Effect of Phase Transformation upon Hole Making Accuracy of Ti6Al4V by Orbital Drilling

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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, and a hole making operation of Ti6Al4V is needed to fasten the parts. When a high speed 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 a small heat conductivity. Incidentally, it is well-known that Ti6Al4V transiently causes phase transformation from α phase (close-packed hexagonal lattice) to β phase (body-centered cubic lattice) as soon as it reaches the transformation temperature of 883 °C (1621 °F).

One of the authors newly developed a hole making machine to enable orbital drilling based on Double Eccentric Mechanism, in which an endmill driven by a built-in AC motor can rotate clockwise on its own axis at high speed and simultaneously can revolve counter-clockwise on eccentric axis at low speed [1]. In dry cut orbital drilling tests of Ti6Al4V by the machine, it was ascertained that a hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole although wear of endmill was maintained to be tiny value. However, by supplying oil mist from oil hole in the endmill the hole diameter was ascertained that a hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole although wear of endmill was maintained to be tiny value. However, by supplying oil mist from oil hole in the endmill the hole diameter was ascertained that a hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole although wear of endmill was maintained to be tiny value. However, by supplying oil mist from oil hole in the endmill the hole diameter was ascertained that a hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole although wear of endmill was maintained to be tiny value. However, by supplying oil mist from oil hole in the endmill the hole diameter was ascertained that a hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole although wear of endmill was maintained to be tiny value. However, by supplying oil mist from oil hole in the endmill the hole diameter was ascertained that a hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole although wear of endmill was maintained to be tiny value. However, by supplying oil mist from oil hole in the endmill the hole diameter was ascertained that a hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole although wear of endmill was maintained to be tiny value. However, by supplying oil mist from oil hole in the endmill the hole diameter was...
1. Introduction

Previously, temperature measurement of cutting edge in drilling was tried using a two-color pyrometer with an optical fiber and 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 in oil mist end milling it was 10-15 % and that in oil mist drilling was 20-25 % compared to the temperature in dry cutting [3].

Li, R. and Shin, A.J. quantified the level of high temperature and effects of cutting speed and cutting time on drill temperature distributions in dry drilling of Ti. The complete temporal and spatial distributions of the drill temperature could be analyzed accurately and validated experimentally. The peak temperature of the drill increased from 480 °C to 1060 °C as the peripheral cutting speed increased from 24.4 m/min to 73.2 m/min after 12.7 mm depth of drilling. The location of peak temperature moved outside toward the drill margin as the peripheral cutting speed increased [4].

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 [5].

Bono, M. and Ni, J. had developed a model to predict the effects of thermal distortion of the drill and work-piece on the diameter and cylindricity of dry drilled holes. The study considered the quality of holes produced when drilling in a work-piece of aluminum 319, using HSS drill of diameter 9.92 mm, with speed ranging from 3000 to 7000 rpm, and with feeds ranging from 127 to 381 μm/rev. The model predicted that thermal distortions of the drill and work-piece leaded 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 to 26 μm [6].

Lye Sun and Y.B. Guo [7] made it clear from 3D chip morphology that β phase transformed severely to α phase in the second shear zone. Although Bayoumi and Xie [8] and Velasquez et al. [9] studied about chip phase transformation of Ti6Al4V and Li et al. investigated about β → α phase transformation and mechanical properties in high-throughout drilling of Ti6Al4V [10], it cannot be found anywhere the research which discloses the effect of phase transformation of machined Ti6Al4V upon hole diameter.

One of the authors examined hole making tests of Ti6Al4V by orbital drilling in the two conditions of dry cut and supplying oil mist from oil hole in the endmill and obtained the following results; although in the case of dry cut the hole diameter decreased from 15.02 mm at the first hole to 14.43 mm at the 40th hole, in the case of supplying oil mist the hole diameter was almost constant from 15.00 mm at the first hole to 14.96 mm at the 40th hole [2]. It is unthinkable that so much decrease of the hole diameter in dry cut may be caused by wear of endmill.

In the previous paper, it was ascertained by checking a temper color of bottom cap chip that the temperature in the material around the hole machined would be over the transformation temperature of 883 °C (1621°F) after the 16th hole drilling in dry cut [2]. Considering this result it is thinkable that a little volumetric increase caused by the phase transformation from α phase (close-packed hexagonal lattice) to β phase (body-centered cubic lattice) in the material around the inner surface of hole may cause the decrease of hole diameter. In this paper the cause for the hole diameter in dry cut to be decreased is disclosed by applying an image data processing to microstructures of the specimens of Ti6Al4V around the inner surface of hole.

2. Experimental Setup and Procedure

In Fig. 1, (a) shows an appearance of AC motor built-in type hole making machine based on double eccentric mechanism, (b) shows a helical nurlock adapter screwed to an end of taper flange and (c)
shows a fitting jig having four sets consisting of a pair of nurlock clamps for one liner bushing. After the bush at end of helical nurlock adapter shown in Fig. 1(b) is inserted into the liner bushing shown in Fig. 1(c), the machine is fixed rigidly to the fitting jig shown in Fig. 1(c) by turning the machine slowly clockwise so that the two taper surfaces of helical nurlock adapter may contact to the two taper surfaces of two nurlock clamps. In Fig. 1 (a) a white pipe from the taper flange is connected to a vacuum cleaner to suck up entirely a lot of small chips by air.

2.1. Material

The experiments were carried out on Ti6Al4V plate having a thickness of 5 mm as work-piece. The sectioned view of Ti6Al4V plate is shown in Fig. 2.

Fig. 1. Hole making machine, helical nurlock adapter and fitting jig.

2.2. Experimental Method and Machining Conditions

Two kinds of diamond coated cemented carbide square endmill of 11 mm diameter having 6 blades shown in Fig. 3 (a) and (b) were chosen for hole making tests. (b) had an axial through hole to supply oil mist and (a) was without an axial through hole. As shown in Fig. 3 (a) and (b), six blades are composed of two pairs of three different shape’s blades. An amount of eccentricity was set at 2.0 mm, therefore, a hole diameter machined was 15.0 mm.

The summary of hole making conditions for Ti6Al4V plate is listed in Table 1. As shown in Table 1, only experiment ① is oil mist Off, experiment ② is oil mist Hi, and experiment ③ and ④ are oil mist Lo. In each experiment of ①②③④ a series of 40 times hole making tests were executed at the interval of about 4 – 5 minutes between each hole by employing the hole making machine in Fig. 1. After a series of hole making tests, hole diameter and roundness of Ti6Al4V plate were measured at the middle position of thickness for every four interval hole by a three coordinate measuring machine. Wear of cutting edges and burr at inlet and outlet of hole were observed and recorded by a microscope.
shows a fitting jig having four sets consisting of a pair of nurlock clamps for one liner bushing. After the bush at end of helical nurlock adapter shown in Fig. 1(b) is inserted into the liner bushing shown in Fig. 1(c), the machine is fixed rigidly to the fitting jig shown in Fig. 1(c) by turning the machine slowly clockwise so that the two taper surfaces of helical nurlock adapter may contact to the two taper surfaces of two nurlock clamps. In Fig. 1(a) a white pipe from the taper flange is connected to a vacuum cleaner to suck up entirely a lot of small chips by air.

3. Results and Discussion

3.1. Hole Diameter in relation to Number of Hole Machined

Figure 4 shows the relationship of hole diameter in relation to number of hole machined for experiment ①, ②, ③ and ④. In Fig. 4 the hole diameter of experiment ① (Oil mist: Off) steeply decreases from 1st hole to 40th hole and the difference of hole diameter between 1st hole and 40th hole is about 0.6 mm. On the other hand, the hole diameter of experiment ② (Oil mist: Hi), experiment ③ (Oil mist: Lo) and experiment ④ (Oil mist: Lo) very gradually decreases from 1st hole to 40th hole and the difference of hole diameter between 1st hole and 40th hole is about 0.05 mm which is about
one twelfth of that of experiment ① (Oil mist: Off).

Table 2 shows mean value and standard deviation (S.D.) of hole diameter for experiment ①, ②, ③ and ④. From Fig. 4 and Table 2 it is clearly ascertained that supplying oil mist is strongly effective to improve the accuracy of hole diameter.

### 3.2. Roundness in relation to Number of Hole Machined

Figure 5 shows the relationship of roundness in relation to number of hole machined. In Fig. 5 the roundness of experiment ① (Oil mist: Off) fluctuates widely within the range of 0.02 to 0.14 mm from 1st hole to 40th hole. On the other hand, the roundness of experiment ② (Oil mist: Hi), experiment ③ (Oil mist: Lo) and experiment ④ (Oil mist: Lo) fluctuates slightly within the range of 0.02 to 0.04 mm from 1st hole to 40th hole.

Table 3 shows mean value and standard deviation (S.D.) of roundness for experiment ①, ②, ③ and ④.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mean (mm)</th>
<th>S.D. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>① (Oil mist: Off)</td>
<td>14.7107</td>
<td>0.189</td>
</tr>
<tr>
<td>② (Oil mist: Hi)</td>
<td>14.9874</td>
<td>0.0147</td>
</tr>
<tr>
<td>③ (Oil mist: Lo)</td>
<td>14.9813</td>
<td>0.0201</td>
</tr>
<tr>
<td>④ (Oil mist: Lo)</td>
<td>14.9811</td>
<td>0.0223</td>
</tr>
</tbody>
</table>

From Fig. 5 and Table 3 it is clearly ascertained that supplying oil mist is strongly effective to improve the accuracy of roundness similarly to the hole diameter.

### 3.3. Verification for Effect of Oil Mist by Temper Color of Ti6Al4V

To verify the effect of oil mist it is necessary to know a temperature rise of both endmill and Ti6Al4V during machining. In this research the temperature rise of Ti6Al4V is especially paid attention. The authors observed a color of bottom cap chip shown in Fig. 6 during machining with their own eyes. As a result, it was ascertained that in experiment ① (Oil mist: Off) the color began to change into light red at the 8th hole, and became red at the 16th hole, deep red at the 24th hole, deeper red at the 32nd hole and dark red at the 40th hole. After machining the red color of bottom cap chip changed into blue which is so-called temper color [11].
Therefore, the temperature rise of Ti6Al4V during machining can be estimated qualitatively by observing the temper color of bottom cap chip shown in Fig.6.

Figure 7 shows a comparison of temper color of bottom cap chip in relation to number of hole machined for experiment ① (Oil mist: Off), ② (Oil mist: Hi), ③ (Oil mist: Lo) and ④ (Oil mist: Lo). As shown in Fig. 7 only in the case of experiment ① (Oil mist: Off) the temper color of bottom cap chip changes widely over the range from 8th hole to 40th hole. Namely, at 8th hole a color in the center changes very slightly, at 16th hole the color becomes violet and at 24th hole the color becomes blue. At 32nd hole a whole area of bottom cap chip shows dark blue and bright in the center area and then at 40th hole the bright area extends.

On the other hand in the cases of experiment ② (Oil mist: Hi), ③ (Oil mist: Lo) and ④ (Oil mist: Lo) the temper color of bottom cap chip hardly changes over the range from 1st hole to 32nd hole, and at 40th hole the color in the center area becomes slightly yellowish. The yellowish color is similar to that of 8th hole in experiment ① (Oil mist: Off).

From the observation for temper color of bottom cap chip it can be ascertained that supplying oil mist is strongly effective to restrain the temperature rise of Ti6Al4V under the transformation temperature of 883 °C (1621 °F). Although the temperature rise of endmill is not measured, an improvement of both hole diameter and roundness by supplying oil mist, which are shown in Fig. 4 and Fig. 5, must be achieved by restraint of temperature rise in the vicinity of Ti6Al4V’s hole having a small heat conductivity.

On the other hand, from the result of experiment ① (Oil mist: Off) that the color of bottom cap chip became red during 16th hole drilling and the temper color is violet as shown in Fig. 7, it is presumed that the temperature of Ti6Al4V during 16th hole drilling would reach at the transformation temperature of 883 °C (1621 °F). Moreover, when the number of hole machined increases from 24th hole to 40th hole, the temperature of Ti6Al4V would become larger than the transformation temperature of 883 °C (1621 °F). Namely, Ti6Al4V drilled after 16th hole was heated up over the transformation temperature of 883 °C (1621 °F) and after that it was cooled by air.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>1st hole</th>
<th>8th hole</th>
<th>16th hole</th>
<th>24th hole</th>
<th>32nd hole</th>
<th>40th hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>① (Oil mist: off)</td>
<td><img src="image1" alt="Image 1" /></td>
<td><img src="image2" alt="Image 2" /></td>
<td><img src="image3" alt="Image 3" /></td>
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<td><img src="image5" alt="Image 5" /></td>
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</tr>
<tr>
<td>② (Oil mist: Hi)</td>
<td><img src="image7" alt="Image 7" /></td>
<td><img src="image8" alt="Image 8" /></td>
<td><img src="image9" alt="Image 9" /></td>
<td><img src="image10" alt="Image 10" /></td>
<td><img src="image11" alt="Image 11" /></td>
<td><img src="image12" alt="Image 12" /></td>
</tr>
<tr>
<td>③ (Oil mist: Lo)</td>
<td><img src="image13" alt="Image 13" /></td>
<td><img src="image14" alt="Image 14" /></td>
<td><img src="image15" alt="Image 15" /></td>
<td><img src="image16" alt="Image 16" /></td>
<td><img src="image17" alt="Image 17" /></td>
<td><img src="image18" alt="Image 18" /></td>
</tr>
<tr>
<td>④ (Oil mist: Lo)</td>
<td><img src="image19" alt="Image 19" /></td>
<td><img src="image20" alt="Image 20" /></td>
<td><img src="image21" alt="Image 21" /></td>
<td><img src="image22" alt="Image 22" /></td>
<td><img src="image23" alt="Image 23" /></td>
<td><img src="image24" alt="Image 24" /></td>
</tr>
</tbody>
</table>

Fig. 7. Comparison of temper color of bottom cap chip in relation to number of hole machined for experiments ①, ②, ③ and ④. 
3.4. Wear of Cutting Edge

Figure 8 (a) shows top view of the used endmill having 6 blades. In Fig.8 (a) Blade 1, Blade 2 and Blade 3 have different shapes respectively, and the other three blades have the same shapes as the opposite blade. Figure 8 (b) and (c) show the comparison between (1) Before drilling and (2) After 40th hole drilling for Blade 1, Blade 2 and Blade 3 in experiment ① (Oil mist: Off), where (b) is Flank surface and (c) is Rake surface respectively.

Blade 1, Blade 2 and Blade 3 in (2) After 40th hole drilling of Fig. 8 (b) Flank surface show narrow flank wears as white lines at the end cutting edges. Although slight abrasion is seen at the outer cutting edges of Blade 1, Blade 2 and Blade 3, micro chipping is hardly seen.

Blade 1, Blade 2 and Blade 3 in (2) After 40th hole drilling of Fig. 8 (c) Rake surface show slight abrasion at outer cutting edges, however, crater wear is not seen on the rake surface and micro chipping is hardly seen similarly to those in Fig 8 (b) Flank surface.

Wears of both flank surface and rake surface in experiment ① (Oil mist: Hi) and ③ (Oil mist: Lo) were hardly different from those in experiment ① (Oil mist: Off) shown in Fig. 8 (b) and (c).

From the cutting edge’s wear of endmill shown in Fig. 8 (b) and (c) it is unthinkable that the hole diameter reduction from 15.02 mm at first hole to 14.43 mm at 40th hole in experiment ① (Oil mist: Off) may be caused by the wear of cutting edge.

3.5. Edge Quality of Hole

Figures 9 (a)(b) and Figs. 10 (a)(b) show inlet and outlet of Ti6Al4V’s hole at 1st hole and 40th hole in experiment ① (Oil mist: Off) and experiment ③ (Oil mist: Lo) respectively.

Compared (a) Inlet and (b) Outlet in Fig.9 in experiment ① (Oil mist: Off) with those in Fig.10 in experiment ③ (Oil mist: Lo), all edges in Fig. 10 are seen more sharp. At all edges in Fig. 9 black circles are seen. Also, the surface around the outlet of 40th hole in Fig. 9 (b) is changed to yellowish color due to temperature rise by dry cut drilling. Considering softening of Ti6Al4V by the temperature rise the black circles shown at inlet and outlet edges in Fig. 9 are presumed to be small burr by elastic deformation.
4. Consideration based on Phase transformation of Ti6Al4V

4.1. Experimental Method

To observe optically a microstructure in the vicinity of inner surface of drilled hole a specimen was cut out by a wire-cut discharge machine as shown in Fig. 11(a). After the section in the thick direction of the specimen was fixed in the resin shown in Fig. 11(b), it was mechanically polished with emery paper (100-2000 mesh) and alumina powders (diameter: 0.03 μm). The surface damaged by wire-cut discharge machining was completely removed by the polishing. Metallography and microstructure were observed optically after the specimen was etched during 35 second by Kroll’s reagent.

The six specimens consisted of the 1st hole, the 8th hole, the 16th hole, the 24th hole, the 32nd hole and the 40th hole were made for experiment ① (Oil mist: Off) and experiment ② (Oil mist: Hi) respectively.

4.2 Observation of Microstructure

The microstructures of experiment ① ’s specimens and experiment ② ’s specimens were optically observed. Figures 12(a)～(f) show the microstructures at the 1st hole, the 8th hole, the 16th hole, the 24th hole, the 32nd hole and the 40th hole specimen of experiment ① (Oil mist: Off) and Figures 13(a)～(f) show the microstructures of the same hole’s specimens of experiment ② (Oil mist: Hi) respectively.

It is well-known that in the microstructures shown in Figs. 12 (a)～(f) and Figs. 13 (a)～(f) dark regions show β phase and the other bright regions correspond to α phase [12][13].
4.3. Method to Obtain Percentage of $\beta$ Phase

To obtain a percentage of $\beta$ phase more precisely, an image data processing was applied to the microstructure’s photographs with magnification of 2000, 2500 and 3000 for one specimen. The process to obtain the percentage of $\beta$ phase is explained in detail for (a) 1st hole in experiment ①’s specimen shown in Fig.12 (a) as follows;

First, the extent for an image data processing to be applied is decided as shown by white square line on the microstructure (A1)$\times$2000, (A2)$\times$2500, (A3)$\times$3000 shown in Fig. 14. Figures 15 (A1) (A2) (A3) show the extent decided from the microstructures of (A1)$\times$2000, (A2)$\times$2500, (A3)$\times$3000 in Fig. 14.

Second, as shown in Fig. 16, .pig file of (A1)$\times$2000 in Fig.15 is changed to .tif file and next to .tif file (monochrome) shown in Fig. 16 is obtained by applying an image thresholding. Next, a software for computing a percentage of dark regions is applied to .tif file (monochrome) of (A1)$\times$2000. As a result a percentage of dark regions corresponding to $\beta$ phase for (A1)$\times$2000 shown in Fig. 14 is calculated.

After the same image data processing is applied to .tif file (monochrome) of (A2)$\times$2500 and (A3)$\times$3000, the percentage of $\beta$ phase for (a) 1st hole in Fig. 12 (a) can be obtained as an average of values calculated for (A1), (A2) and (A3) in Fig. 14.

4.4. Percentage of $\beta$ Phase in Relation to Number of Hole Machined

Table 4 shows the percentage of $\beta$ phase for ×2000, ×2500, ×3000 and average in relation to (a) 1st hole ~ (f) 40th hole in Fig.12 and Fig.13.

Figure 17 shows the percentage of $\beta$ phase in relation to number of hole machined for experiment ① (Oil mist: Off) and experiment ② (Oil mist: Hi).
file (monochrome) shown in Fig. 16 is obtained by applying an image thresholding. Next, a software for computing a percentage of dark regions is applied to .tif file (monochrome) of (A1) × 2000. As a result a percentage of dark regions corresponding to $\beta$ phase for (A1) × 2000 shown in Fig. 14 is calculated. After the same image data processing is applied to .tif file (monochrome) of (A2) × 2500 and (A3) × 3000, the percentage of $\beta$ phase for (a) 1st hole in Fig. 12 (a) can be obtained as an average of values calculated for (A1), (A2) and (A3) in Fig. 14.

4.4. Percentage of $\beta$ Phase in Relation to Number of Hole Machined

Table 4 shows the percentage of $\beta$ phase for × 2000, × 2500, × 3000 and average in relation to (a) 1st hole ~ (f) 40th hole in Fig.12 and Fig.13. Figure 17 shows the percentage of $\beta$ phase in relation to number of hole machined for experiment ① (Oil mist: Off) and experiment ② (Oil mist: Hi).
In Fig. 17 it is seen that the percentages of $\beta$ phase from 8th hole to 40th hole of experiment $①$ (Oil mist: Off) exist in the range of 34.6 to 35.1% and also show a slightly increasing tendency except for 32nd hole.

On the other hand the percentages of $\beta$ phase of experiment $②$ (Oil mist: Hi) are smaller than those of experiment $①$ (Oil mist: Off) except for 1st hole and they exist in the range of 34.0 to 34.35% except for 24th hole.

### 4.5. Consideration for Hole Diameter and Roundness

By comparing Fig. 4 with Fig. 7 and Fig. 17 in the consideration that the phase transformation from $\alpha$ (close-packed hexagonal lattice) to $\beta$ (body-centered cubic lattice) would cause an extremely little volumetric increase, it can be disclosed that the reduction of hole diameter of experiment $①$ (Oil mist: Off) from 15.02 mm at the first hole to 14.43 mm at the 40th hole might be caused by the phase transformation from $\alpha$ to $\beta$ of Ti6Al4V.

Figure 18 shows an inner surface of 40th hole in experiment $①$ (Oil mist: Off). In Fig. 18 a slant black line is seen in the middle of thickness on the inner surface. It is verified that the black line is a groove from a profile measurement. It can be presumed that the groove would be generated the cutting edges of endmill scratched the inner surface of hole having 14.43 mm diameter in the return process of drilling. Figure 19 shows a roundness curve at that time. In the drilling after 16th hole of experiment $①$ (Oil mist: Off) the groove was seen clearly on the inner surface of hole machined. Therefore, it can be presumed that the larger roundness of experiment $①$ (Oil mist: Off) shown in Fig. 5 may be caused by the groove.

On the other hand, in experiment $②$ (Oil mist: Hi) shown in Fig. 5 may be caused by the groove.

### Table 4. Percentage of $\beta$ phase for (a)～(f) in Fig.12 and .Fig.13.

<table>
<thead>
<tr>
<th>Experiment $①$ (Oil mist: Off)</th>
<th>Percentage of $\beta$ phase (%)</th>
<th>Experiment $②$ (Oil mist: Hi)</th>
<th>Percentage of $\beta$ phase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 1st hole</td>
<td>34.17 × 2500 34.19 × 3000 33.19</td>
<td>(a) 1st hole</td>
<td>34.16 × 2500 34.51 × 3000 33.96</td>
</tr>
<tr>
<td>(b) 8th hole</td>
<td>34.92 × 2500 34.32 × 3000 34.72</td>
<td>(b) 8th hole</td>
<td>34.02 × 2500 34.59 × 3000 34.81</td>
</tr>
<tr>
<td>(c) 16th hole</td>
<td>34.98 × 2500 35.68 × 3000 34.82</td>
<td>(c) 16th hole</td>
<td>34.45 × 2500 34.53 × 3000 34.35</td>
</tr>
<tr>
<td>(d) 24th hole</td>
<td>34.19 × 2500 34.93 × 3000 34.84</td>
<td>(d) 24th hole</td>
<td>33.28 × 2500 34.38 × 3000 33.20</td>
</tr>
<tr>
<td>(e) 32nd hole</td>
<td>33.53 × 2500 35.38 × 3000 34.60</td>
<td>(e) 32nd hole</td>
<td>33.17 × 2500 34.96 × 3000 34.32</td>
</tr>
<tr>
<td>(f) 40th hole</td>
<td>34.44 × 2500 35.50 × 3000 35.08</td>
<td>(f) 40th hole</td>
<td>33.79 × 2500 34.43 × 3000 34.03</td>
</tr>
</tbody>
</table>

Fig. 17. Percentage of $\beta$ phase in relation to number of hole machined.

Fig. 18. Inner surface of 40th hole in experiment $①$ (Oil mist: Off).

Fig. 19. Roundness curve of 40th hole in experiment $①$ (Oil mist: Off).
Hi) the groove was not seen on the inner surface of hole machined and the roundness shows small value within the range from 0.02 to 0.04 mm over the 1st hole to the 40th hole as shown in Fig. 5.

5. Conclusions

After several series of orbital drilling tests of Ti6Al4V were carried out on the drilling conditions of dry and oil mist, by means of observing the temper color of bottom cap chip and applying the image data processing to the microstructures in the vicinity of inner surface of drilled hole the following conclusions were summarized as follows;

(1) In the hole making of Ti6Al4V by orbital milling, supplying oil mist from oil hole in the endmill is strongly effective to improve the accuracy of hole diameter, roundness and edge quality at inlet and outlet of hole.

(2) It is ascertained that the temperature of Ti6Al4V would reach over the transformation temperature of 883 °C (1621 °F) after the 16th hole drilling in experiment (Oil mist: Off) from observing the color of bottom cap chip during drilling by the naked eye and also its temper color after drilling.

(3) The percentage of β phase can be calculated by applying the image data processing to .tif file (monochrome) obtained from microstructure’s photograph of the Ti6Al4V’s specimen in the vicinity of the inner surface of hole.

(4) Since the percentage of β phase during dry drilling is larger than that during oil mist drilling and also it increases slightly as the increase of drilled hole, it can be disclosed qualitatively that the reduction of hole diameter from 15.02 mm at the 1st hole to 14.43 mm at the 40th hole during dry drilling would be caused by the phase transformation from α to β of Ti6Al4V.

Although in this research the authors calculated the percentage of β phase from optical microstructures of extremely small extent around the inner surface of hole, the effect of phase transformation upon hole diameter may become more clearly if it is possible to observe optical microstructures of more wider extent around the inner surface of hole.

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