Cutting Force in Drilling with Flat Bottom Drill
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Abstract. Flat bottom drills at a point angle of 180 deg. have recently been applied to not only drilling on inclined surfaces but also flat bottom holes in terms of the dimensional accuracy and the process efficiency. Controlling the cutting force, the tool damage, and the surface finish, the corner shape is a critical parameter in the design of the flat bottom drill. The paper discusses the effect of the corner radius on the cutting forces and the surface finish in drilling with flat bottom drills. The typical differences in the cutting force are confirmed during the edge engagement. Then, the cutting force is simulated with a chip flow model, in which the chip flow angle is determined to minimize the cutting energy. The cylinder surface finishes and the burr formations are associated with the chip flow direction and the uncut chip thickness at the end of the lip.

Introduction

Drilling is an important process that occupies more than one-third of machining operations in industries [1]. A large number of drillings have been conducted in aerospace, automobile, medical device, and die and mold industries. Conventional twist drills with a point angle are inappropriate for the drillings of an inclined surface with respect to the tool axis and the expansion drillings for an eccentric pre-machined hole. The flat bottom drills with a point angle of 180 deg. have been applied to those drillings as well as drillings of flat bottom blind holes because the cutting force in the radial direction of the drill becomes smaller in comparison to that of the drill with a point angle of under 180 deg. Authors discussed the cutting force of drilling with a flat bottom drill for an inclined surface [2]. The radial component of the flat bottom drill is stable because the radial component does not depend on the inclination angle. Heisel and Pfeifroth conducted drillings of carbon fiber reinforced plastic with twist drills with different point angles [3]. The burr and the delamination at the entrance were little obtained when using the drill with a point angle over 180 deg.

In drilling of counterbored holes for screw head bolt, the corner radius is required to reduce the stress concentration at the corner of the hole. The flat bottom drill with a corner radius depending on the design of the corner radius of the hole is employed in terms of high production rate and dimensional accuracy. Therefore, the cutting conditions should be determined by considering the cutting forces during drilling for the corner radius of the flat bottom drill.

This study discusses the effect of the corner radius of flat bottom drill on the cutting force and the surface finish. The drillings of blind holes were performed with flat bottom drills with a sharp corner and round corner in cutting tests, first. The cutting processes are analyzed for the fundamental understanding with a chip flow model, in which the orthogonal cuttings are piled up in the plane containing the cutting direction and chip flow direction [4].

Cutting Experiment

Experimental Procedure. Figure 1 shows a schematic diagram of a cutting test to measure cutting forces in a machining center (FANAC RoboDrill α-T14iF). 10 mm thick of an aluminum alloy (A7075 in JIS) plate was used as workpiece material. Flat bottom drills with a sharp corner and a radius of 0.4 mm were employed for the cutting tests to discuss the effects of corner radius on the
cutting processes, where the tools of 6 mm diameter were coated by AlCrTi thin layer, as shown in Fig. 2. The edge radius of lips was confirmed to be less than 5 μm at each tool. In this paper, the tools with sharpened corners and rounded corners are expressed as ‘Tool S’ and ‘Tool R’, respectively. A 2mm diameter hole was pre-machined before the cutting test to ignore the effects of the chisel edge on the cutting process. The blind drill of 3 mm deep was machined in cutting conditions shown in Table 1. The thrust and the torque in drilling of aluminum alloy were measured with a piezoelectric dynamometer (Kistler 9272) mounted on the machine table. The cutting forces were acquired in 0.1 msec. period with a data acquisition system (Keyence NR-500).

**Cutting Force Measurement.** Figure 3 shows measured cutting forces from the edge engagement to the steady cutting processes at a spindle speed of 2654 min⁻¹ and a feed rate of 0.0125 mm/tooth. Depending on tool geometries, the differences appear in cutting forces with Tool S and Tool R. Regarding the cutting force in drilling with Tool S, the flat bottom edges expanding up to the end of lips penetrate the workpiece simultaneously. The thrust and the torque rapidly increase (from ‘O’ to ‘A’ in Fig. 3(a)). After 0.05 seconds in cutting time (at ‘A’ in Fig. 3(a)), the cutting force is stable in the steady cutting process. Although the cutting time required for the uncut chip thickness to be constant is 0.011 seconds corresponding to a geometrical calculation with the spindle speed and the number of teeth, the cutting force suggests that the cutting time was required approximately 0.05 seconds to stabilize the friction on the tool-chip interface. While, regarding the cutting force in drilling with Tool R, the cutting force increases similar to that of tool S at the edge engagement because the flat bottom edges of Tool R expand up to a rotation radius of 2.6 mm (from ‘O’ to ‘A’ in Fig. 3(b)).

![Fig. 1 Cutting test to measure cutting force](image)

![Fig. 2 Flat bottom drills employed](image)

Diameter, 6 mm; Helix angle, 20 deg.; Material, Carbide; Coating, AlCrTi.

**Table 1 Cutting conditions**

| Condition                          | No. 1     | No. 2     | No. 3     | No. 4     |
|-----------------------------------|-----------|-----------|-----------|-----------|
| Feed rate [mm/tooth]              | 0.0125    | 0.0125    | 0.25      | 0.25      |
| Spindle speed [min⁻¹]             | 2654 (50) | 5308 (100)| 2654 (50) | 5308 (100) |
| (Cutting speed at a rotation radius of 3 mm [m/min]) |           |           |           |           |
| Lubrication                       | Water based coolant |           |           |           |
Then, the rounded corner edges arranged 0.4 mm in the axial direction penetrate the workpiece gradually with the cutting time corresponding to the cutter feed (up to ‘B’ in Fig. 3(b)). The cutting force increases gradually for 0.36 second until the end of the lips penetrate the workpiece.

The averaged cutting forces in steady cutting processes are shown in Fig. 4. When comparing conditions of No. 1 and 3, the effect of the feed rate on the cutting force is concerned. The change rate of thrust is relatively small in comparison to the rate of torque, regardless of tool geometry. It is considered that the effect of indentation of the edge radius is relatively larger on the thrust component at smaller feed rate. When the effect of spindle speed is concerned in comparing conditions of No. 3 and 4, the cutting force slightly decreases with the increase of spindle speed. Then, regarding the tool geometry, the cutting force with Tool R becomes larger than that with Tool S at the same cutting conditions. Because the axial and the radial rake angle of Tool R was small in comparison to that of Tool S, it is considered that the small rake angle induces the large cutting force.

**Chip Morphology.** The chip in the steady cutting process is shown in Fig. 5. The smoothly curled chips are formed in drilling with Tool S regardless of cutting condition, as shown in Fig. 5(a), (b), and (c). While, when drilling with Tool R at a small feed rate, as shown in Fig. 5(d) and (e), tears and large strains in opposite direction with respect to the curvature of the chip curl are observed at the outside edge of chips, which is formed with the end of the lip. Although further research is needed to discuss the formation of the tears and the strains, the rounded corner edge induces a large strain in the chip. In Fig. 5(f), the outside end of the chip is slightly strained outward, which is the same tendency as that of the small feed rate, but no tear is observed. According to the measurement of the chip thickness with an outside micrometer, the thicknesses in drilling with Tool R were approximately 0.049 and 0.071 mm at the cutting conditions of No. 3 and 4, where the feed rates were 0.0125 and 0.025 mm/tooth, respectively. Although the uncut chip thickness should be defined along the chip flow direction, the uncut chip thickness is regarded as the feed rate at this moment. The cutting ratio defined as a ratio of uncut chip thickness to the chip thickness becomes larger at the condition of No.
Therefore, the relatively small shear strain of the chip suppresses the tear of the chip in the condition of No. 4.

**Quality of Machined Hole.** Figure 6 shows height distributions around the entrances of holes, which were measured with the laser microscope. The large burrs are observed on the hole edges drilled with Tool R, as shown in Fig. 6(b). Corresponding to the chip formation shown in Fig. 5, the large strain at the end of the lip induces the large burr formation.

The cylinder surfaces machined at the cutting condition of No. 4 are observed with the optical microscope, as shown in Fig. 7. Uniform surface is obtained in drilling with Tool S, while the small black areas are observed on the surface machined with Tool R, which are considered as adhesions because it was confirmed that the areas were slightly higher than the surface surrounding the areas. Meanwhile, the profiles in the axial direction are shown in Fig. 8, which are averaged 30 profiles measured at 0.5 µm from the adjacent cross-section. The periodical change in surface roughness is observed in accordance with the feed rate of 0.025 mm/tooth. The larger surface roughness is confirmed in drilling with Tool S, despite the uniform surface shown in Fig. 7. In the cutting process around the end of lip of Tool R, since the cutting edge at the rounded corner approaches the axial direction with the increase of the rotation radius, the uncut chip thickness in the normal direction of the cutting edge decreases. Therefore, although the adhesion is accumulated thinly on the machined surface, the surface roughness may become small.
Analysis of Cutting Process

Cutting Force Model. The force model for drilling was presented in Reference [5]. The force model is briefly described here. The cutting force is predicted in the chip flow model, as shown in Fig. 9. Three dimensional chip flow is interpreted as a piling up of the orthogonal cuttings in the planes containing the cutting velocities $V$ and the chip flow velocities $V_c$. The cutting edges are divided into small discrete segments to make the orthogonal cutting models using the following data:

$$\begin{align*}
\phi &= f(V, t_1, \alpha) \\
\tau_s &= g(V, t_1, \alpha) \\
\beta &= h(V, t_1, \alpha)
\end{align*}$$

(1)

where $\phi$, $\tau_s$, and $\beta$ are the shear angle, the shear stress on the shear plane and the friction angle, $\alpha$, $V$ and $t_1$ are the rake angle, the cutting velocity, and the uncut chip thickness in the orthogonal cutting.

Fig. 9 Chip flow model in drilling
The cutting force should be regarded as the sum of the edge force component due to the ploughing and the cutting component due to shearing in the shear zone and friction on the rake face. For the sake of simplicity, this study employs the orthogonal cutting data expressed as Eq. (1) on the assumption that the cutting component is the major effect here, where the edge force component is associated with the parameters for the uncut chip thickness. Eq. (1) can be obtained in the orthogonal cutting tests. When the chip flow angle is assumed, the orthogonal cutting models piled in the chip flow can be made by Eq. (1) with the rake angles and uncut chip thicknesses. The cutting energy is consumed into the shear energy in the shear plane and the friction energy on the rake face. Then, the cutting energy is given in the orthogonal cutting model made. Because the cutting energy depends on the chip flow direction, the chip flow angle is determined to minimize the cutting energy. As a consequence, the cutting force can be predicted in the determined chip flow model.

**Cutting Force Simulation.** The cutting forces were simulated for cutting of aluminum alloy with cemented carbide tool coated by AlCrTi thin layer. The following orthogonal cutting data were used:

\[
\begin{align*}
\phi &= \exp(0.05057V + 22880t_i + 2.110\alpha - 1.682) \\
\tau_s &= \exp(-0.09526V - 29560t_i - 0.5304\alpha + 20.700) \\
\beta &= \exp(0.005542V - 4191.3t_i - 0.3338\alpha - 0.08743)
\end{align*}
\]

(2)

Figure 10 shows cutting force predictions with Tool S and Tool R at the cutting condition of No. 1. Although the thrust in drilling with Tool R is slightly smaller than the measurement one in the drill penetration process, the cutting forces are predicted well in comparison to the measured ones. The force model is verified in the agreement of the simulation with the measured ones.

**Chip Flow Model at End of Lip.** The chip flow models at the end of the lips are discussed in drilling with Tool S and R at the cutting condition of No. 4, as shown in Fig. 11. In terms of the chip flow angles, which are defined as the angles between the projected directions of the tool axes on the rake faces and the chip flow directions. The chip, therefore, flows into the radial direction with...
increasing the chip flow angle. The smaller chip flow angle while drilling with Tool S is predicted than that of Tool R due to the horizontal edge inclination. Since the resultant force on the tool-chip interface is loaded to the workpiece along the chip flow direction, the force is applied to the radial direction of the hole with increasing the chip flow angle. Therefore, the removal area is extruded outside the hole and piled up as a large burr in drilling with Tool R, as shown in Fig. 6.

Regarding the uncut chip thickness at the end of the lips, the thickness in drilling with Tool S is predicted as 0.025 mm which is the same value of the feed rate, while the thickness in drilling with Tool R becomes smaller than the feed rate due to the large chip flow angle. The smaller friction angle, then, is predicted at the large uncut chip thickness when using Tool S because the negative value is characterized for the parameter of uncut chip thickness in the friction angle of the orthogonal cutting data. The thrust in drilling with Tool S, therefore, becomes small, as shown in Fig. 4.

Summary

The cutting processes of aluminum alloy with the flat bottom drills have been discussed in the cutting experiment and the cutting simulation based on minimum cutting energy.

In the drill penetration, the cutting force increases suddenly with the flat bottom drill with sharpened corners due to the simultaneous edge penetration from the center to the end of the lip. While the cutting force with the corner rounded drill gradually increases with the cutter feed corresponding to the corner radius. The thrust becomes small in drilling with the flat bottom drill with sharpened corners because the friction angle is smaller than that of the corner rounded drill.

In drilling with the corner rounded drill, the cylinder surface is finished with small surface roughness because the rotation radius of the tool gradually increases with the cutter feed. The large burr, however, is formed around the entrance because the cutting force loads in the radial direction corresponding to the chip flow direction.

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