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Effect of Coolant upon Hole Making Accuracy of Ti6Al4V by Drilling — Consideration of Hole Diameter in the Depth Direction —

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Abstract

Ti6Al4V, which is one of difficult-to-cut metals, is widely used in an aircraft structure, parts of a gas turbine and medical equipment so that a hole making operation of Ti6Al4V is indispensable to fasten the parts. When a highspeed drilling by a conventional twist drill is applied to hole making of Ti6Al4V, it is very difficult to obtain highly accurate hole in diameter, roundness and inlet-outlet edge quality due to a rise of cutting temperature caused by its small heat conductivity. Moreover, it is well-known that Ti6Al4V causes transiently phase transformation from α phase (close-packed hexagonal lattice) to β phase (body-centered cubic lattice) as soon as it reaches the phase transformation temperature of 883 ℃ (1621 ℉).

When coolant is spouted from two coolant holes at the tip of twist drill to decrease a rise of cutting temperature, the temperature rise of twist drill and chip will be restrained thoroughly. However, it is thinkable that the temperature of Ti6Al4V neighboring the hole's wall drilled would not be reduced so much since heat entering the workpiece is scarcely carried away by supplying coolant. In a machining site a deep hole shape of Ti6Al4V drilled often faces to be smaller in the depth direction although it is well-known that those of steel and aluminum alloy are smaller at the top than near the bottom such as a bell shape.

To make clear the effect of coolant upon hole diameter in drilling of Ti6Al4V, a lot of holes having ϕ 8 mm × 24 mm depth for Ti6Al4V were machined by dry drilling and wet drilling on the condition that a feed rate is fixed at 0.05 mm/rev and a rotational speed is varied at 12 steps from 500 rpm to 2500 rpm. After hole diameter and roundness were measured in relation to depth of hole, effect of temperature heated and phase transformation of workpiece upon hole diameter is considered by using the temperature distribution in Ti6Al4V neighboring the hole's wall drilled, which is estimated by referring the temperatures of workpiece, machined surface and drill during drilling verified by previous researchers, and metallurgy of phase transformation.

Consequently, it was ascertained that the hole shape of Ti6Al4V, which is larger at the top than near the bottom, is caused by contraction and phase transformation of Ti6Al4V due to heat entering workpiece, and coolant is not effective to correct the hole shape in the depth direction although it decreases hole diameter uniformly from the top to the bottom due to reduction of drill's heat expansion.

Keywords: Ti6Al4V, Drilling, Hole making accuracy, Effect of coolant, Hole diameter, Phase transformation;

1. Introduction

Temperature measurement of cutting edge in drilling was previously tried using a two-color pyrometer with an optical fiber. The temperature distribution along the cutting edge of a drill was measured, and the influence of spindle speed and feed rate on the tool temperature was investigated by Ueda, T., Nozaki, R and Hosokawa, A. The maximum tool temperature was observed during the drilling of carbon steel. Moreover, the effect of oil mist supplied from oil holes in the drill on the tool temperature was examined and the result was compared to that in turning and end milling. The temperature reduction in oil mist turning was approximately 5 %, while that in oil mist end milling was 10-15 % and that in oil mist drilling was 20-25 % compared to the temperature in dry cutting [1].

Li, R. and Shin, A.J. quantified the effects of cutting speed and cutting time on drill temperature distributions in dry drilling of Ti (ϕ9.92 mm). The complete temporal and spatial distributions of the drill temperature could be analysed accurately and validated experimentally. The peak temperature of the drill increased from 480 ℃ to 1060 ℃ as the peripheral cutting speed increased from 24.4 m/min to 73.2 m/min after 12.7 mm depth of drilling under the feed rate fixed at 0.051 mm/rev. The location of peak temperature moved outside toward the drill margin as the peripheral cutting speed increased [2].

Dandekar, C., Orady, E. and Mallick, P. K. disclosed following results from comparative study of drilling characteristics between polypropylene composite and an aluminum alloy; during drilling, both cutting speed and feed rate had an effect on temperature rise in the material around the hole. The maximum temperature rise, which occurred close to the drill exit point, was significantly higher for aluminum specimens. The maximum temperature rise occurred at the lowest feed rate and the highest cutting speed [3].

K. Watanabe, K. Yokoyama and R. Ichimiya had developed thermal and experimental analyses of the temperature distribution for a workpiece and drill and analysed thermal deformations of the workpiece and drill. The results indicated that the calculated temperature of the workpiece and drill are found to be close to the experimental results for carbon steel S50C and maximum inner diameter of the drilled hole appears near the end of drilling.[4].

Bono, M. and Ni, J. had developed a model to predict the effects of thermal distortion of the drill and workpiece on the diameter and cylindricity of dry drilled holes. The study considered the quality of holes produced when drilling in a workpiece of aluminum 319, using HSS drill of diameter 9.92 mm, with speed ranging from 3000 rpm to 7000 rpm, and with feed ranging from 127 μm/rev to 381 μm/rev. The model predicted that thermal distortions of the drill and workpiece led to oversized holes, with diameter errors ranging up to 26 μm. The holes had a bell shape and were smaller at the top than near the bottom, and the diametral variations within individual holes ranged from 17 μm to 26 μm [5].

L. C. Brandao, R. T. Coelho and C. H. Lauro had assessed temperature during drilling of hardened AISI H13 steel using embedded thermocouples which were fixed at distances very close to the hole's wall in three depth positions of the workpiece. Obtained results showed the maximum temperature assessed increases approximately linearly in the depth direction during both dry drilling and wet drilling [6].

M. Sato, H. Tanaka and S. Takeda had measured machined surface temperature in drilling by using fiber-coupled pyrometer. From dry drilling tests of SUS304 having 5 mm, 10 mm, 15mm thickness by cemented carbide drill ϕ12 mm at rotational speed of 300 rpm ～ 1200 rpm and feed rate of 0.04 mm/rev ～0.13 mm/rev, the maximum temperature of machined surface at the position of oil hole, which was shown after for the tip of drill to reach the undersurface of workpiece, was about 750 ℃ at 1200 rpm. The maximum temperature increased as the rotational speed increased, however, it was not so affected by feed rate [7][8].

Recently one of the authors examined ϕ15 mm hole making tests of Ti6Al4V plate having 5 mm thickness by orbital drilling with dry cut and supplying oil mist from oil holes of endmill. Obtained results showed that hole diameters by dry cut decreased from ϕ15.02 mm of first hole to ϕ14.43 mm of 40th hole, however, those by supplying oil mist were almost constant from ϕ 15.00 mm of first hole to ϕ14.96 mm of 40th hole [9]. Next, by applying an image data processing to the microstructures of specimens of Ti6Al4V neighboring the inner wall of hole it was ascertained that the ratio of β phase increased slightly as the hole number by dry drilling increased. Consequently, it was disclosed that since phase transformation from α phase (close-packed hexagonal lattice) to β phase (body-centered cubic lattice) would cause volumetric increase slightly, the hole diameter would be decreased slightly as increasing of hole number by dry drilling [10].

In this paper to make clear the effect of coolant upon hole diameter in drilling of Ti6Al4V a lot of holes having ϕ 8 mm × 24 mm depth for Ti6Al4V were machined by dry drilling and wet drilling on the condition that a feed rate is fixed at 0.05 mm/rev and a rotational speed is varied at 12 steps from 500 rpm to 2500 rpm. After that hole diameter and roundness were measured in relation to depth of hole. Finally, the effect of cutting temperature upon hole diameter in the depth direction is considered by using the temperature distribution neighboring hole's wall drilled, which is estimated by referring the temperatures of drill, workpiece and machined surface measured during drilling Ti, AISI H13 steel and SUS304 previously by other researchers [2][6][7].

This paper would contribute highly accurate hole making of Ti6Al4V for engineers to manufacture medical equipment and others.

2. Drilling Tests and Experimental Procedure

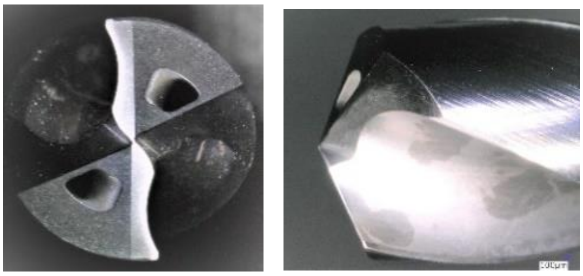
2.1. Experimental Apparatus and Workpiece

All drilling tests were carried out by using a vertical type machining center V33 made in Makino Milling Machine Co., Ltd. and a conventional twist drill having ϕ 8.0 mm of cemented carbide given Al-Cr heat-resistant coating made in OSG corporation. Workpiece of Ti6Al4V was 24 mm thickness, which is consisted of six stacks of 4 mm plate, and block of 25 mm thickness. Table 1 shows experimental apparatus, workpiece and coolant.

Figure 1 (a) (b) shows a tip's shape of conventional twist drill used and Figure 2 (a) (b) shows appearance of experimental apparatus, a drill attached to the main spindle of the machining center and a workpiece of Ti6Al4V, which is consisted of six stacks of 4mm plate, fixed on the table of machining center by attaching jig.

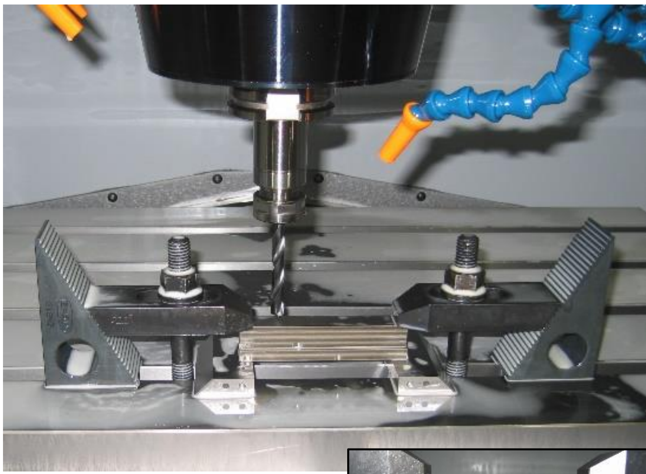
Table 1 Experimental apparatus, workpiece and coolant.

Machine used	Vertical type machining center V33 (Makino Machine Co., Ltd.)
Twist drill used	ϕ8×118 mm, Cemented carbide, Al-Cr heat-resistant coating (OSG corporation)
Workpiece Ti6Al4V	24 mm thickness (Six stacks of 4 mm plate) Block of 25mm thickness
Coolant	Soluble type B-cool 9965, 10%, 1.5MPa

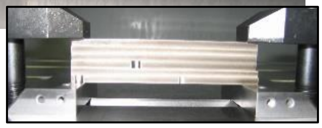


(a) Top view (b) Side view

Fig. 1 Tip's shape of conventional twist drill used (ϕ 8 mm).



(a) Appearance of experimental apparatus



(b) Workpiece (Six stacks of 4mm plate)

Fig. 2 Appearance of experimental apparatus and workpiece of Ti6Al4V fixed on table by attaching jig.

2.2 Drilling Conditions and Experimental Procedure

Summary of drilling conditions is shown in Table 2. As shown in Table 2 dry drilling and wet drilling were carried out on the condition that a feed rate is fixed at 0.05 mm/rev and a rotational speed of drill is varied at 12 steps in the range from 500 rpm to 2500 rpm.

After drilling operations hole diameter was measured by Mitutoyo Measuring Microscope Type MF at the back surface of each de-burred plate having 4 mm thickness and roundness was measured by Tokyo Seimitsu RONDCOM 60A at the inner surface of hole near back surface of the plate.

Based on the measured data hole diameter and roundness were indicated on a diagram in relation to depth of hole. To clearly verify the effect of cutting temperature, hole diameter and roundness were plotted as average values which were computed for three groups: the first group of 500 rpm, 600 rpm, 700 rpm and 800 rpm, the second group of 1800 rpm, 1900 rpm, 2000 rpm and 2100 rpm, and the third group of 2200 rpm, 2300 rpm, 2400 rpm and 2500 rpm.

Table 2 Summary of drilling conditions.

Drilling conditions		
Feed rate	0.05 mm/rev, fixed	
Coolant	Dry	Wet
Rotational speed of drill	Exp ① 500 rpm	Exp ❶ 500 rpm
	Exp ② 600 rpm	Exp ❷ 600 rpm
	Exp ③ 700 rpm	Exp ❸ 700 rpm
	Exp ④ 800 rpm	Exp ❹ 800 rpm
	Exp ⑤ 1800 rpm	Exp ❺ 1800 rpm
	Exp ⑥ 1900 rpm	Exp ❻ 1900 rpm
	Exp ⑦ 2000 rpm	Exp ❼ 2000r pm
	Exp ⑧ 2100 rpm	Exp ❽ 2100 rpm
	Exp ⑨ 2200 rpm	Exp ❾ 2200 rpm
	Exp ⑩ 2300 rpm	Exp ❿ 2300 rpm
	Exp ⑪ 2400 rpm	Exp ⓫ 2400 rpm
	Exp ⑫ 2500 rpm	Exp ⓬ 2500 rpm

3. Experimental Results

3.1. Hole Diameter and Roundness by Dry Drilling

Table 3 shows measured values and average values of three groups for hole diameter and roundness in relation to depth of hole by dry drilling.

Figure 3 shows the relation of average hole diameter in relation to depth of hole and Fig.4 shows the relation of average roundness in relation to depth of hole, respectively.

Table 3 Measured values and average values of three groups for hole diameter and roundness in relation to depth of hole by dry drilling.

Exp No.	Items	Depth of hole					
		4 mm	8 mm	12 mm	16 mm	20 mm	24 mm
Exp ① 500 rpm	Diameter (mm)	8.0309	8.0237	8.0232	8.0181	8.0053	8.0038
	Roundness (μm)	45.4	23.8	9.7	17.4	15.0	12.1
Exp ② 600 rpm	Diameter (mm)	8.0184	8.0156	8.0098	8.0060	8.0025	8.0040
	Roundness (μm)	49.6	26.0	11.1	16.2	10.3	8.7
Exp ③ 700 rpm	Diameter (mm)	8.0058	8.0128	8.0078	8.0066	8.0008	8.0022
	Roundness (μm)	30.9	9.1	6.3	7.6	6.0	8.9
Exp ④ 800 rpm	Diameter (mm)	8.0040	8.0107	8.0049	8.0056	8.0061	8.0047
	Roundness (μm)	34.8	11.9	9.8	9.8	6	6.7
Average of ①～④	Diameter (mm)	8.0148	8.0157	8.0114	8.0091	8.0037	8.0037
	Roundness (μm)	40.2	17.7	9.2	12.8	9.3	9.1
Exp ⑤ 1800 rpm	Diameter (mm)	8.0122	8.0145	8.0115	8.0121	8.0065	8.0141
	Roundness (μm)	41.7	18.2	15.7	17.6	16.5	25.2
Exp ⑥ 1900 rpm	Diameter (mm)	8.0258	8.0125	8.0045	8.0080	8.0026	7.9997
	Roundness (μm)	42.3	23.4	14.0	13.0	12.1	17.7
Exp ⑦ 2000 rpm	Diameter (mm)	8.0482	8.0245	8.0101	8.0115	8.0025	8.0008
	Roundness (μm)	59.6	56.0	23.7	32.6	24.1	23.0
Exp ⑧ 2100 rpm	Diameter (mm)	8.0298	8.0175	8.0162	8.0043	7.9977	8.0053
	Roundness (μm)	64.0	52.5	20.8	27.1	15.6	10.5
Average of ⑤～⑧	Diameter (mm)	8.0290	8.0173	8.0106	8.0090	8.0023	8.0050
	Roundness (μm)	51.9	37.5	18.6	22.6	17.1	19.1
Exp ⑨ 2200 rpm	Diameter (mm)	8.0221	8.0238	8.0203	8.0144	8.0163	8.0239
	Roundness (μm)	57.4	45.9	17.1	20.8	17.8	11.1
Exp ⑩ 2300 rpm	Diameter (mm)	8.0212	8.0172	8.0104	8.0145	8.0111	8.0134
	Roundness (μm)	58.0	43.7	17.7	24.7	14.6	12.9
Exp ⑪ 2400 rpm	Diameter (mm)	8.0248	8.0188	8.0114	8.0087	8.0012	8.0023
	Roundness (μm)	72.1	42.0	24.6	28.0	12.0	11.0
Exp ⑫ 2500rpm	Diameter (mm)	8.0250	8.0147	8.0130	8.0106	8.0086	8.0017
	Roundness (μm)	50.5	21.9	14.0	14.1	13.3	8.5
Average of ⑨～⑫	Diameter (mm)	8.0233	8.0186	8.0138	8.0121	8.0093	8.0103
	Roundness (μm)	59.5	38.4	18.4	21.9	14.4	10.9

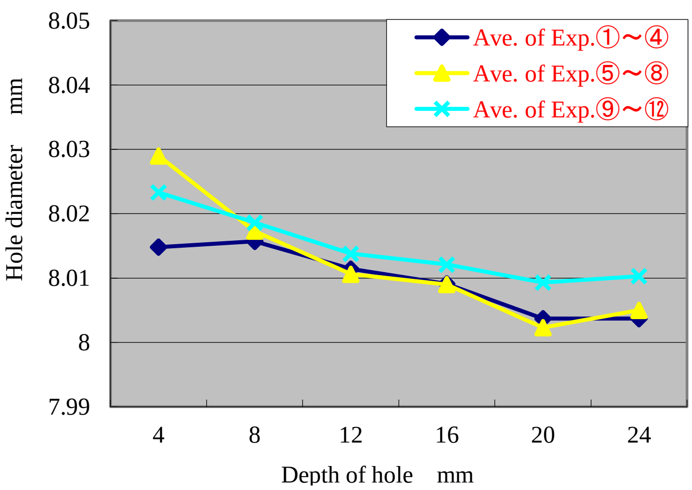


Fig. 3 Relation of average hole diameter in relation to depth of hole.

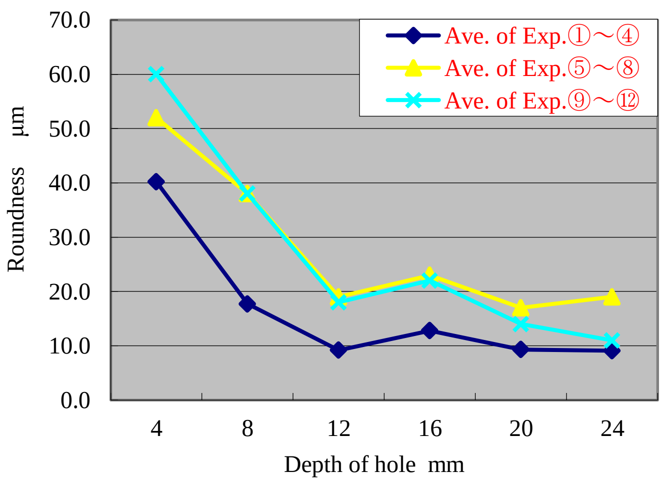


Fig. 4 Relation of average roundness in relation to depth of hole.

3.2. Hole Diameter and Roundness by Wet Drilling

Table 4 shows measured values and average values of three groups for hole diameter and roundness in relation to depth of hole by wet drilling.

Figure 5 shows the relation of average hole diameter in relation to depth of hole and Fig. 6 shows the relation of average roundness in relation to depth of hole, respectively.

Table 4 Measured values and average values of three groups for hole diameter and roundness in relation to depth of hole by wet drilling.

Exp No.	Items	Depth of hole					
		4 mm	8 mm	12 mm	16 mm	20 mm	24 mm
Exp ❶ 500 rpm	Diameter (mm)	7.9996	7.9953	7.9941	7.9934	7.9928	7.9855
	Roundness (µm)	45.8	41.3	16.6	16.7	14.3	16.7
Exp ❷ 600 rpm	Diameter (mm)	8.0001	7.9916	7.9891	7.9900	7.9829	7.9807
	Roundness (µm)	40.7	31.1	17.3	17.9	22.5	20.8
Exp ❸ 700 rpm	Diameter (mm)	8.0010	7.9928	7.9895	7.9887	7.9840	7.9753
	Roundness (µm)	37.6	29.0	9.7	25.4	20.9	15.3
Exp ❹ 800 rpm	Diameter (mm)	8.0015	7.9895	7.9872	7.9866	7.9819	7.9755
	Roundness (µm)	37.5	35.3	21.8	13.7	21.6	15.4
Average of ❶~❹	Diameter (mm)	8.0006	7.9923	7.9900	7.9897	7.9854	7.9793
	Roundness (µm)	40.4	34.2	16.4	18.4	19.8	17.1
Exp ❺ 1800 rpm	Diameter (mm)	7.9950	7.9851	7.9877	7.9859	7.9812	7.9814
	Roundness (µm)	32.9	30.8	17.9	13.8	16.8	18.0
Exp ❻ 1900 rpm	Diameter (mm)	7.9872	7.9834	7.9846	7.9847	7.9848	7.9877
	Roundness (µm)	25.3	19.3	16.6	11.5	13.8	8.8
Exp ❼ 2000 rpm	Diameter (mm)	7.9875	7.9844	7.9850	7.9860	7.9878	7.9856
	Roundness (µm)	30.8	26.6	15.8	11.8	15.3	12.3
Exp ❽ 2100 rpm	Diameter (mm)	7.9960	7.9886	7.9855	7.9855	7.9813	7.9763
	Roundness (µm)	27.0	20.4	11.6	10.9	13.1	13.6
Average of ❺~❽	Diameter (mm)	7.9941	7.9854	7.9857	7.9855	7.9838	7.9828
	Roundness (µm)	29.0	24.3	15.5	12.0	14.8	13.2
Exp ❾ 2200 rpm	Diameter (mm)	7.9966	7.9892	7.9861	7.9823	7.9784	7.9740
	Roundness (µm)	29.6	19.1	10.3	10.3	9.5	11.9
Exp ❿ 2300 rpm	Diameter (mm)	7.9999	7.9901	7.9857	7.9848	7.9785	7.9794
	Roundness (µm)	19.9	21.1	10.5	18.4	17.5	18.8
Exp ⓫ 2400 rpm	Diameter (mm)	7.9918	7.9879	7.9858	7.9814	7.9784	7.9801
	Roundness (µm)	14.1	17.9	18.0	10.0	18.7	8.6
Exp ⓬ 2500rpm	Diameter (mm)	7.9867	7.9817	7.9800	7.9824	7.9835	7.9869
	Roundness (µm)	23.9	15.6	15.4	12.4	19.6	14.1
Average of ❾~⓬	Diameter (mm)	7.9938	7.9872	7.9844	7.9827	7.9797	7.9801
	Roundness (µm)	21.9	18.4	13.6	12.8	16.3	13.4

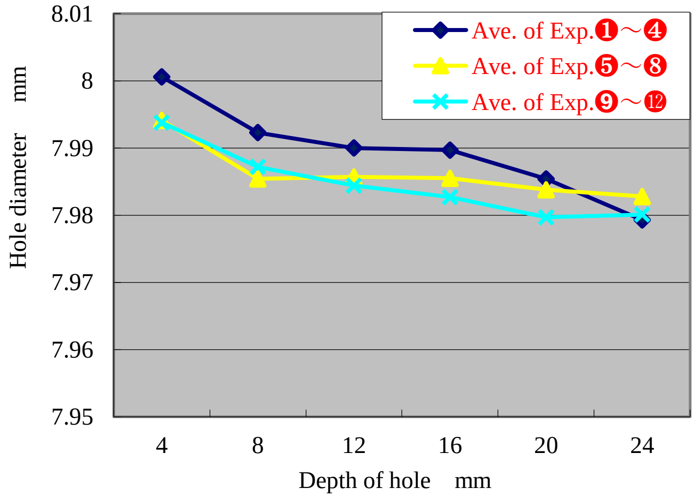


Fig. 5 Relation of average hole diameter in relation to depth of hole.

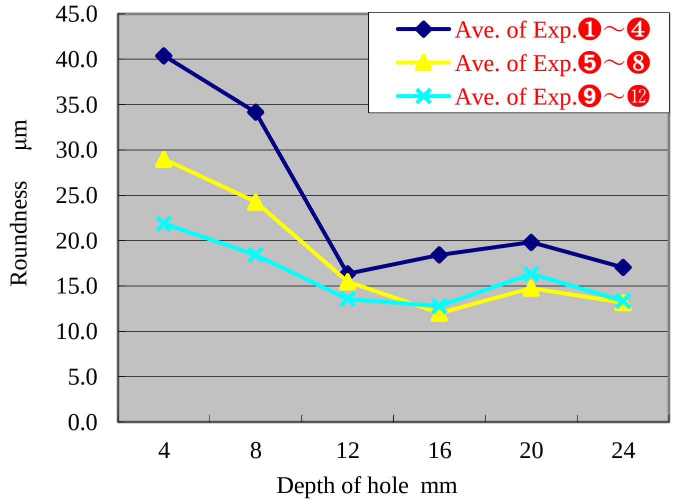


Fig. 6 Relation of average roundness in relation to depth of hole.

3.3. Comparison between Dry Drilling and Wet Drilling

To verify the effect of coolant upon hole diameter and roundness both results of dry drilling and wet drilling are shown duplicated in the one diagram as shown in Fig. 7 and Fig. 8, respectively.

As shown in Fig. 7 the average hole diameters of dry drilling are about 0.025 mm lager than those of wet drilling over the range of depth of hole from 4 mm to 24 mm. Additionally, the average hole diameter at depth of hole 4 mm is 0.010 mm ～ 0.025 mm larger than that at depth of hole 24 mm in both dry drilling and wet drilling.

In Fig. 8 the average roundness in both dry drilling and wet drilling shows a similar decreasing tendency up to the depth of hole 12 mm. After that they are scattering within about 10μm in the range of depth of hole from 12 mm to 24 mm.

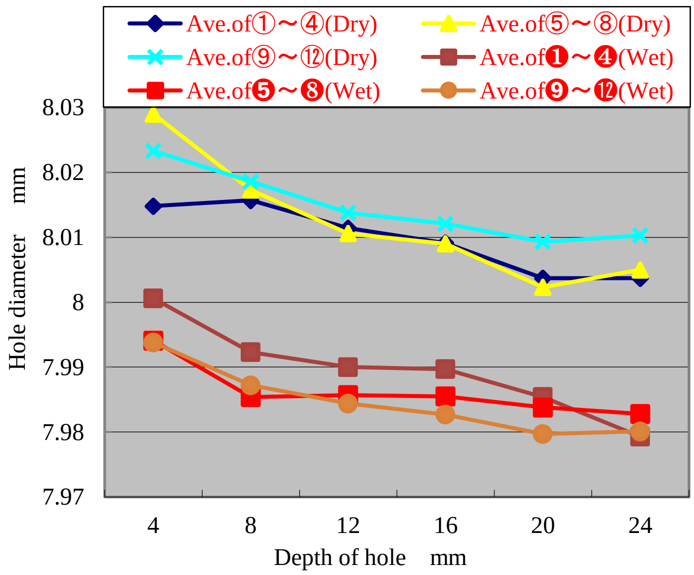


Fig. 7 Comparison of average hole diameter in relation to depth of hole between dry drilling and wet drilling.

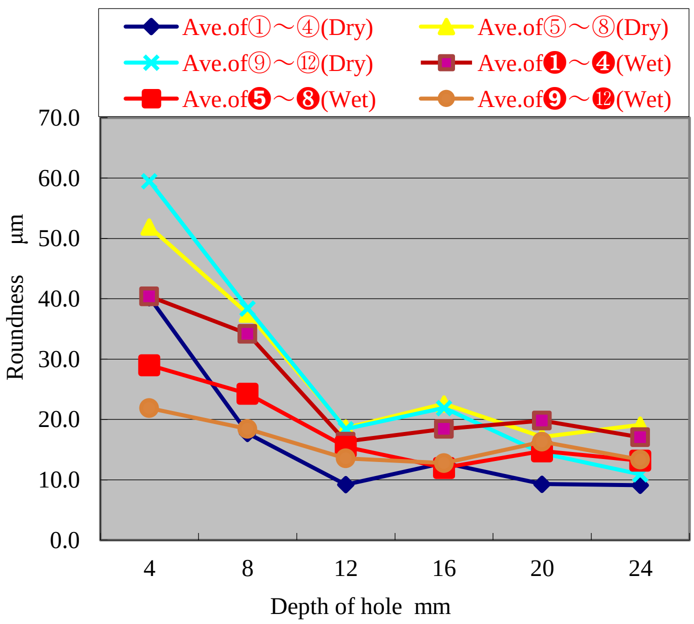


Fig. 8 Comparison of average roundness in relation to depth of hole between dry drilling and wet drilling.

3.4. Verification of Tool Wear

To verify a change of drill diameter due to wear, drill diameter was measured by Tool Pre-seter (STP46EZ-QC made in SPERONI) at the six positions from shoulder shown in Fig. 9. Figure 9 shows the relation of drill diameter in relation to distance from shoulder for unused drill ①② and used drill by dry drilling and wet one. As shown in Fig. 9 the drill diameters after being used by dry and wet coincide well with those of unused ① and ②. From this result, it can be understood that the effect of drill's wear upon hole diameter is not at all.

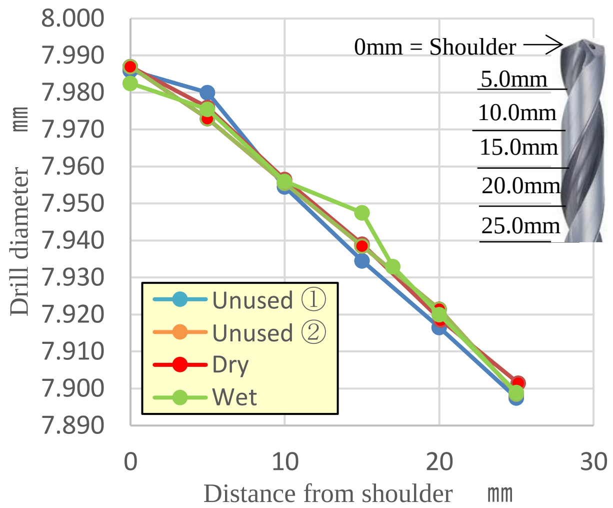


Fig. 9 Relation of drill diameter in relation to distance from shoulder.

4. Consideration of Hole Diameter in the Depth Direction

We need to understand how the temperature inside hole's wall distributes in the depth direction during drilling before considering the deviation of hole diameter shown in Fig.7. Then the inside thermal distribution of Ti6Al4V being drilled is estimated by referring the temperatures, which were measured at distances very close to the hole's wall during drilling AISI H13 steel [6] and at machined surface during drilling SUS304 [7], and drill's temperature during drilling Ti [2] by previous researchers.

.4.1. Thermal Distribution Estimated

Figure 10 shows thermal distribution during drilling estimated. As shown in Fig. 10 when the tip of drill is position of 'a', high temperature area would be generated by 'Area A' since cutting speed is zero at the tip and maximum at the outer cutting edge. The Ti6Al4V neighboring outer cutting edge must become high temperature. When the tip of drill reaches undersurface 'b' of Ti6Al4V, high temperature area will be extended to 'Area B'.

M. Sato et al. had revealed that machined surface temperature at oil hole increases after the tip reaches undersurface 'b' and it becomes maximum for a period until the outer cutting edge reaches undersurface [7]. When the temperature becomes maximum, the triangular 'High temperature area' shown in Fig. 10 must become most widely in inside Ti6Al4V according as the temperature distribution in the depth direction obtained by L. C. Brandao et al. [6].

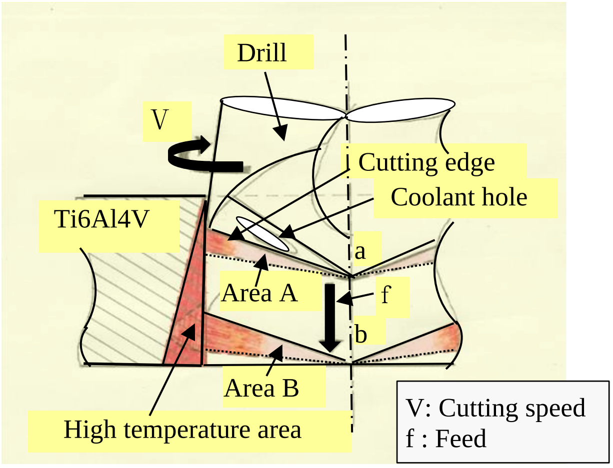


Fig. 10 Thermal distribution during drilling estimated.

M. Sato et al. verified when SUS 304 of 5 mm thickness was machined by dry drilling of ϕ12 mm at fixed feed rate of 0.1 mm/rev and four rotational speeds from 300 rpm to 1200 rpm, maximum machined surface temperature reached from 400 ℃ to 750 ℃ at the position of oil hole [7]. On the other hand, Li, R. et al. verified by dry drilling of ϕ9.92 mm for Ti that the peak temperature of the drill increased from 480 ℃ to 1060 ℃ after drilling 12.7 mm depth as the peripheral cutting speed increased from 24.4 m/min to 73.2 m/min under fixed feed rate of 0.051 mm/rev [2].

Considering the much smaller heat conductivity 6.6 W/m･℃ of Ti6Al4V than 16.3 W/m･℃ of SUS304 and 17 W/m･℃ of Ti, it can be presumed that the temperature of the triangular 'High temperature area' shown in Fig. 10 must exceed the phase transformation temperature of 883 ℃ (1621 ℉) of Ti6Al4V.

When coolant is spouted from oil holes at the tip of drill, it carries away heat generated by cutting with chips. At the same time coolant restrains the temperature rise of drill for it to pass through inside of drill. However, it can be presumed that the temperature of 'High temperature area' shown in Fig. 10 would not be reduced so much since the heat entering the workpiece would be scarcely carried away even if coolant is spouted.

4.2. Why Hole Diameter of Dry Drilling is Larger than that of Wet Drilling ?

As shown in Fig. 7 the hole diameters of dry drilling are about 0.025 mm lager than those of wet drilling in the range of depth of hole from 4 mm to 24 mm.

The effect of drill's wear upon hole diameter is not at all from the data shown in Fig. 9. Therefore, it can be presumed that a thermal expansion of drill during dry drilling would cause the larger hole diameter than that of wet drilling since the contraction of workpiece caused by the heat entering workpiece must be almost equal between dry drilling and wet drilling.

4.3. Why Hole Diameter becomes Smaller in the Depth Direction by Wet Drilling as well as Dry Drilling ?

Although we could not measure the temperature at the triangular 'High temperature area' shown in Fig. 10 during drilling, it is thinkable that the temperature must exceed the phase transformation temperature of 883 ℃ (1621 ℉) of Ti6Al4V by guessing from the temperature about 750℃ of SUS304's machined surface measured during dry drilling at the position of oil hole [7] and the peak temperature 1060 ℃ of drill during dry drilling of Ti [2].

Moreover, it was confirmed by previous research that heat conductivity in the thickness direction of six stacks of Ti6Al4V plate becomes much smaller than the native value of Ti6Al4V [11]. Therefore, it is thinkable that the temperature rise of six stacks of Ti6Al4V plate is larger than that of block having same thickness as six stacks.

As shown in Fig. 11 phase transformation of Ti6Al4V from α phase (close-packed hexagonal lattice) to β phase (body-centered cubic lattice) must induce transiently volumetric increase slightly since atomic packing factor of α phase is 74 % and that of β phase is 68 %.

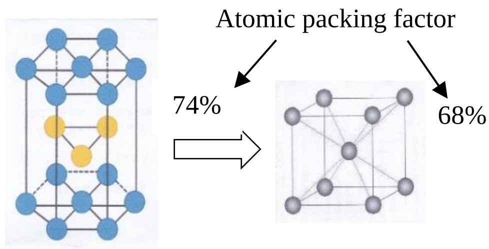


Fig. 11 Phase transformation of Ti6Al4V from α phase to β phase.

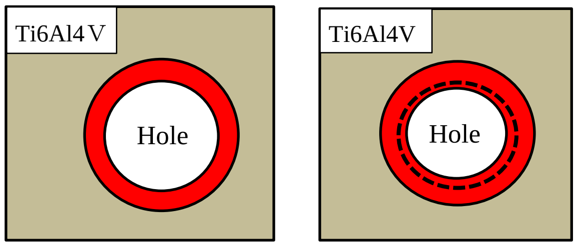


Fig. 12 Reduction of hole diameter caused by phase transformation of Ti6Al4V.

Figure 12 explains reduction of hole diameter caused by phase transformation of Ti6Al4V. In Fig. 12 (a) red ring area shows the area of Ti6Al4V heated over phase transformation temperature by drilling. When the part of α phase in the red ring area is transformed to β phase, the volume of the red ring area shown in Fig.12 (a) must increase transiently. Since the outside of red ring area is fixed by solid body, the volumetric increase will result in inside widened red ring area shown in Fig. 12 (b). As a result, hole diameter will be reduced from dotted circle to inner solid circle as shown in Fig. 12 (b).

As described in the previous paper [5] metal material drilled is distorted by the heat entering workpiece and at the same time a drill is expanded by the heat entering drill. After a drilling operation, the hole diameter machined by expanded drill reduces by contraction of workpiece. Specially, in the case of Ti6Al4V, for a reduction of hole diameter caused by phase transformation to be added a final hole diameter is settled.

Since the red ring area shown in Fig 12 becomes wider in the depth direction, the hole diameter may become smaller in the depth direction.

In Fig. 7 the reduction of hole diameter up to the depth of hole of 12 mm may be affected by run out of drill since the roundness shown in Fig. 8 shows large value in this area. However, the reduction of hole diameter in the depth of hole from 12 mm to 24 mm must be caused by contraction and phase transformation of Ti6Al4V induced by the heat entering workpiece. This reducing tendency of hole diameter is recognized during wet drilling as well as dry drilling as shown in Fig. 7.

Although it was ascertained previously that drilled holes of carbon steel S45C verified by K. Watanabe et al. [4] and drilled holes of aluminum 319 verified by M. Bono and J. Ni [5] have bell shapes in either case, which are smaller at the top than near the bottom, this paper disclosed that drilled holes of Ti6Al4V have inverse bell shapes, which are larger at the top than near the bottom. The inverse bell shape hole of Ti6Al4V must be induced by small heat conductivity and phase transformation of Ti6Al4V.

4.4. Hole Diameter and Roundness by Wet Drilling of Ti6Al4V Block having 25 mm Thickness

Figure 13 and Fig. 14 show relations of average hole diameter and average roundness in relation to depth of hole when wet drillings of Ti6Al4V block having 25 mm thickness were executed on the same drilling conditions shown in Table

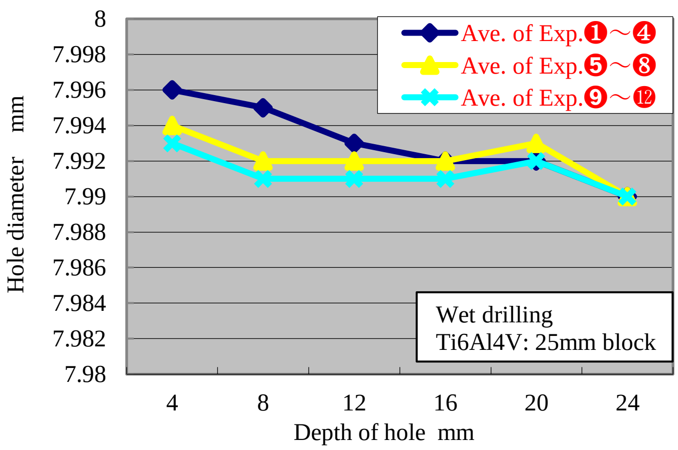


Fig. 13 Relation of average hole diameter in relation to depth of hole.

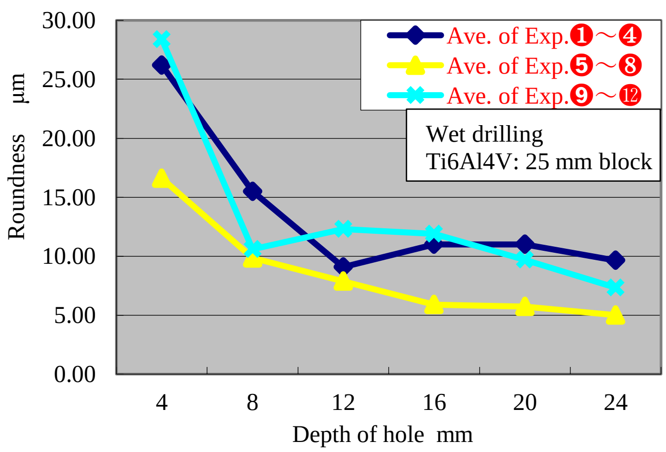


Fig. 14 Relation of average roundness in relation to depth of hole.

2. As shown in Fig.13 the hole diameter of Ave. of Exp.❶～❹ in the range of depth of hole from 12 mm to 24 mm shows a similar reducing tendency to the six stacks of 4 mm plate shown in Fig. 7, however, those of Ave. of Exp.❺～❽ and Ave. of Exp.❾～⓬ show a different tendency in the range of depth of hole from 12 mm to 24 mm.

This different tendency for hole diameter in the range of depth of hole from 12 mm to 24 mm would be caused by larger heat conductivity of block than that of stacks in the thickness direction [11]. Because the extent of the triangular'High temperature area' shown in Fig. 10 becomes smaller than that of stacks since the temperature rise would be reduced due to the larger heat conductivity in the thickness direction than that of stacks.

4.5. Check of Hole Diameter for Ti6Al4V Block by Pin Gauge

Figure 15 (a) (b) (c) shows the checking situation of hole diameter for Ti6Al4V block having 25 mm thickness by two kinds of pin gauge having ϕ 7.950 × 50 mm and ϕ 7.975 × 50 mm. Figure 15 (a) shows the hole drilled at 500 rpm, (b) shows that drilled at 1800 rpm and (c) shows that drilled at 2500 rpm.

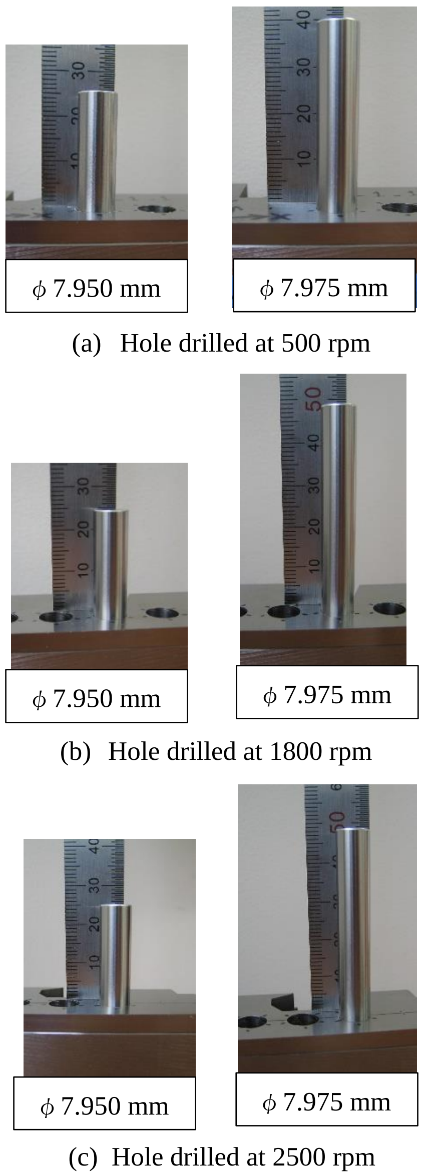


Fig. 15 Checking situation of hole diameter by pin gauge.

As shown in the left side of Fig. 15 (a) (b) (c) when pin gauge is ϕ 7.950 × 50 mm, the length of pin gauge from the upper surface of Ti6Al4V block shows about 25 mm on the back scale in each case of (a), (b) and (c). On the other hand, as shown in the right side of Fig. 15 (a) (b) (c) when pin gauge is ϕ 7.975 × 50 mm, the length of pin gauge is about 40 mm in (a), and about 48 mm in both (b) and (c).

From the above result it is supposed that the hole shape shows inverse bell shape, which is larger at the top than near the bottom in each case of (a), (b) and (c).

Conclusions

To make clear the effect of coolant upon hole making accuracy of Ti6Al4V by drilling, a series of dry drilling tests and wet drilling ones, in which the rotational speed of drill having ϕ 8 mm was changed 12 steps from 500 rpm to 2500 rpm under the fixed feed rate of 0.05 mm/rev, were carried out for the workpiece of 24 mm thickness, consisted of six stacks of 4mm plate, and a block having 25 mm thickness. Based on the tested results the effect of cutting temperature upon hole diameter was considered by using the temperatures measured during drilling of Ti, AISI H13 steel and SUS304 measured previously by other researchers [2][6][7].

Obtained conclusions are summarized as follows:

(1) Coolant, which passes through in the body of drill and is spouted from the coolant holes at the tip of drill, is effective to restrain thermal expansion of drill. As a result the hole diameter of wet drilling is about 0.025 mm smaller than that of dry drilling in the range of depth of hole from 4 mm to 24 mm whenever any rotational speed from 500 rpm to 2500 rpm.

(2) In the workpiece having 24mm thickness, consisted of six stacks of 4 mm plate, the reduction of hole diameter in the depth direction is induced at any rotational speed by wet drilling as well as dry drilling. This is thinkable as following phenomenon; the reduction of hole diameter induced by thermal distortion and phase transformation increases in the depth direction since the area neighboring hole's wall heated over phase transformation temperature widens in the depth direction due to the increment of heat entering workpiece as a progress of drilling.

(3) In the workpiece of Ti6Al4V block having 25 mm thickness a reduction of hole diameter in the depth direction is not recognized clearly comparing with the result of six stacks of 4 mm plate. The reason is thinkable that the heat conductivity in the thickness direction of block is larger than that of stacks.

(4) The hole shape of Ti6Al4V drilled often shows inverse bell shape, which is larger at the top than near the bottom. This shape is inverse to bell shape of steel and aluminum alloy verified by previous researchers. It must be caused by small heat conductivity and phase transformation of Ti6Al4V.

The authors wish that the reduction of hole diameter in the depth direction in drilling of Ti6Al4V, which were revealed experimentally by this paper, would be solved theoretically by metallurgical experts around the world as soon as possible.

Acknowledgement

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