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Effects of Twist Drill Point Geometry on Torque and Thrust

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In this study, the effects of the point geometry on cutting performance of twist drills with straight lips are investigated systematically. Many drills with different web thicknesses, point angles, lip relief angles, helix angles and margin lengths were used, and torque and thrust in drillings were measured. The experimental results are assessed using variance analysis. Torque significantly increases with the web thickness and the margin length, and conversely decreases with the helix angle. There is an optimum point angle to minimize torque. Thrust significantly increases with the web thickness and the relief angle, and conversely decreases with the point angle and the helix angle. Twist drills with a web thickness of 1.0 to 1.5 mm, a point angle of about 118 deg., a relief angle of 8 to 13 deg., a helix angle of 29 to 39 deg. and a margin length of about 1 mm, are effective to reduce torque and thrust.

1. INTRODUCTION

In drilling operations, torque, thrust and drill life is significant criteria to evaluate the drill performance. Therefore, many investigations on torque and thrust have been performed for various drill diameters, drill point shapes, workpiece materials and cutting conditions, and important findings to reduce torque and thrust or predict them have been obtained [1 - 14]. Particularly regarding the relationships between drill point geometry and torque and thrust, Galloway [2] reported the effects of point angle, relief angle and helix angle. Kinman [3] showed the effect of chisel edge angle, while Lorenz [10] clarified the effect of helix angle. Watson [12] showed the effects of point angle and relief angle. However, no twist drill has been reported which simultaneously shows the effects of all the point parameters on torque and thrust. Although drill flute shapes vary with point parameters, no study to date on the cutting performance of all drills with straight lips for conical grinding has been reported.

In this study, torque and thrust were measured using five types of drills, which have different web thicknesses, point angles, lip relief angles, helix angles and margin lengths, respectively. The experimental results obtained were assessed using variance analysis, and the effects of the point geometry on the cutting performance of twist drills with straight lips were systematically investigated.

NOMENCLATURE

D	drill diameter (mm)
D_{rc}	relative depth between thinned chisel edge parts (mm)
F_c	nominal cutting force (kN)
H_{rl}	relative lip height (mm)
M_a	margin length (mm)
N	spindle speed of drilling machine (rpm)
r	drill radius (mm)
T_o	torque in drilling (kN・mm)
T_h	thrust in drilling (kN)
W_t	web thickness (mm)
α_0	relief angle at drill outer corner (deg.)
γ_0	helix angle of drill flute (deg.)
2κ	point angle (deg.)
ξ	chisel edge angle (deg.)

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2. DRILL POINT GEOMETRY

According to British Standard [15] and American National Standard [16] describing twist drill features, a twist drill point geometry with straight lips is identified by a web thickness W_t, a point angle 2κ, a lip relief angle α_0, a helix angle γ_0, a margin length M_a and a chisel edge angle ξ as shown in Fig. 1. Therefore, in order to clarify the effects of all the point parameters except for a chisel edge angle on torque and thrust, the five types of drills listed in Table 1 were used in the experiment. For example, W-type drills (W1-,W2- and W3-drills) are ones having different web thicknesses (W_t = 1.0, 1.5 and 2.0 mm, respectively), but the other point parameters, i.e., 2κ, α_0, γ_0 and M_a, are kept constant as indicated in Table 1. P-, R-, H- and M-type drills are ones having different point angles, lip relief angles, helix angles and margin lengths, respectively, and coded in the same manner as W-type drills. P2-, R2-, H2- and M2-drills are the same as a W2-drill. As shown in Table 1, W-, R-, H- and M-type drills were varied at three levels but four levels for P-type drills. All the twist drills used in this experiment were straight shank twist drills with 9 mm in diameter, 124 mm in overall length and 89 mm in flute length, and made of high speed tool steel. Two drills were prepared for each drill shown in Table 1.

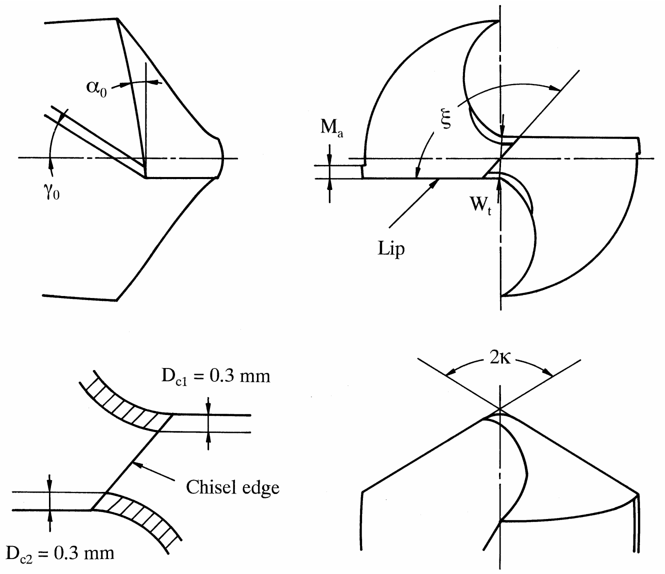

Fig. 1 Drill point geometry

Table 1 Dimensions and angles of drill point

Drill	Web Thickness W_t (mm)	Point Angle 2κ (deg.)	Relief Angle α_0 (deg)	Helix Angle γ_0 (deg.)	Margin Length M_a (mm)	Chisel Edge angle ξ (deg.)
W1	1.0	118	13	29	1.0	130
W2	1.5	118	13	29	1.0	130
W3	2.0	118	13	29	1.0	130
P1	1.5	110	13	29	1.0	130
P2(W2)	1.5	118	13	29	1.0	130
P3	1.5	130	13	29	1.0	130
P4	1.5	140	13	29	1.0	130
R1	1.5	118	8	29	1.0	130
R2(W2)	1.5	118	13	29	1.0	130
R3	1.5	118	18	29	1.0	130
H1	1.5	118	13	22	1.0	130
H2(W2)	1.5	118	13	29	1.0	130
H3	1.5	118	13	39	1.0	130
M2(W2)	1.5	118	13	29	1.0	130
M3	1.5	118	13	29	1.5	130
M4	1.5	118	13	29	2.0	130

In this experiment, all the drill points were shaped by a conical grinding method. In order that a drill lip becomes straight in this method, a flute shape in a plane normal to the drill axis (particularly A - B in Fig. 8 which generates a lip) must be varied corresponding to the web thickness W_t, the point angle 2κ and the helix angle γ_0, as described by the following parametric equations [2];

$$\begin{aligned} r &= \frac{W_t}{2}\operatorname{cosec}\,\phi \\ \nu &= \phi + \frac{W_t}{D}\tan\gamma_0 \cot\phi\,\cot\kappa \end{aligned} \qquad (1)$$

where r and ν are the polar coordinates of the flute shape and ϕ is the web angle. Therefore, the flute shapes of R- and M-type drills were the same as the flute shape of W2-drill, while the flute shapes of W-, P- and H-type drills differed from that of W2-drill. Conical grinding operations were carried out carefully so that each drill had the point angle and the relief angle prescribed in Table 1. Table 2 shows the mean relative lip height H_{rl}, which indicates the symmetry of two lips.

Since the increase of the web thickness enlarges a chisel edge, thrust in drilling operations may increase due to the enlarged chisel edge. Therefore, a thinning operation for the chisel edge was carried out for all but the W1-drill, which had the shortest chisel edge. The thinning operation was carried out carefully so that the depth of the thinned chisel edge parts (hatched portions in Fig. 1) was kept at round 0.3 mm. The mean relative depth between these two thinned parts ($D_{rc} = D_{c1} - D_{c2}$) is listed in Table 2.

Table 2 Relative lip height and relative depth between thinned chisel edge parts

Drill	H_{rl} (mm)	D_{rc} (mm)
W1	0.007	-
W2	0.052	0.088
W3	0.022	0.110
P1	0.000	0.031
P2(W2)	0.052	0.088
P3	0.037	0.070
P4	0.060	0.045
R1	0.000	0.113
R2(W2)	0.052	0.088
R3	0.027	0.025
H1	0.010	0.052
H2(W2)	0.052	0.088
H3	0.017	0.046
M2(W2)	0.052	0.088
M3	0.047	0.042
M4	0.065	0.057

3. EXPERIMENTAL METHOD

Drilling tests were performed on a drilling machine in order to measure torque and thrust. The experimental apparatus used is shown in Fig. 2. A drill was equipped in the spindle, and a workpiece was fixed on a dynamometer as shown in the figure. While the drill was boring a hole with a depth of 15 mm, the torque and the thrust generated on the workpiece were detected by the dynamometer and stored in a microcomputer through amplifiers and an A/D converter.

Two spindle speeds of 530 and 690 rpm were used, and the feed rate was constant at 0.1 mm/rev. The dimensions of workpieces used were 25 mm in diameter and 25 mm in length, and the material was rolled steel for general structure with a tensile strength of 450 MPa and a hardness of 143 H_B. All drilling tests were carried out without coolant. The experiment was repeated four times for each drill.

As described above, the drill point geometry and the spindle speed were varied as two main factors. Therefore, two factorial experiments for each type of drills were performed, consisting of six different combinations of factors (eight combinations for P-type drills). The effects of the drill point geometry and the spindle speed on torque and thrust were then assessed using variance analysis.

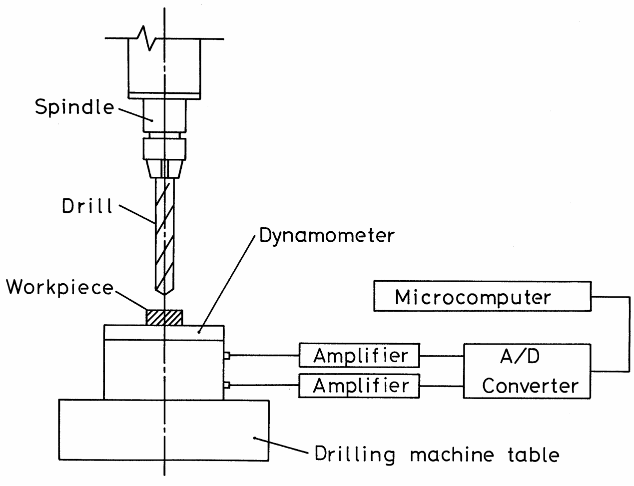

Fig. 2 Experimental set-up for measuring torque and thrust

4. EXPERIMENTAL RESULTS

4.1. Procedure for variance analysis

Figures 3 to 7 show the experimental results of torque and thrust obtained from the use of W-, P-, R-, H- and M-type drills, respectively. In the figures, the average values of torques or thrusts measured in eight drilling operations are plotted.

The procedure for variance analysis is shown in Table 3, in which the torque obtained from the use of W-type drills was analyzed. The main effects on the torque of the web thickness W_t and the spindle speed N, and the effect of their interaction on the torque, are shown in the same table. The effect of the web thickness W_t on the torque is significant at the 1 % critical rate indicated by the asterisk, because the F-ratio = 6.56 of the web thickness is larger than $F(2,42)_{0.01} = 5.16$ obtained from the F-distribution table [19]. The effects of the spindle speed N and the interaction $W_t \times N$ on the torque are insignificant. The F-ratios of the web thickness W_t, the spindle speed N and the interaction between them $W_t \times N$ obtained from Table 3 are summarized in Table 4 together with the F-ratios of the other drill point parameters.

Furthermore, in order to investigate the effects between two different levels (drills) in the same type of drills on torque and thrust, the following variance analysis was performed. The mean difference in torque and the mean difference in thrust between two different drills were obtained, and the results are summarized in Table 5. The values with an asterisk in the table are significant at the 1 % critical rate, because, for example, the mean difference in torque between W1- and W2-drills (307 N･mm) is larger than the value obtained from the following equation [19].

$$t_{0.01}[hk(q-1)]\left[\frac{2S'_E}{kq}\right]^{0.5} = 295 \qquad (2)$$

Where h = 3, k = 2 and q = 8 are the level of W-type drills, the level of the spindle speeds and the repetition of the experiments for each drill, respectively. S'_E is the mean square of the residual error (95395) indicated in Table 3, and $t_{0.01}[hk(q-1)]$ is the value of the t-distribution with the 1 % critical rate. Based upon these variance analyses shown in Tables 4 and 5, the experimental values of torque and thrust plotted in Figs. 3 to 7 were linked using curved lines.

Table 3 Variance analysis for torque of W-type drills

Source	Sum of squares	d.f.	Mean squares	F-ratio	Significance
Web thickness W_t	1252470	2	62635	6.56	*(a)
Spindle speed N	369440	1	369440	3.87	(b)
Interaction $W_t \times N$	252660	2	126330	1.32	(a)
Residual error	4006570	42	95395		
Total	5881140	47			

(a) $F(2, 42)_{0.01} = 5.16$; (b) $F(1, 42)_{0.01} = 7.29$.

Table 4 F-ratios of torque and thrust

	F-ratio			
	Torque		Thrust	
Web thickness W_t	6.56	*(a)	77.35	*(a)
Spindle speed N	3.87	(b)	2.68	(b)
Interaction W_t×N	1.32	(a)	0.22	(a)
Point Angle 2κ	8.91	*(c)	19.21	*(c)
Spindle speed N	21.18	*(d)	3.25	(d)
Interaction 2κ×N	0.66	(c)	0.20	(c)
Relief Angle α_0	2.37	(a)	12.10	*(a)
Spindle speed N	7.29	*(b)	12.32	*(b)
Interaction α_0×N	1.35	(a)	0.97	(a)
Helix Angle γ_0	14.38	*(a)	40.38	*(a)
Spindle speed N	20.79	*(b)	12.99	*(b)
Interaction γ_0×N	2.00	(a)	3.59	(a)
Margin Length M_a	28.06	*(a)	32.99	*(a)
Spindle speed N	20.00	*(b)	4.41	(b)
Interaction M_a×N	1.32	(a)	0.78	(a)

* significance (a) $F(2, 42)_{0.01} = 5.16$ (b) $F(1, 42)_{0.01} = 7.29$
(c) $F(3, 56)_{0.01} = 4.17$ (d) $F(1, 56)_{0.01} = 7.13$

Table 5 Differences in torque and thrust between two different drills

Drill	Torque (N·mm)				Thrust (N)			
	W1	W2	W3		W1	W2	W3	
W1	-				-			
W2	307*	-			144*	-		
W3	369*	63	-		380*	235*	-	
	P1	P2	P3	P4	P1	P2	P3	P4
P1	-				-			
P2	-292*	-			-56*	-		
P3	-121	171*	-		-77*	-21	-	
P4	-67	226*	55	-	-119*	-63*	-42	-
	R1	R2	R3		R1	R2	R3	
R1	-				-			
R2	-191	-			27	-		
R3	-32	159	-		72*	45*	-	
	H1	H2	H3		H1	H2	H3	
H1	-				-			
H2	-440*	-			-132*	-		
H3	-387*	53	-		-157*	-25	-	
		M2	M3	M4		M2	M3	M4
M2		-				-		
M3		301*	-			38*	-	
M4		517*	217*	-		-54*	-92*	-

4.2. Effect of spindle speed

Table 4 shows that the effects of the spindle speed N on torque are significant except for W-type drills, whereas the effects of the spindle speed on thrust are insignificant except for R- and H-type drills. Figures 4 to 7 show that the increase in spindle speed, (i.e., the increase in cutting speed) diminishes the torque.

As a drilling action is mainly carried out at the lips and the chisel edge of a drill, torque and thrust are influenced by cutting force generated at the lips and the chisel edge. Most of the torque is due to the cutting action at the lips, because the drill radius along the lips is longer than the radius along the chisel edge. On the other hand, a considerable amount of thrust is due to the cutting action at the chisel edge [4, 7]. This is in turn due to a large negative rake angle along with a very small cutting velocity in the chisel edge zone. Therefore, it is clarified that the effect of the spindle speed on torque is generally greater than the effect of the spindle speed on the thrust within the cutting conditions and the workpiece material used in the experiment.

4.3. Effect of web thickness

Table 4 shows that the effects of the web thickness W_t on the torque and the thrust are significant at the 1 % critical rate. As shown in Fig. 3 and Table 5, the thrust shows an extreme increase with web thickness, since the chisel edge length increases with the web thickness. In addition, the rake angle at the thinned chisel edge parts of W2- and W3-drills is still negative. On the other hand, the torque slightly increases between the web thickness $W_t = 1.0$ and 1.5 mm, but hardly between $W_t = 1.5$ and 2.0 mm, since the torque depends mainly on the cutting action at the lips. Therefore, it is clarified that the effect of the web thickness on the thrust is greater than the effect of the web thickness on the torque.

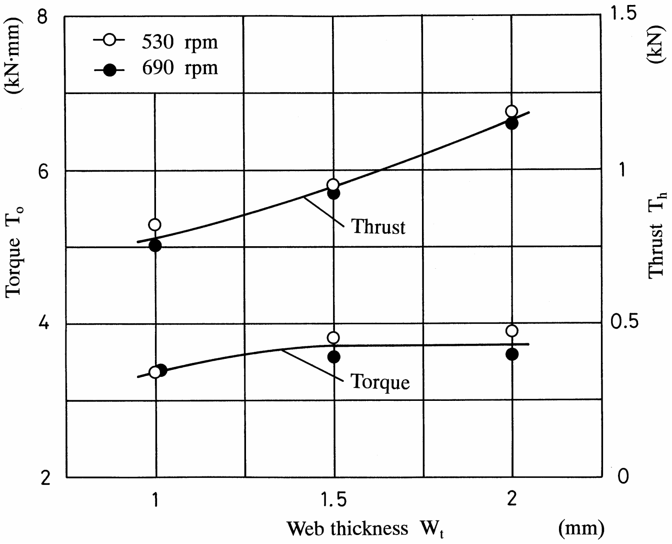

Fig. 3 Torque and thrust of W-type drills

4.4. Effect of point angle

Table 4 shows that the effects of the point angle 2κ on the torque and the thrust are significant. Figure 4 and Table 5 show that the thrust slightly decreases with the point angle. Since torque is lowest at 118 deg., this point angle is desirable to minimize torque.

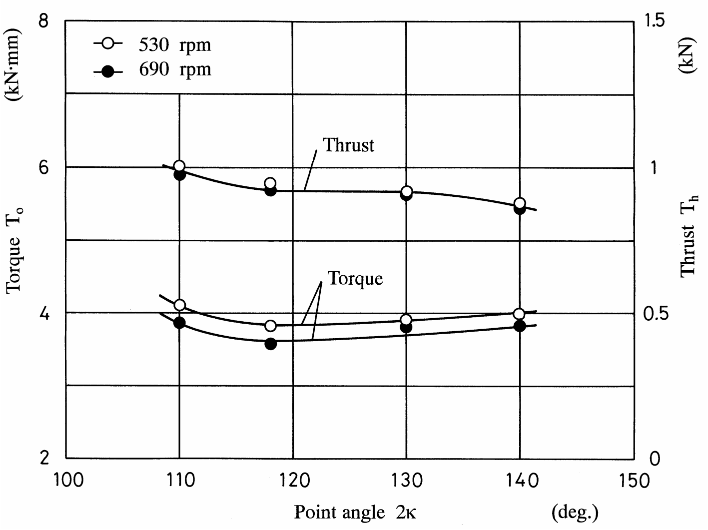

Fig. 4 Torque and thrust of P-type drills

4.5. Effect of relief angle

The effect of the relief angle α_0 on the thrust is significant, whereas the effect on the torque is insignificant as shown in Table 4. It is clear from Fig. 5 and Table 5 that the thrust does not vary between the relief angle $\alpha_0 = 8$ and 13 deg., but slightly increases between $\alpha_0 = 13$ and 18 deg.. On the other hand, the torque maintains a constant value corresponding to the spindle speed.

Therefore, the effect of the relief angle on the thrust is greater than on the torque. In addition, the increase in relief angle often causes whirling vibration in drilling operations [17, 18]. Therefore, a relief angle of 8 to 13 deg. is suitable to diminish thrust and suppress the whirling vibration in drilling.

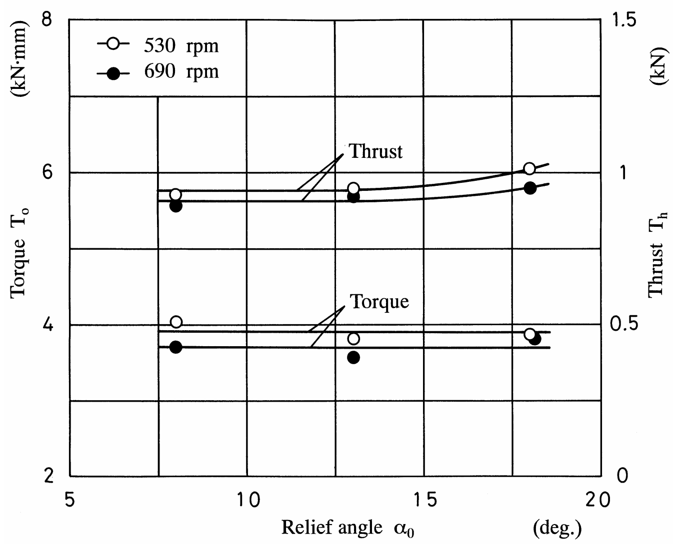

Fig. 5 Torque and thrust of R-type drills

4.6. Effect of helix angle

Table 4 shows the significant effects of the helix angle γ_0 on the torque and the thrust. It is clear from Fig. 6 and Table 5 that the torque and the thrust rapidly decreases between the helix angle $\gamma_0 = 22$ and 29 deg., since a rake angle on the lips increases with the helix angle. However, the torque and the thrust remain constant in spite of the further increase in helix angle. This may be explained by the fact that an excessive helix angle makes a chip flow difficult in the flutes, because the increase in helix angle decreases the area of the flute zone as shown in Fig. 8. Furthermore, an excessive increase in helix angle weakens the drill lips. Therefore, a helix angle of 29 to 39 deg. is suitable to diminish torque and thrust.

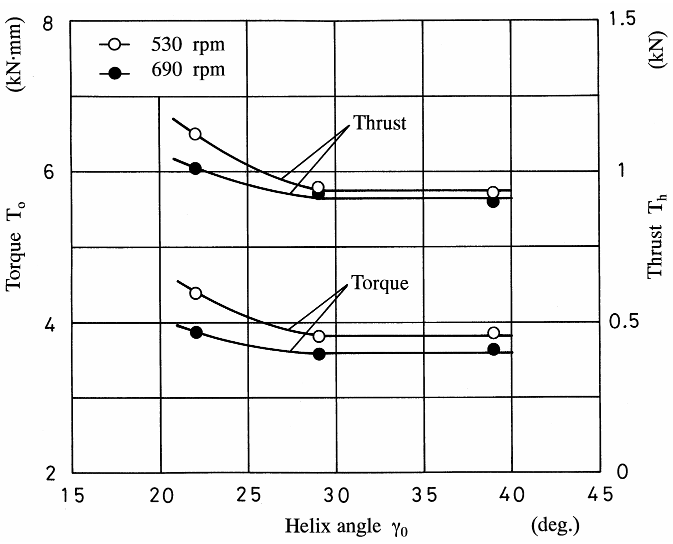

Fig. 6 Torque and thrust of H-type drills

4.7. Effect of Margin length

It is found from Table 4 that the effects of the margin length M_a on the torque and the thrust are significant. Figure 7 and Table 5 show that the torque considerably increases with the margin length due to the friction between the drill margin and the inner surface of a hole bored. Therefore, it is important to avoid the use of drills with unnecessarily large margin in order to reduce the torque; a margin length of about 1 mm is suitable.

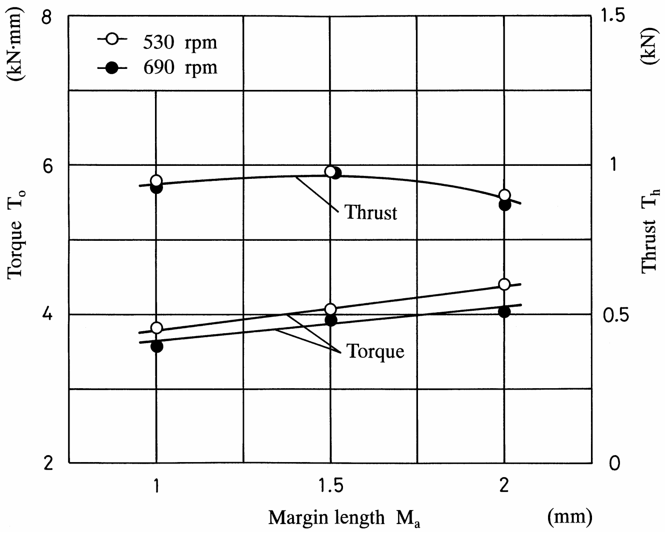

Fig. 7 Torque and thrust of M-type drills

4.8. Comparison of all drills

The effects of each drill point parameter on torque and thrust have been clarified in the previous sections, but a comparison of all the drills used in the experiment was not made. Therefore, a mean torque for each drill was obtained including the two spindle speeds. Figure 9 shows the mean torques for all the drills arranged in order of magnitude. Figure 10 shows the mean thrusts obtained by the same manner as for torque. In terms of torque, W1-drill is the most effective, followed by W2- and H3-drills, in that order. As for thrust, W1-drill is the most effective, followed by P4- and M4-drills. Thus, the cutting performance of drills should be assessed using both torque and thrust.

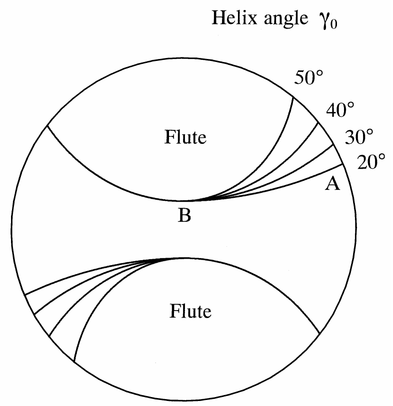

Fig. 8 Flute shape in a plane normal to drill axis ($D = 9$ mm, $W_t = 1.5$ mm, $2k = 118$ deg.)

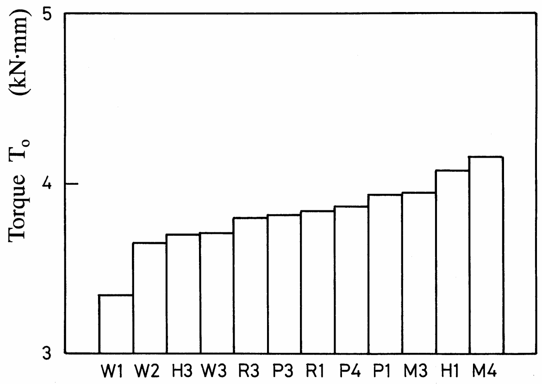

Fig. 9 Torque of all drills

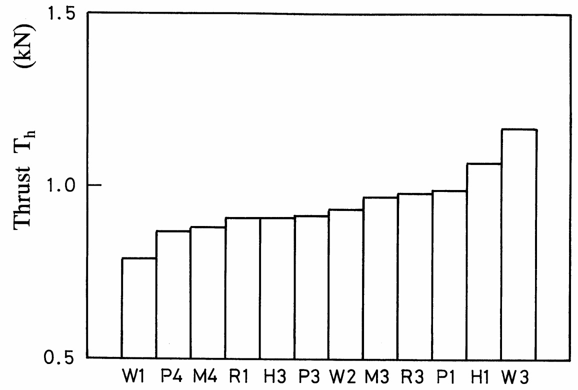

Fig. 10 Thrust of all drills

In an assumption that the torque measured during a drilling operation acts at the middle of a lip (a half of drill radius r = 9/4 mm), a nominal cutting force F_c was calculated from the following equation.

$$F_c = \left[\left(\frac{T_0}{r}\right)^2 + T_h^{\ 2}\right]^{0.5} \tag{3}$$

Figure 11 shows the nominal cutting forces estimated in this manner. It is found from the figure that W1-, W2- and H3-drills are effective. W3-, M-4 and H1-drills are less effective because of the largest thrust in W3-drill, the largest torque in M4-drill and the considerably large torque and thrust in H1-drill, as shown in Figs. 9 and 10. In addition, the nominal cutting forces estimated for other lip positions within r = 9/4 ± 0.5 mm are similar to the results shown in Fig. 11. W1-, W2- and H3-drills are similar to the drills recommended in handbooks for producing holes in steel materials [20, 21]. The results obtained in this study provide evidence to explain why these drills are widely used in practical operations.

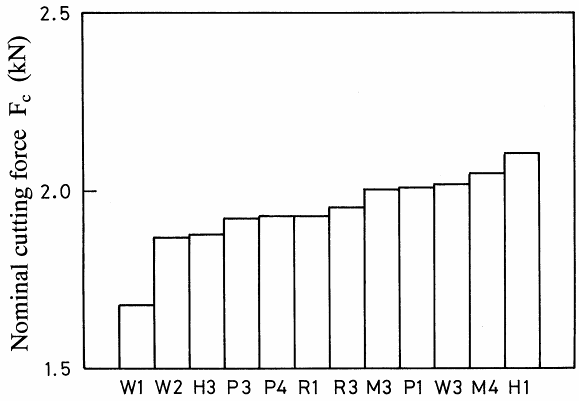

Fig. 11 Nominal cutting force of all drills

5. CONCLUSIONS

Torque and thrust in drillings were measured using twist drills with various point shapes. The effects of the point geometry on the cutting performance of twist drills were assessed by variance analysis, and the following conclusions can be made within the cutting conditions and the workpiece material used in the experiment.

(1) The effect of the spindle speed on torque is generally significant, and the increase in spindle speed reduces torque. However, the effect of spindle speed on thrust is generally insignificant.

(2) Torque significantly increases with the web thickness and the margin length, and conversely decreases with the helix angle. Torque is not affected by the relief angle. There is an optimum point angle to minimize torque. Thrust significantly increases with the web thickness and the relief angle, and conversely decreases with the point angle and the helix angle. The margin length generally does not affect thrust.

(3) Twist drills with a web thickness of 1.0 to 1.5 mm, a point angle of about 118 deg., a relief angle of 8 to 13 deg., a helix angle of 29 to 39 deg., and a margin length of about 1 mm, are effective to reduce torque and thrust.

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