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Technical paper

High speed milling processes with long oblique cutting edges

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ABSTRACT

High speed end milling processes using an inclined end mill with long oblique end teeth was investigated to minimize the scallop height of the finished surface. The optimal cutting conditions were found to improve the tool life and machining accuracy. According to the results of cutting tests, the cutting force decreased with increasing cutting speed due to the change in chip formation. Although the cutting temperature increased with cutting speed, it was found that the change in the tool wear mechanism with cutting speed minimized the tool wear at a higher cutting speed. Moreover, although the surface roughness of the machined surface deteriorates due to the tool wear when cutting length is increased, it is found that the deflection of the tool increases due to the increase of cutting forces and it improves the surface roughness.

1. Introduction

Development of the machine tools with a high speed spindle and table and the improvement of the cutting performance of tool materials have dramatically increased the cutting speed and material removal rate.

Furthermore, the widespread multi-axis machine tools permit the high efficiency and high precision machining of products with complex geometry. For example, it is possible to machine free surface of a product by controlling the trajectory and the posture of a ball end mill [1]. Additionally, turning with an end mill so called turn-milling is proposed instead of turning with a single point cutting tool [2–4,11]. This method prevents troubles often caused by a long continuous chips produced in turning process and permits the automation of machining processes. However, height of cusps generated on the curved surface machined with a ball end mill or a corner radius end mill is often larger than the height of feed marks in turning with a single point tool.

For example, as shown in Fig. 1, the cusp height of the surface machined by a ball end mill with the radius of R_c is theoretically expressed as the following equation;

$$R_{th} = \frac{p_f^2}{8R_c} \quad (1)$$

where p_f is the pick feed of the end mill.

On the contrary, by inclining the tool revolution axis in order that the oblique linear cutting edge becomes parallel to the pick feed direction, it is possible to reduce the cusp height and improve the surface roughness. In Fig. 2, the linear cutting edge is inclined at angle θ from the rotation surface. The tool revolution axis is inclined at the same angle to the feed direction, and the pick feed p_f is smaller than the cutting edge length ℓ. This kind of cutting tool can be used to reduce the surface roughness of a cylindrical surface. However, this cutting tool generates the surface by transcribing the linear cutting edge, so a change in the cutting edge geometry due to tool wear affects surface roughness or machining accuracy. Accordingly, the present research aims to clarify the effects of cutting conditions on tool wear and the effects of tool wear on surface roughness in the machining process by using an end mill with the long oblique end cutting edge in order to improve the efficiency and accuracy of the machining of curved surface.

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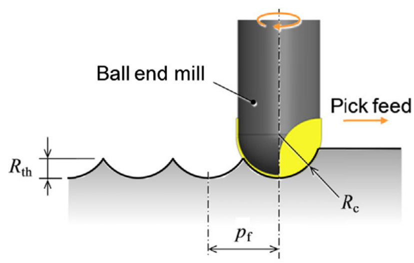

Fig. 1. Cusp height of surface machined with a ball end mill.

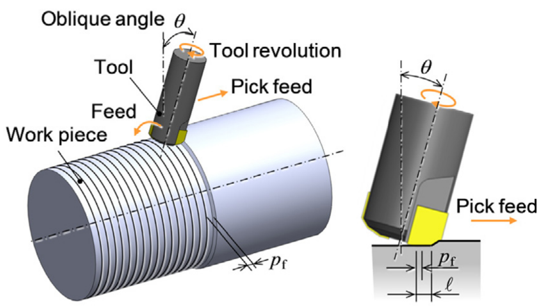

Fig. 2. Machining of curved surface with an oblique Edge cutting tool.

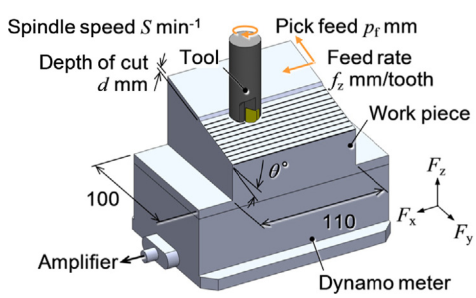

Fig. 3. Experimental setup for the measurement of cutting forces and tool wear.

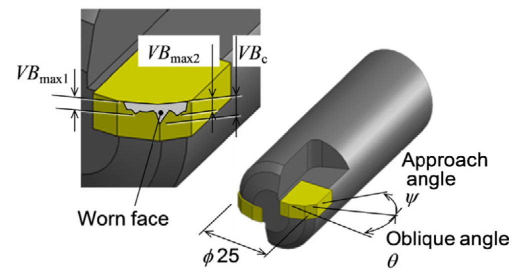

Fig. 4. Geometry of cutting tool.

2. Experimental configurations

Cutting tests were conducted by milling an oblique surface of a work piece. As shown in Fig. 3, the surface was inclined at angle $\theta = 15°$ and parallel to the oblique cutting edge of the end mill. The work piece was mounted on a dynamometer, and cutting forces generated during the tests were measured. Depth of cut normal to the surface is represented by d mm, and feed direction of the end mill is in the x direction. F_x, F_y, and F_z are the cutting forces in the feed direction, cross-feed direction, and axial direction respectively. The dynamometer used in this experiment is Kistler 9257B. Cutting force signals from the dynamometer was amplified with a charge amplifier and analyzed with a digital recorder. The work piece material is 13 Cr steel (hardness HB 241) with length of 110 mm and width of 100 mm. Diameter of the cutting tool was 25 mm, oblique angle of the linear cutting edge θ was 15°, and approach angle ψ was 30°. Tool wear of the cutting edge after the cutting tests was observed by microscope and evaluated by VB_c (namely, corner wear), VB_{max1} (namely, wear of the oblique linear cutting edge), and VB_{max2} (wear of the principal cutting edge). The machined surface is measured by a surface roughness tester Talysurf 5 manufactured by Taylor Hobson, Ltd. The geometry of the cutting tool used for the cutting tests is shown in detail in Fig. 4. Inserts made from coated tungsten carbide were mounted in the body of a steel cutter body. Cross point of the linear oblique cutting edge and principal edge is the position of the diameter of 21 mm. The accuracy of the oblique angle of the cutting edge on the machine tool was within 15° ± 1 min on machine tool. The length of the cutting edge is $\ell = 4.6$ mm and the radius of the corner R is 0.2 mm.

In Fig. 5, since pick feed p_f must be smaller than the length which the corner radius R subtracted from the cutting edge length ℓ, it follows that;

$$p_f \le \ell - \frac{R}{\tan\{(180-\psi-\theta)/(2)\}} \tag{2}$$

From this equation, $p_f < 4.5$ mm. The pick feed was set to 4 mm. Then, temperature of the cutting edge during the cutting process was measured by using a covered constantan wire embedded in the work piece as shown in Fig. 6. A 0.15 mm wide slot was machined on the work piece, and the enamel covered constantan wire with width of 0.076 mm was embedded in the slot. This wire was machined at the same time as the work piece, and a thermoelectromotive force was generated by the conduction with the burr of work piece when the cutting edge passes [5–8].

Since the thermoelectromotive force when the cutting edge passes is small, it is necessary to electrically isolate the work piece and the wire from the machine tool in order to avoid the influence of the noise. The work piece was thus put between ceramic plates and mounted in a machine vise. Furthermore, the vertical machining center used for this experiment uses a ceramic bearing for the tool spindle, so the machine tool and work piece do not conduct through the cutting tool.

The above described experimental configurations are specified in Table 1. Depth of cut was 0.5 mm normal to the machine surface, feed rate of the end mill was 0.3 mm/tooth, and pick feed was 4 mm. The feed direction was down milling and soluble cutting fluid was provided.

3. Experimental results

3.1. Relationship between cutting conditions and tool wear

The relationship between cutting velocity and tool wear after cutting a length of 11 m is shown in Fig. 7. According to the figure, corner wear VB_C is the largest. Generally, tool wear increases as cutting velocity increases.

This result indicates that V_c is increased by the increase of the cutting velocity. However, VB_{max2} and VB_{max1} are minimum at cutting velocity of 200 m/min and 400 m/min, respectively. Additionally, they increases steeply at higher cutting velocity (i.e., more than 600 m/min). Since the flank wear of the oblique cutting edge VB_{max1} is considered to affect the surface roughness directly, cutting velocity of 400 m/min is the optimal condition. Observations of the tool wear taken with a scanning electron microscope are shown in Fig. 8.