CIRP Annals - Manufacturing Technology 64 (2015) 101–104

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Study on 5-axial milling on microstructured freeform surface using the macro-ball cutter patterned with micro-cutting-edge array

J. Xie *, Y.H. Li, L.F. Yang

School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, China
Submitted by K.-D. Bouzakis (1), Thessaloniki, Greece.

ARTICLE INFO

Keywords:
Micro-machining
Milling
Micro-grinding

ABSTRACT

A 5-axial micro-replication milling of microstructured freeform surface is proposed by a novel ball cutter, on which micro-cutting-edge array is patterned by a diamond wheel V-tip in micro-grinding. It can efficiently and precisely machine arbitrary-curved microgroove and micro-pyramid arrays on aluminium alloy and die steel. The form errors reach 6.6 μm in 253.6 μm in microstructure depth and 1.6 μm with 50 mm in macro-freeform, respectively. The rake angle, however, is decreased so as to increase cutting temperature. Moreover, increasing wheel speed and decreasing feed speed decrease micro-form errors and surface roughness. The cross-spark-out cutting may deburr.

1. Introduction

A hybrid of microstructure array and freeform surface may produce higher value-added applications for surface engineering, but its fabrication needs higher operation degree and finer tool tip. Although a 5-axial milling has been employed to fabricate freeform surface by using a macro-cutter [1,2], the microstructure surface was milled by using a micro-cutter [3]. Similarly, the 5-axial grinding was a possibility to machine such curved surfaces in high form accuracy and surface quality by macro-curved grinding wheel [4], but the microstructure array was ground by a micro-diamond wheel V-tip [5]. Moreover, the laser machining had the difficulty to control the machined micro-form accuracy [6]. The etching had no way to precisely machine the microstructure array on macro-freeform surface [7].

In this paper, a novel hybrid of macro- and micro-millings is proposed to efficiently and precisely replicate the micro-cutting-edge array of macro-ball cutter on freeform workpiece in 5-axial milling. First, a mutual-wear form-truing was developed to control the sharpness and accuracy of micro-diamond wheel V-tip; then it was used to perform the micro-grinding of micro-cutting-edge array on ball cutter surface; next, the geometrical relation between the micro-cutting-edges and the milled microstructure was constructed; finally, the milling experiments were performed to investigate cutting temperature, micro-form accuracy, surface roughness and micro-deburring.

2. Micro-grinding of micro-cutting-edge array on ball cutter

Fig. 1 shows the micro-grinding of micro-cutting-edge array on ball cutter by using a diamond wheel V-tip. In wheel V-tip truing, a CNC mutual-wear between rotary grinding wheel and positioned dresser was employed along the V-shaped linear interpolation movement (see Fig. 1a). The form-trued wheel V-tip angle was identical to the angle θ_0 of V-shaped truing paths [5].

Then, the form-trued diamond wheel V-tip was employed to perform a micro-grinding. The rotary axes of ball cutter and grinding wheel were positioned on the *YZ*-section (see Fig. 1b). The rotary cutter moved along wheel cutting direction at the feed rate v_f. Along with an accumulate depth of cut *a*, the wheel V-tip profile at the wheel speed v_w was gradually replicated on the ball cutter surface through micro-cuttings with many diamond grains protruded along wheel V-tip profile. After that, next micro-grinding was performed with an interval *w*. Finally, the micro-cutting edge array was produced on the arc edge profile of cutter.

Fig. 2 shows the geometrical parameters of micro-cutting-edge array on ball cutter surface. The micro-cutting-edges were informally patterned on the arc edge profile of cutter by overlapping each neighbouring microgrooves whose shapes were derived from the wheel V-tip profile (see Fig. 1a). Its location was dominated by the position angle α.

Although the semi-angle θ_1 was equal to half of wheel V-tip angle θ_0, the semi-angle θ_2 became larger due to the non-orthogonal rotation between grinding wheel and ball cutter (see Fig. 1b). The semi angles θ_1 and θ_2 are described as follows:

$$\begin{cases} \theta_1 = \dfrac{\theta_0}{2} \\ \theta_2 = \max\left\{\arctan\left(\dfrac{2R - a_p}{2(R + r - a_p)} \times \tan(90^\circ - \alpha)\right), \theta_1\right\} \end{cases} \quad (1)$$

where *R* is the wheel radius and *r* is the cutter radius (see Fig. 1).

Because the micro-cutting-edge was formed by the circumferential V-groove, the flank angle β_n (n = 1, 2, responding to θ_1 and θ_2) decreased to 0° from the original β_0 (see Fig. 2b). The rake angle γ_n was also decreased in comparison with the original γ_0 due to the

* Corresponding author.
E-mail address: jinxie@scut.edu.cn (J. Xie).

http://dx.doi.org/10.1016/j.cirp.2015.04.075
0007-8506/© 2015 CIRP.

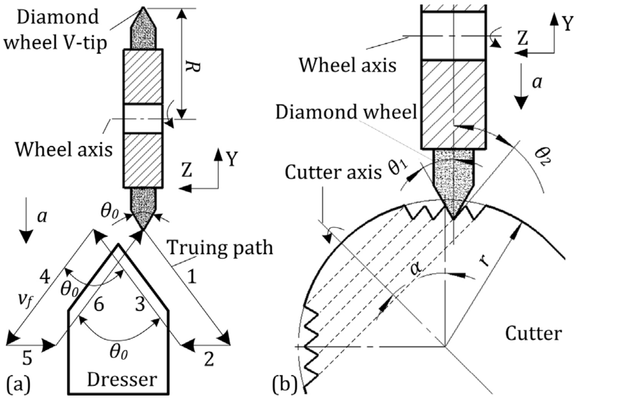

Fig. 1. Micro-grinding of micro-cutting-edge array on ball cutter surface using a diamond wheel V-tip: form-truing (a) and micro-grinding (b).

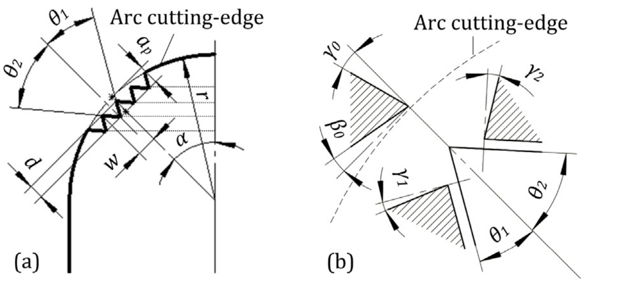

Fig. 2. The parameterization of micro-cutting-edge array of cutter: geometrical parameters (a) and cutting parameters (b).

semi-angle θ_n. They are described as follows:

$$\begin{cases} \gamma_n = \arcsin(\sin\gamma_0 \times \sin\theta_n) \\ \beta_n = 0, \quad n = 1, 2 \end{cases} \tag{2}$$

3. 5-axial milling of microstructured freeform surface

Fig. 3 shows the 5-axial milling of microgrooved freeform surface. The microgroove array was machined by the micro-cutting-edges of cutter along the curved microgroove direction (see Fig. 3a). The micro-pyramid array was formed through the cross-milling of microgrooves. The cutter locations $\mathbf{cl_i}$ (x, y, z) are described as follows:

$$\boldsymbol{cl_i} = \boldsymbol{cc}_i + (r - a_\mathrm{p}) \times \boldsymbol{n}_i \tag{3}$$

where $\mathbf{n_i}$ is a unit normal vector on the tangent point $\mathbf{cc_i}$ and $\mathbf{i}$ is the cutting point number.

The cutter axis vector $\mathbf{t_i}$ was controlled to be vertical to the tangent direction of microgroove. Namely, the angle between the normal vector $\mathbf{n_i}$ and the cutter axis vector $\mathbf{t_i}$ was equal to the cutter posture angle α (see Figs. 1b and 3b). In 5-axial milling, the $\mathbf{t_i}$ was used to control the rotation axes C and A. Hence, these

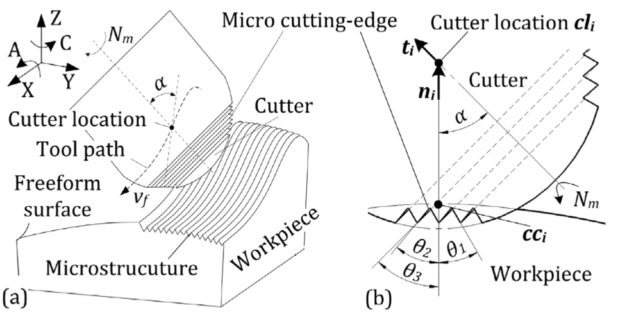

Fig. 3. The 5-axial milling scheme of microgrooved freeform surface: the microstructure replication (a) and the cutter location cl_i (b).

constraints are described as follows:

$$\begin{cases} \boldsymbol{t_i} \cdot \left(\dfrac{\boldsymbol{cc}_{i+1} - \boldsymbol{cc}_{i-1}}{|cc_{i+1}cc_{i-1}|} \right) = 0 \\ \dfrac{\boldsymbol{t_i} \cdot \boldsymbol{n_i}}{|\boldsymbol{t_i}| \cdot |\boldsymbol{n_i}|} = \cos(\alpha) \end{cases} \tag{4}$$

Due to the cutter rotation in milling, the milled microgroove angle θ is different from micro-cutting-edge angle (see Fig. 3b). It is described as follows:

$$\theta = \theta_1 + \theta_3 \tag{5}$$

where the semi angle θ_3 is given by

$$\theta_3 = \max\left\{\theta_2, 90^\circ - \alpha\right\} \tag{6}$$

4. Experiments and measurements

4.1. Experiments

Fig. 4 shows the experimental scenes. First, the form-truing experiment of diamond wheel V-tip was performed (see Fig. 4a). In form-truing, the angle θ_0 of inverted V-shaped linear truing paths was designed as 60°, thus the trued wheel V-tip was 60° [5]. The truing conditions are shown in Table 1. It may protrude micro SD600 grains from the wheel V-tip (see Fig. 4a). The mean value of form-trued wheel V-tip angle reached 60.7°.

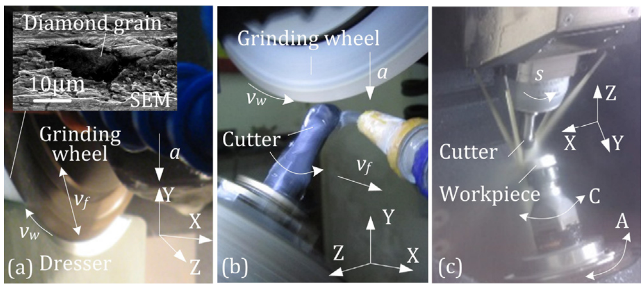

Fig. 4. Experimental scenes: form-truing (a), micro-grinding (b) and 5-axial milling (c).

Table 1
The form-truing conditions of diamond wheel V-tip.

CNC grinder	SMART-B818
Grinding wheel	SD600, bronze-bonded, R = 75 mm
Dresser	#600 GC stone
Truing path	60° V-shaped linear interpolation movement
Truing variables	v_w = 15.7 m/s, v_f = 200–100 mm/min
Coolant	BM2 soluble synthetic

In the micro-grinding experiment (see Fig. 4b), the micro-cutting-edge array width w, depth d and number n_c were designed as 400 μm, 253.6 μm and 4 for the cutter with r = 6 mm, and 200 μm, 126.8 μm and 5 for the cutter with r = 1.5 mm, respectively. The micro-grinding conditions are shown in Table 2.

Finally, the 5-axial milling experiments of microstructured freeform surface were performed (see Fig. 4c). The freeform surface was designed by functional point cloud [2]. The 5-axial milling conditions are shown in Table 3.

Table 2
The micro-grinding conditions of micro-cutting-edges on cutter surface.

CNC grinder	SMART-B818
Grinding wheel	SD600, bronze-bonded, 60° V-tip
Ball cutter	r = 1.5 mm; r = 6 mm
Grinding variables	v_w = 18.8 m/s, v_f = 10 mm/min, a_p = 310/210 μm
Coolant	BM2 soluble synthetic