and DIN1897 drills (S: stub series) are ultra-short length drills. Fig.1 shows four different kinds of point geometry used in this experiment. "A" is a conventional point finished

Table 1 Dimension and type of tested tools

Symbol of drill type	Tool standard	Dimension		Overhang length lo mm	Bending stiffness N/ μ m	Drill type
		Overall length L mm	Flute length l mm			
J	DIN338	93	57	60	0.083	Jobber length
S	DIN1897	66	28	35	0.34	Extra stub
E	JIS B4301	100	68	75	0.028	Standard length

* Received 5th June, 1981.

** Professor and Research Associate, Faculty of Engineering, Kyushu University, Hakozaki, Fukuoka, 812.

*** Engineer, Nippon Steel Co., Tobata, Kitakyushu, 804.

by cone grinding method.

"B" is a split point which is formed by applying X type thinning on "A" point.

"C" is a spiral point finished by spiral grinding method.

"D" is a "three-rake" point finished by special grinding method ("Avyac" type).

To minimize inaccuracy between each cutting lip of tool, all tested drills were produced by precise flute grinding process (only JISB4301 tools were produced by hot rolling process). Table 2 shows statistical values in geometrical accuracy of the drill point, which is thought to influence the hole accuracy(4).

A bed type NC milling machine (7.5Kw, Model MHA400II by Osaka Kiko Co.) was used. Tested tool was clamped in a collet type tool holder to keep the magnitude of tool runout less than 10 μ m. For the tested work material, AISI 1045 steel plates (BHN 190, 120 $\times$ 120 $\times$ 22mm) were prepared. Further, in order to eliminate the influence of unevenness of the workpiece

surface as much as possible at the beginning of cut, both sides of the plates were surface ground (roughness along grinding direction: Ra 0.14 μ m, that across this direction: Ra 0.30 μ m), and the setting of the plates on machine table was ascertained to be within 0.01mm/100mm.

In experiments, fifty blind holes were drilled without guide bushing to a depth of 21mm with each tool and the values of positional deviation of holes measured after drilling were statistically analyzed to examine the degree of scatter.

The cutting conditions were chosen as follows: cutting velocity $V=0.38$ m/s (23m/min, spindle rotational speed $N_s=1200$ rpm), feed rate $f=0.15$ mm/rev and emulsion type cutting fluid was supplied during cutting.

Fig.2 shows the measuring procedure for positional accuracy of drilled hole. Signals of spindle rotation obtained through a gear on the top end of the spindle synchronize the movement of the rotating table of a polar graph (PL-2P by Riken Denshi Co.). Deflection signal obtained by a strain-gauge type runout measuring instrument (own made), which is clamped on the tool after each drilling, can be recorded on this polar chart. The relation between the axis of rotating table of instrument and the axis of machine spindle is checked using a master ring gauge of 10mm diameter. Since both profiles are in good agreement as shown in Fig.3, it is thought that the axis of rotating table coincides with the axis of machine spindle.

Positional accuracy of the drilled hole was measured at several sections of depths of $h=0, 5, 10$, and 15mm. A strain-gauge type cutting dynamometer(5), which indicates torque, thrust and radial forces in two directions (X,Y), was used to examine the deflecting mechanism of the tool and the formation of a multi-corner profiled hole.

A:Conventional point
B:Split point(X-thinning)
C:Spiral point
D:Three-rake point(Avyac type)

Fig.1 Type of point geometry

Table 2 Measured values of drill point geometry of tested tools (DIN338 standard tools)

Measured item	Standard value	Measured value							
		J_A		J_B		J_C		J_D	
Point angle	$118 \pm 3^\circ$	$59^\circ 46'$ (29')	$119^\circ 37'$ (51')	$59^\circ 44'$ (21')	$119^\circ 30'$ (45')	$59^\circ 54'$ (11')	$119^\circ 55'$ (22')	$59^\circ 50'$ (7')	$119^\circ 40'$ (16')
Lip height difference mm	<0.06	$m=0.006$ ($s=0.002$)		0.012 (0.006)		0.013 (0.013)		0.034 (0.017)	
Primary lip relief angle	$16 \pm 3^\circ$	$15^\circ 25'$ (37')		$15^\circ 35'$ (15')		$11^\circ 45'$ (18')		$13^\circ 40'$ (23')	
		$15^\circ 6'$ (36')		$15^\circ 42'$ (21')		$11^\circ 56'$ (21')		$13^\circ 46'$ (26')	
Secondary lip relief angle	—	—		—		—		$35^\circ 30'$ (24')	
		—		—		—		$35^\circ 30'$ (14')	
Web eccentricity mm	<0.07	0.014 (0.004)		0.015 (0.002)		0.010 (0.001)		0.008 (0.004)	

m:mean value s:standard deviation

Fig.2 Measuring procedure of positional deviation of drilled hole

Fig.3 Relation between the axis of rotating table of polar graph and the axis of spindle rotation

3. Tool Behavior in Entry of Hole (J_A -tool)

The positional difference between the axis of spindle rotation (O_I) and the axis of drilled hole (O_{II} , the center of inscribed circle of the sectional profile obtained) is defined as the deviation of hole axis ($e_c = O_I - O_{II}$, see Fig.2).

For experimental method of observing tool behavior in drilling, a cylindrical master ring is usually clamped on tested drill. But we did not adopt this method, because installing of this ring may change the rigidity of the tool and it may influence the testing results. So, in this experiment, we examined the tool behavior by measuring unbalanced radial forces in two directions (X,Y), especially rotating component of radial force with spindle rotation and fixed component of radial force (fixed radial force). The deflecting movement of tool axis drifting away from spindle axis can be examined by observing the change of fixed component of radial forces in two directions. Direction and magnitude of tool deviation can be estimated by this.

A typical radial force diagram recorded on an oscillograph is shown

Tool: J_A (DIN338) Cutting conditions: Spindle rotational speed: $N_s = 120$ rpm Feed rate: $f = 0.15$ mm/rev

Fig.4 Variation of radial force when beginning of penetration

in Fig.4, using a conventional point drill (J_A -tool). It is found that right after the tool contacts with the workpiece surface, fixed radial force (the difference between the mean line and the reference line) arises, and there is little change in either its direction or magnitude after the shoulder portion of the tool enters into the hole (see Fig.22). Therefore, it seems that the positional deviation of hole from the true axis may be mostly determined at the beginning of penetration.

A special device was prepared to examine the relation between the direction of chisel edge in contacting with the workpiece surface and the direction of drift of drilled hole axis. The direction of chisel edge was calculated from the phase lag between the contacting-signal of an electric circuit of the spindle rotation mark. The eccentric direction of hole axis was measured by the aforementioned method. The results obtained are shown in Fig.5. When drilling with $f = 0.15$ mm/rev, directions of deviation of hole axis are concentrated in the left side, and when with a very small feed ($f = 0.01$ mm/rev), the deviating directions are scattered (see Fig.5). But this direction of deviation is not correlated with the direction of chisel edge. Therefore, the deflecting mechanism of the tool in one spindle rotation from start of cut, is considered to be such as shown in Fig.6.

The straight portion of chisel edge may not contact with the workpiece surface in full length (see Fig.20). Instead, a certain point on the chisel edge out of the tool axis (O_{IV}), by the effect of errors in manufacturing or setting-up of the tool, may make first contact (in the case of $f = 0.15$ mm/rev in Fig.5, a given point on the chisel edge of the asterisk mark side). For example, let the initial state be ①. As the spindle rotates, the chisel edge with the aforementioned contact point P_1 or another point near it, a rotating axis (O_I') makes a rotational movement in the direction of the arrow mark on the solid line, and proceeds to state ②. Then, the tool axis moves in the direction of the arrow mark on the dotted line. Following that, P_2 on the opposite side of P_1 on the chisel edge becomes a rotating axis and proceeds to state ③ and O_{IV} also moves. The drilled hole axis may deviate from the true axis due to the above. Considering the movement of the

tool in approximately one spindle rotation, $O_I - O_{II}$ is equivalent to the magnitude of positional deviation. It seems that O_{II} or O_I' near it may become a rotating axis because of little change in magnitude in fixed radial forces and no "walking" phenomena of drill are seen after that as shown in Fig.4.

In drilling operations with J_A - tools, some errors in manufacturing or setting-up may inevitably cause a deviation of drilled hole axis from the true axis.

4. Influence of Feed Rate on Positional Accuracy of Drilled Hole

Fig.7 shows the relation between the feed rate and the magnitude of positional deviation in drilled hole using J_A - tools. There was small influence on measured values at the usual range of feed rate. Fig.8 shows the drift direction of hole axis, in which special tendency of direction is not observed. But this is different from the experimental results obtained by C.H.Kahng et al.(1)(2), using upright drilling machines. It is considered that the above results are due to the high rigidity of machine tool in our experiment. Therefore, the influence of the tool geometry on drilling can be discussed

Fig.5 Direction of deviation of tool axis

Fig.6 Deflecting mechanism of tool axis from the true axis

in our paper.

Further, drilling test with a two-step-feed method was carried out, using a numerical control device as follows;
 1st cut: drilling depth $h=0.3\text{mm}$ with a very small feed ($f=0.01\text{mm/rev}$).

2nd cut: drilling depth $h=21\text{mm}$ with a regular feed ($f=0.15\text{mm/rev}$).

Mean values of positional deviation obtained by the above method are about 40% smaller than those in the conventional feed and its distribution patterns are also different as shown in Fig.9.

Fig.10 shows the comparison of the hole profile when countersunk with the two feed methods (quick returning the tool after dwelling $2/3$ of a spindle rotation at a depth of $h=0.3\text{mm}$). The profile obtained with $f=0.15\text{mm/rev}$ looks almost circular and with $f=0.01\text{mm/rev}$, a three cornered polygonal profile is clearly observed, which is formed by "walking" of drill.

In Fig.11, variation of radial force which changes two times per spindle rotation shows that "walking" of drill

Fig.7 Effect of feed rate on positional deviation of hole

Fig.8 Direction of deviation in drilled hole axis

occurs. As shown in Fig.12, thrust force with $f=0.15\text{mm/rev}$ rises rapidly, while with $f=0.01\text{mm/rev}$ it arises gradually. The value of thrust force with $f=0.01\text{mm/rev}$ is so small that the tool can move easily in a horizontal direction. This is also confirmed from the pattern of drift direction of hole axis in Fig.5. Further, hole diameter by countersinking is larger than the point portion of the tool. So, it is possible that elastic recovering force has an effect on the tool deflection, and the tool axis makes a move within the range including the spindle rotating axis (see Fig.11). Therefore, the hole axis by countersinking in the case of a very small feed should be located close to O_I unlike the conventional feed. When the feed rate is changed from $f=0.01\text{mm/rev}$ to $f=0.15\text{mm/rev}$ with NC program, the tool follows the countersunk hole and goes deeper, resulting in a small positional deviation.

In the case of ordinary feed value, "walking" phenomenon of drill including O_I is suppressed because thrust force is large at the beginning of penetration. This is shown in out-of-roundness diagram.

5. Influence of Tool Geometry on Positional Accuracy of Drilled Hole

5.1. Effect of Tool Overhang Length

Fig.13 shows the distribution (histogram) of values of hole positional deviation (e_c) obtained in drilling tests using conventional point drills of different

1st cut: Drilling depth 0.3mm with fine feed ($f=0.01\text{mm/rev}$)
2nd cut: Drilling depth 21mm with regular feed ($f=0.15\text{mm/rev}$)
Measured section of hole: 5mm depth

Fig.9 Positional deviation of drilled hole with the two-step-feed method

(a) $f=0.15\text{mm/rev}$ (b) $f=0.01\text{mm/rev}$
Spindle rotational speed: $N_s=1200\text{rpm}$
Dwelling: $2/3$ revolution
Cutting depth: $h=0.3\text{mm}$

Fig.10 Comparison of hole profiles during countersinking

overhang lengths (see Table 1). Overhang length of drill is significant for tool rigidity (rigidity of S_A -tool is about four times as large as that of J_A -tool, and that of J_A -tool is about three times as large as that of E_A -tool). It is clearly seen that the tool rigidity influences the mean value of positional deviation.

The variation of radial force in drilling with S_A -tool and J_A -tool shown in Fig.14 shows that the magnitude of variable radial force component of S_A -tool is about three times as large as that of J_A -tool, which means the tool enters into the hole under small tool deflection.

Fig.15 shows roundness profiles in the drilled hole section at a depth of $h=3\text{mm}$. Multicorners were not observed in the hole profile by drilling of S_A -tool, but many irregular scratches in the hole wall surface were noticed.

5.2. Effect of Tool Point Geometry

(1) Case of Standard Length Tool (DIN338 type, jobber length)

Fig.16 shows the distribution of measured values of hole positional deviation obtained by tools with a variety of point geometries (A, B, C, D), in which m indicates mean value and s indicates standard deviation of runout.

There is small difference in mean values between the J_A -tools, but a considerable scatter of individual value is observed. Because of the deflecting mechanism of the J_A -tool discussed in Section 3, it is difficult for this tool to give a precise hole whose axis agrees

Tool: J_A (DIN338) Cutting conditions: Spindle rotational speed: $N_s=1200\text{rpm}$ Feed rate: $f=0.01\text{mm/rev}$

Fig.11 Variation of radial force with a fine feed at the beginning of penetration

Spindle rotational speed: $N_s=600\text{rpm}$

Fig.12 Comparison of thrust force between regular feed method and two-step-feed method

with the spindle rotating axis. The operation was repeated fifty times under each condition. Specific values of hole positional deviation were usually obtained continually. It seems that the above may occur because of some small fragments sticking to the chisel edge, changing in size and position periodically. And this seems to be the cause of the scatter of values.

When using split point drills (J_B -tools), mean values of positional deviation are larger than those of J_A -tools and differences between the tools are also

Cutting conditions: Spindle rotational speed: $N_s=1200$ rpm Feed rate: $f=0.15$ mm/rev
Measured section of hole: 5mm depth

Fig.13 Effect of tool overhang length on the positional deviation of hole (A type tool)

Fig.14 Effect of tool overhang length on unbalanced radial force

(a) S_A (DIN1897) (b) J_A (DIN338)

Measured section of hole: 3mm depth

Fig.15 Comparison of roundness profile

observed. The split point shape is formed by grinding off the rear side of the chisel edge of a conventional point drill one side at a time. Therefore, this type of tool has secondary straight edge near the top. The hole sections in the longitudinal direction was photographed in Fig.17. Since the center point is somewhat peaked, thrust force at the beginning of penetration in Fig.18 rises in a more gradual slope than with the other drills. It was expected to give smaller values than the other types of tools in hole positional deviation. But it was difficult to apply accurately symmetrical thinning on the both cutting edges. Unbalanced force occurs by an unsymmetrical cutting action of the both edges, especially the secondary edges, during countersinking as shown in Fig.19. It seems that the component of radial force may cause the tool axis to deviate from the true axis. The difference in values of positional deviation between the tools is also considered to be caused by the difference in the deflection of the tools due to the unsymmetry of thinning.

Mean values of positional deviation by the spiral point drills (J_C -tools) of a curved and S-shaped chisel edge were smaller than those of other drills. Compared with J_A -tools, an arbitrary point on the chisel edge close to the tool axis (O_{IV}) makes first contact with the workpiece surface as shown in Fig.20. Even if the tool deflects at the beginning of penetration, which gives self-piloting action, may act on the tool. So, the tool deflection tends to be reduced (see Fig.19). This type of drill is produced by using the formed wheel corresponding to spiral geometry in the point

Cutting conditions: Spindle rotational speed: $N_s=1200$ rpm Feed rate: $f=0.15$ mm/rev
Measured section of hole: 5mm depth

Fig.16 Effect of the point geometry of tool on the positional deviation of hole (DIN338 standard tool)

portion of the tool. It seems that the curved and S-shaped chisel edge may reduce the hole positional deviation.

"Three-rake" point drills (J_D -tools) are the type of tools which have the secondary edges (cutting lips). Since the point portion is peaked as shown in Fig.17, thrust force rises gradually. Further, smaller variation of radial force during countersinking in entrance of hole was observed. However, regarding the amount of hole positional deviation, this type of point was not as effective as the J_C -tool. The cutting action of each edge, if inaccurately ground individually by grinding, may be the same cause as in the case of the J_B -tool.

Work material: Aluminium A2017
Cutting conditions: Spindle rotational speed: $N_s=600$ rpm Feed rate: $f=0.15$ mm/rev
Dwelling: 2/3 revolution

Fig.17 Comparison of hole profile in longitudinal direction when varying the point geometry

Cutting conditions: Spindle rotational speed: $N_s=600$ rpm Feed rate: $f=0.15$ mm/rev

Fig.18 Variation of thrust force at the beginning of penetration

Cutting conditions: Spindle rotational speed: $N_s=120$ rpm Feed rate: $f=0.15$ mm/rev

Fig.19 Comparison of radial force at the beginning of penetration (split point drill, spiral point drill)

(2) Case of Stub Length Tool (DIN1897 type, stub length)

A histogram of hole positional deviation obtained in drilling with DIN1897 standard tools shows that difference is not significant in mean value or range of scatters for a variety of point geometries as shown in Fig.21. In the case of these tools, having about four times higher rigidity than that of DIN338 tools, it is clearly seen that the positional deviation is very small and multicornered profile is not formed in each hole. But irregular scratches were observed in hole wall surface.

6. Relation between Positional Deviation and Roundness Error in Drilled Hole

Fig.22 shows the relation between positional deviation and roundness error calculated by the "center of inscribed circle" method, changing the type of feed method of the tool.

The feed method influences not only the positional deviation but also the magnitude of roundness error and its profile in the drilled hole. Multicornered form error occupies the greater part in roundness error. In case of the two-step-feed method, the forming phenomenon of multicornered profile, namely "walking" of drill during countersinking, continues to the end of cut.

On the other hand, in case of the ordinary feed method, "walking" of drill during countersinking was not observed (see Fig.14). It seems that multicornered

Fig.20 Difference of the tool contact condition on the workpiece surface

Cutting conditions: Spindle rotational speed: $N_s=1200$ rpm Feed rate: $f=0.15$ mm/rev
Measured section of hole: 5mm depth

Fig.21 Effect of the point geometry of tool on positional deviation (DIN1897 standard tool)

profile at a depth of $h=5\text{mm}$ is formed by this movement occurring from the entering of the shoulder portion of the tool. This can be confirmed from Fig.4. Because of the inclination of the tool axis (6) due to its deflection, some time lag is observed when the two shoulders of the tool enter into the hole which changes the relative magnitude between the thrust force and the radial forces, especially the fixed radial forces. In ordinary feed method, the multicornered profile tends to be formed by this.

It is considered that multicornered in drilled hole may be not only formed by "walking" of drill (7)(8) at the beginning of penetration, but also by the radial forces caused by deflection of the tool axis from the true axis.

The value of roundness error in the drilled hole with the two-step-feed method can be within the stock of removal by the secondary process. Therefore, the two-step-feed method is thought to give desirable results with NC machine tools, etc.

7. Conclusions

From this study, the following conclusions can be drawn:

1) In the case of conventional point drill of ordinary length, a hole positional deviation is caused by the movement

of axis of the tool rotation around a certain point on the chisel edge at the beginning of penetration into the workpiece.

2) The start of drilling with a very small feed can suppress the positional deviation.

3) The magnitude of positional deviation of hole is mostly determined at the beginning of penetration, and it keeps almost constant after the tool shoulder enters into the hole.

4) It is very effective to shorten the tool overhang length, on the reduction of the positional deviation. In this case, type of point geometry is not significant. A stub drill of high rigidity should be utilized in precise drilling.

5) A spiral point drill with a curved chisel edge gives smaller positional deviation than drills with other type of point geometry.

6) Tool deflection causes unbalanced radial force during cutting. Tool vibration, excited by this force, reflects on the surface of hole wall and multicornered profile is formed.

References

- (1) Kahng, C.H., Ann. CIRP, Vol.24, No.1 (1975), p.27.
- (2) Yuki, A., Research Bull. Fac. Education, Oita Univ., Vol.4, No.4(1974), p.39.
- (3) Garina, T.I., et al., Machines & Tooling, Vol.43, No.9(1972), p.47.
- (4) Kalder, S. and Lenz, F., Ann. CIRP, Vol.29, No.1(1980), p.23.
- (5) Sakuma, K. and Kiyota, H., Report in Meeting, Japan Soc. Prec. Engg. (in Japanese), (Oct. 1980), p.673.
- (6) Galloway, D.F., Trans. ASME, Vol.79 (1957), p.191.
- (7) Tueda, M., et al., Trans. Japan Soc. Mech. Engg. (in Japanese), Vol.27, No.178(1961), p.816.
- (8) Sakuma, K. and Kiyota, H., Jour. Japan Soc. Prec. Engg. (in Japanese), Vol.46, No.7(1980), p.856.

Tool: JA (DIN338) Spindle rotational speed: $N_s=1200\text{rpm}$ Measured section of hole: 5mm depth

Fig.22 Effect of feed method on roundness error

Tool: JA (DIN338) Cutting conditions: Spindle rotational speed: $N_s=120\text{rpm}$ Feed rate: $f=0.15\text{mm/rev}$

Fig.23 Radial force after the tool shoulder enters into hole (continued from that in Fig.4)