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Generation of a regularly aligned surface pattern and control of cutter marks array by patch division milling

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Abstract

In this paper, a patch division milling technique that can generate a geometric surface pattern by means of a ball-end mill on a surface is proposed. The finished surface is divided into many same-size small patch segments such as triangles, quadrilaterals, or hexagons. The whole inside area of each patch is machined along a helical tool path with a high feed rate. A geometric surface pattern is generated by the cutting edges of the ball-end mill within the patch area, and after the machining of a series of patches, the machined surface is covered with many patches. It is shown that the aligned state of the cutter marks array on the patch can be controlled by the cross-feed, the feed speed per tooth, the number of teeth and the side length of the patch. A simulator was also developed to predict the aligned state of the cutter marks array in the patch. Comparing the machining on the patch division milling between an inclined flat surface and a cylindrical surface, the regularly aligned surface pattern and cutter marks array were found to agree well with the simulation results. The objective of this research is to establish the cutting method of generating regularly aligned surface pattern on the complex-shaped workpiece efficiently. If the surface pattern on the complex-shaped workpiece could be formed only by the ball-end milling with a machining center, it will be a very effective tool for the machinery industry.

Keywords: Cutter marks; Surface pattern; Ball-end mill; Tool path; Machining center

1. Introduction

The surface pattern is used for various products. There are two general purposes of generating such a surface pattern: to add a specific physical function to the surface and to make an ornamental design. Some examples of the use of a functional surface include the control of wettability and water-repellent quality by arranging cylindrical and square pillars in a grid on the surface [1–3], the use of surface patterns to decrease the drag forces of air and water [4,5], the use of surface patterns to decrease the friction between sliding parts [6], and the control of the light correction and refraction of optical components such as microlens arrays [7,8]. The ornamental surface is used to create graining, wall tile, figured glass, etc. in the interior parts of a car. The algorithm by which surface designs of various shapes can be created quickly and smoothly has been researched [9].

The surface pattern can be generated by a chemical method such as etching and by machining methods such as cutting, grinding and shot-blasting. In this paper, a milling process is employed to make surface patterns because the milling process is generally used to make certain shapes and also it is an efficient low-cost method. In particular, the ball-end milling using a 5-axis machining center is widely used to machine complex-shaped workpieces.

The key idea of this study is to make a surface pattern by controlling the alignment of cutter marks on the machined surface. The various cutter marks are generated on a machined surface by means of ball-end milling. A surface pattern with constant scallop height and a regularly aligned cutter marks array can be realized by controlling the cutter marks array. Various investigations of the surface pattern of cutter marks arrays produced by ball-end milling have been conducted from the viewpoint of the relationship

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between the scallop height and the tool path strategy, because the surface pattern and the surface roughness have a close connection. Toh [10] experimentally demonstrated that a variance of surface roughness depends on the cutter path orientations on a workpiece. Feng and Su [11] have demonstrated an integrated approach to the concurrent optimization of tool path and feed rate for the finishing machining of 3D plane surfaces (a flat surface inclined in two directions) using ball-end milling. This approach exhibited that the required machining efficiency, the scallop height and the machining error were satisfied. In Ref. [12], the relationship among the main cutter path strategies of milling (offset, single direction raster and raster), surface texture, tool life, etc. was reported.

Among the investigations describing the mechanism of generating surface texture by ball-end milling, Zhao et al. [13] showed the relationship between cutting conditions and surface roughness. Hao et al. [14] theoretically analyzed ball-end milling to elucidate the generating mechanism of machined surfaces. A method for calculating the position of the cutting edge that passes through a specified direction has also been proposed. Chen et al. [15] have presented the relationship between scallop height and three respective quantities: the tool radius, the tool-axis inclination angle, and the feed/pick ratio. Saito et al. [16,17] demonstrated that a desired surface pattern can be generated by adjusting the phase difference of the tool rotation angle, the eccentricity and the traverse distance along the tool path. The phase difference of the tool rotation angle was controlled by adjusting of the air cut time between each path. However, calculation of the air cut time along the tool path over a complex surface is rather complicated. Therefore, it is very difficult to generate a regular surface pattern on a workpiece with a complex shape.

To resolve these issues, a new surface machining method has been developed to create a series of geometric patterns. In this paper, a patch division milling method that can generate a geometric pattern using a ball-end mill on a surface is proposed. When patch division milling is used, the surface pattern is covered with a selected patch shape that is generated on the whole machined surface. Then the regular surface pattern is generated by the cutter marks array in each patch. This method can generate the surface pattern with a regular cutter marks array only by machining with a helical tool path and using a constant feed speed in the patches. In this research, a mold of turn signals cover of a car and a light reflector in an illumination lamp, and exterior parts for the ornamental design are targeted. The objective of this paper is to establish the cutting method of giving function of desire and generating surface pattern efficiently to these parts. In this paper, the mechanism of patch division milling and the relationship among the parameters that determine the cutter marks array are described, and the method for aligning the cutter marks array in the patch is proposed. The experimental results of applying this proposed method to an inclined plane and a cylindrical surface are also described.

2. Detail of patch division milling

2.1. Outline

The procedure of the patch division milling proposed in this study is described as follows.

(1) As shown in Fig. 1(a), the whole surface is divided into many same-size small patches. The patches can be triangles, quadrilaterals, or hexagons.
(2) As shown in Fig. 1(b), the whole inside area of each patch is machined along a helical tool path with which a high feed rate is on the same order as the cross-feed.

After these procedures, a regularly aligned surface pattern is generated within a patch area by cutting with the ball-end mill. In addition, the whole surface can be covered with regularly aligned patches. It should be noted that the tool axis should be inclined to the machining surface and the machining with the tip of the ball-end mill should be avoided.

2.2. Phase difference of tool rotation angle between adjoining tool paths

The phase difference of the tool rotation angle $\omega_{n\to n+1}$ is defined as the difference of the tool rotation angle between the nth path and the $(n+1)$th path when the tool is in a feed motion with self-rotation along the tool path as shown by the dash line in Fig. 2 [17]. The phase difference of tool rotation angle is called as "the phase difference" hereafter. As shown Fig. 2(a), well-aligned identical shape cutter marks can be formed on the machined surface when the phase difference is kept constant on every tool path. On the other hand, when the phase difference changes as shown in Fig. 2(b), the regularity of the alignment state of the cutter marks is lost, and the surface pattern aligns along the elliptic line. The cause of the difference in the surface pattern between Fig. 2(a) and (b) is that the cutter marks array is shifted to the feed direction by every tool path changing. The cutter marks array is the set of hemispherical ovals generated by the cutting edge of the ball-end mill. Therefore, the relationship between the tool path and the phase difference is important for the control of the cutter marks array. In patch division milling, a ball-end mill moves along the helical tool path in each patch at a constant feed speed. The phase difference in this simulation is discussed below.

In order to calculate the difference in the tool rotation angle between adjoining tool paths, the total tool rotation angle along the helical tool path is described for a square patch as an example. Fig. 3(a) shows the helical tool path in a square patch. Fig. 3(b) shows four triangular areas divided by diagonal lines, i.e., straight lines that connect