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Paper:

Generation of Uniformly Aligned Dimples on a Curved Surface Using a Curved-Surface, Patch-Division Milling Technique

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Many products are designed with surface textures that enhance the aesthetic and tactile qualities of the product. In this paper, a curved-surface, patch-division milling technique is proposed for creating uniform aligned cutter marks on a curved surface. Previous research demonstrated a ball-end milling technique that divides the surface into small planar patches where each patch is generated by a helical tool path with dimples in uniform alignment. Because the patches are planar, it is impossible to precisely machine a concave or convex surface. However, the technique could only approximate a method for machining curved surfaces. To resolve this issue, curved surface patches were developed to generate the patch directly according to the shape of the targeted curved surface. The dimples are expected to be uniformly aligned on curvedsurface patches. Therefore, the targeted surface should be cut using an appropriate machining condition. According to the test results, the distribution of dimples was the same as the pre-determined distribution. In addition, the dimples were regularly aligned when viewed from a specific angle. This proposed method overcomes the deviation of the dimple's positions, which is caused by the acceleration–deceleration of the machine tool and the change of the cutting point during five-axis machining.

Keywords: ball-end mill, surface texture, geometric pattern, machining center

1. Introduction

A textured surface is defined as a surface with a regular alignment of surface height features that can be described using deterministic methods [1]. Common reasons for generating a textured surface on industrial products include improved appearance and/or tactile properties as well as potentially increasing the product's value. However, the surface texture may also have a functional role [2]. A typical example of a functional textured surface is the control of aerodynamic drag using dimples on golf balls [3–5]. Previous research has shown the advantageous properties of natural textures or mechanical features of artificial textures [6–11].

Grinding is the method most often used to generate textural features and structures on the surfaces of hard and brittle materials [12]. Electrochemical etching is used to generate patterns and multilayered structures on stainless steel [13, 14]. A textured cutting tool has also been proposed to enhance the frictional characteristics of various surfaces [15]. However, while these processes are very precise, they are also time consuming when adding a texture to a complex curved surface.

A ball-end mill is often used for the machining complex curved surfaces of products that fit on a five-axis machining center because the milling capability is superior because of the high degrees of freedom and machining efficiencies [16]. A previous study proposed a method whereby machining accuracy was estimated using the pattern errors when cutting a textured pattern onto a surface [17]. Thus, this method could significantly reduce the production labor, cost, and time if post-processing of the textured surface was no longer required. The generation of random texture patterns and machined samples, when using milling techniques that assessed patch-boundary distortions, was proposed as a less complex surface texture generation technique based on indiscriminate wide-area patterns [18]. However, the texture patterns were regarded as general surface roughness during assessments of machining quality and were removed by post-processing techniques such as grinding or polishing [19]. To generate cutter marks as regularly aligned dimples in high-speed milling, the relationship between the dimple spacing and cutting condition should be known. Toh noted that three main tool path strategies are commonly employed in milling [20], and that a vertical upward orientation gave the best surface texture [21]. Those studies demonstrated that the tool path plays a key role in the generation of surface texture. In addition, Chen found that parameters such as tool radius, feed/pick ratio, and the initial cutting edge entrance angle affected the distribution of dimples [16]. Finally, as reported in earlier studies, the cutting conditions also have a significant effect on dimple alignment. Saito et al. used an experimental method in which a tilting planar work piece was machined with

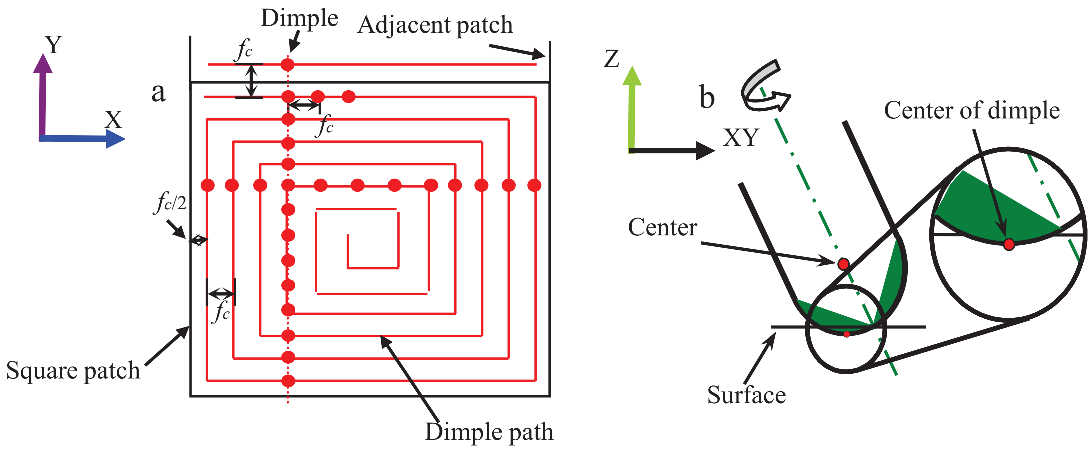

Fig. 1. Planar square patch on plane (a) Outline of patch and dimple path (b) Relation between center of tool and center of dimple.

the cutter strategy of a single-direction raster [22]. Their study revealed that regularly aligned dimples were generated with a constant phase difference.

For milling a curved surface with regularly aligned dimples, the complex geometry can introduce intricate calculations in order to establish the cutter path and cutting conditions. To overcome these difficulties, Matsuda et al. proposed a new surface machining method called patch-division milling [23]. By using this method, a curved surface can be closely approximated through a series of planar surface patches. Uniformly aligned dimples can then be machined on the planar surface patches assuming that specific machining conditions have been established. A new type of patch called a curved surface patch was used for our research because it is difficult to represent a smooth curved surface using planar surface patches. Uniformly aligned dimples can then be machined onto the surface of a curved surface patch assuming specific machining conditions have been established.

2. Curved Surface Patch-Division Milling

2.1. Planar Surface Patch Division

The term patch-division indicates that an entire surface is divided into small patches. Within the areas of the patches, uniformly aligned dimples can then be generated using a ball-end mill. To facilitate the understanding of patch-division milling, an experiment that generated uniformly aligned dimples on a plane is described. As shown in **Fig. 1a**, the plane was divided into square patches where the dimples were generated along a helical path, hereafter called the dimple path, within the entire area of each square patch. The dimple path was machined based on a constant distance f_c during cross feed. When each dimple maintained the same distance f_c from the adjacent dimples along the dimple path, then the dimples were uniformly aligned across the whole plane.

After designing the uniformly aligned dimples for a patch, it was necessary to calculate the tool path according to the distribution of the dimples. The method for calculating the tool path is described by the following process. When the cutting edge is vertical to the plane, the deepest point on the cutting edge represents the center of the dimple as shown in **Fig. 1b**. The tool path is determined by tracing out the moving path of the tool's center. The position of the tool's center can then be given by shifting the center of the dimple along the normal vector of planar surface with a distance equivalent to the radius of the tool. The tool path, the appropriate spindle speed S, the feed speed F, and the number of cutting teeth N are then selected based on Eq. (1), where f_c is the distance between two adjacent dimples along the dimple patch:

$$f_c = F/S \cdot N \quad \text{. . . . .} \quad (1)$$

2.2. Curved Surface Patches for Curved Surfaces

To prove that planar surface patch division milling is an approximate method, the following experiments were conducted. First, a smooth Bezier curved surface was machined onto a workpiece to create the initial prepared machined surface as shown in **Fig. 2a**. Then multiple planar surface patches were machined onto this surface for the final machined surface. However, as shown in **Fig. 2b**, the concave section could not be machined using this type of patch since the planar patch located above concave surface was considered a two-dimensional representation. The area below the straight line (i.e., the planer surface patch as indicated by the red line) could not be machined in this case.

Therefore, Xu and Sasahara created a pyramid-shape patch using the shape of the target surface to adjust the position and direction of the tool path [24]. This type of pyramid patch can reduce the area of sections that cannot be machined. However, this method cannot be used in precision machining for curved surfaces. For the purposed of our research, a new surface-machining method was developed by changing the shape of the tool path of a pyramid patch to create a series of curved-surface patterns.

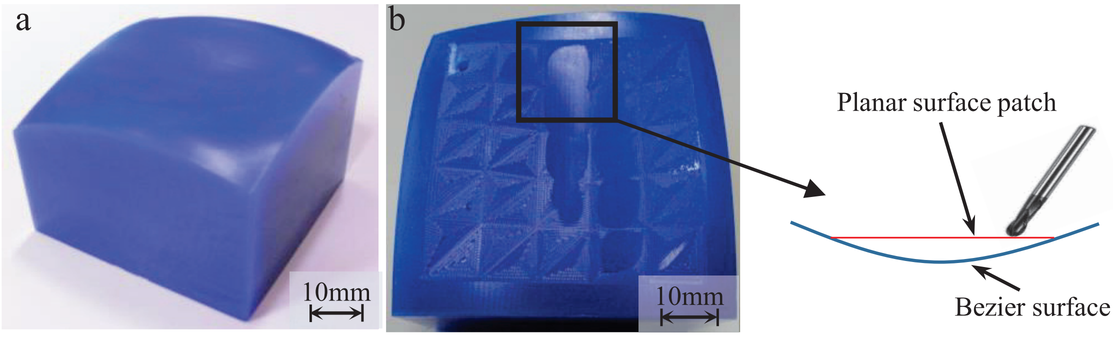

Fig. 2. Planar square patch on Bezier surface (a) Work piece with a smooth Bezier surface (b) The result of experiment and 2D diagram drawing why the concave part cannot be machined.

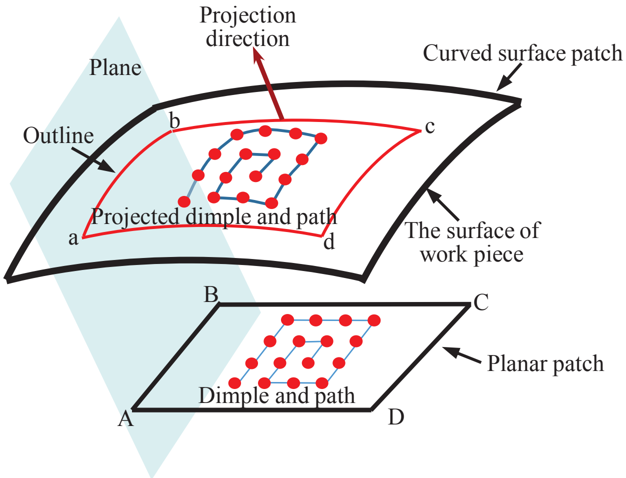

Fig. 3. Projection of planar patch on curved surface.

2.2.1. Generation of Curved-Surface Patches

To define the curved-surface patch, the outlines of the patch on the targeted surface should be determined. An outline of a curved surface is quite complex. Therefore, the outline should be constrained by certain assumptions. For this research, the curved line is defined as an intersection line at which a plane intersects the surface. Hence, the outline of the patch becomes a curved line on a planar surface. For this reason, the method for positioning objects is based on the idea of shadows, which are outlines of selected objects projected onto the surface.

For example, as shown in **Fig. 3**, the outline ab of the curved-surface patch is a projection of the straight outline AB. When the direction of the projection has been specified, a plane can be projected onto the curved surface patch. Additionally, the curved surface patch becomes part of the targeted surface surrounded by the outlines. In the same way, the uniformly aligned dimples on a square planar patch can be projected onto a curved surface patch. Thereby, a curved surface patch that has regularly aligned dimples can now be generated. As the dimples on the square planar patch are aligned along a helical line, the projected dimples are distributed along a helical dimple path as well.

2.2.2. Setting of Projection Direction

The projection direction determines the shape of the curved-surface patch. Once the projection direction is specified, the curved-surface patch is the sole projection for the planar patch. Different projection directions will affect the position and alignment of the projected dimples on the entire surface. Thus, the method of the projection direction should first be specified. The projection directions for the dimples are unified along the vertical vector of the XY plane while the alignment of the projection dimples can be viewed from the vertical direction of the XY plane for the purposes of our research. If the coordinate value of a dimple on a planar patch is $(X_n, Y_n, 0)$ then the coordinate value of the projected dimple on the Z axis can be obtained by substituting X_n and Y_n into the mathematical expression of the targeted surface. (i.e., the mathematical expression of spherical surface is $X^2+Y^2+Z^2=R^2$)

3. Machining Conditions for Uniformly Aligned Dimples

3.1. Relationship Between the Cutter Orientation and Generation of Projected Dimples

For milling a patch with uniformly aligned dimples, the movement of the tool should be accurately controlled through constant spindle and feed speeds. The machining conditions are important for generating projected dimples at the desired position. The machining conditions were represented by the instantaneous position of the tool and the instantaneous cutter orientation at the moment of cutting the dimple's center. When the position of the projected dimple is known, the instantaneous position of the tool can be calculated based on the theory discussed in Section 2.1. After the tool position is identified, the cutter orientation can be calculated to generate a cutter mark at the aimed point. **Fig. 4** shows a schematic of the cutter orientation for generating the cutter mark dimple at the aimed point on a curved surface. A vector normal to the curved surface with its origin at the cutting point is assumed. Then the cutting edge of the ball-end mill makes contact with the curved surface at this point. The view from the arrow shows the cutting point from the tool axis

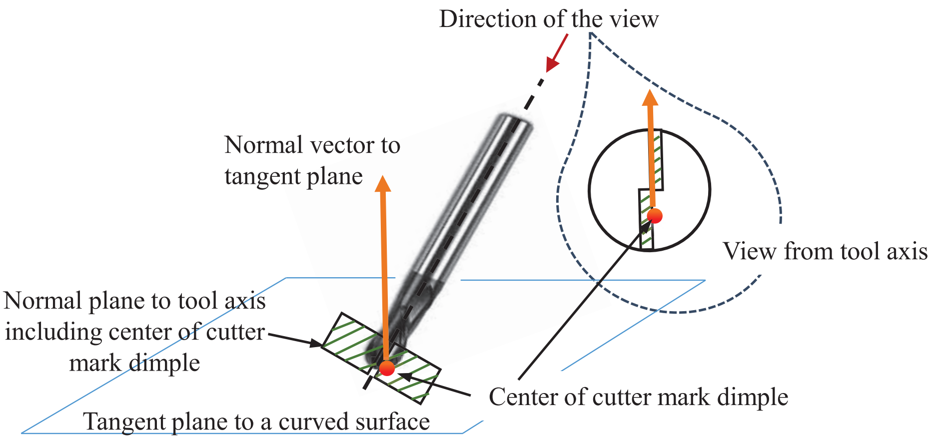

Fig. 4. Schematic of cutter orientation to generate cutter mark dimple at the aimed point on a curved surface.

direction thereby allowing for definition of the tool orientation at the time when the tool is passing the dimple center. A vector in this view shows the projection of the normal vector onto the normal plane of the tool axis. It can then be seen that the tool orientation should be in the same direction as the normal vector.

3.2. Machining Method for Expected Alignment

Based on the relationship between the cutter orientation and the dimple's center as mentioned above, the cutter orientations along the dimple path are obtained as shown in **Fig. 5a**. The cutter orientations differ significantly depending on the dimple's location on the curved surface. The phase differences λ_n between two cutter orientations for adjacent dimples should satisfy Eq. (2), where L_n is the travel distance of the tool and $2\pi \times S/F$ is the rotary phase required to move 1 mm:

$$\lambda_n = L_n \frac{2\pi S}{F} \qquad (n = 1, 2, 3 \ldots) \quad . \ . \ . \ . \ . \ . \quad (2)$$

Using the cutter orientations shown **Fig. 5** and Eq. (2), the phase differences λn and travel distances can be determined. However, the calculated travel distances are not equal to linear distances. In order to adjust the travel distances between two dimples, polygonal tool paths were employed. The two tool paths, 1–2 and 4–5 shown in **Figs. 5b** and **c**, can be used as examples. The lengths of the polygonal line tool paths can then be adjusted to ensure that both sides of Eq. (2) are equivalent with each other. In other words, after traveling the adjusted length L_n, the tool can rotate from one cutter orientation to the next cutter orientation under constant spindle speed and feed speed. However, adjusting the tool path is insufficient to generate the dimples according to the expected alignment since the dimples might not be cut with the expected cutter orientation. In the next sub-section, the method used for controlling cutter orientation is described.

3.3. Method of Controlling the Cutter Orientation

To generate the expected pattern on the curved surface patches, the dimples should be cut with the calculated cutter orientation. In conventional machining it is difficult to control the cutter orientation at any specified position due to the installation of the tool and acceleration of the rotation. An experimental method based on the adjusted tool path is proposed for controlling the cutter orientation.

For cutting the curved surface patches on the surface, the first patch is used to control the cutter orientation. The method can be considered as dictating that cutting takes place only when the practical cutter orientation is the same as the calculated cutter orientation with a small error as shown in **Fig. 6a**. In the same way, if the practical cutter orientation deviates significantly from the calculated cutter orientation, the edge of the ball-end mill cannot contact the surface as indicated in **Fig. 6b**. To control the cutter orientation, the number of dimples is established as an amount greater than 180. In addition, the phase difference between the cutter orientation of the first dimple and that of the second dimple is set to be Λ_n, where Λ_1 = the calculated phase difference $\lambda_1 + 1° + 1800°$, $\Lambda_2 = \lambda_2 + 1° + 1800° \ldots$, and $\Lambda_n = \lambda_n + 1° + 1800° \ldots$. The value $1800°$ is the additional rotation required such that the travel distance is longer than the linear distance and the tool path forms an acute triangle as shown in **Fig. 6a**. Based on the phase differences Λ_n, the travel distances were calculated and the tool path formed a zigzag path as shown in **Fig. 6c**. The cutter orientation is $\alpha_n = (\alpha_1 + x) + (\lambda_1 + \lambda_2 + \ldots + \lambda_{n-1}) + 1° \times (n-1) + 1800° \times (n-1)$, where x is the error between the first practical cutter orientation and the first calculated cutter orientation. Because $\alpha_1 + (\lambda_1 + \lambda_2 + \ldots + \lambda_{n-1})$ can be considered to be the calculated cutter orientation, the practical cutter orientation α_n accumulates at $1°$ intervals. Therefore, the practical cutter orientation is similar to the calculated cutter orientation. Finally, the tool returns to the origin of the machining center and the cutter orientation returns to the initial cutter orientation.

The phase difference between the practical cutter orientation and the calculated cutter orientation is obtained according to the cutter marks. By adjusting the travel distance between the origin and the first cutter orientation, this ensures that the first dimple can be cut with the expected cutter orientation.

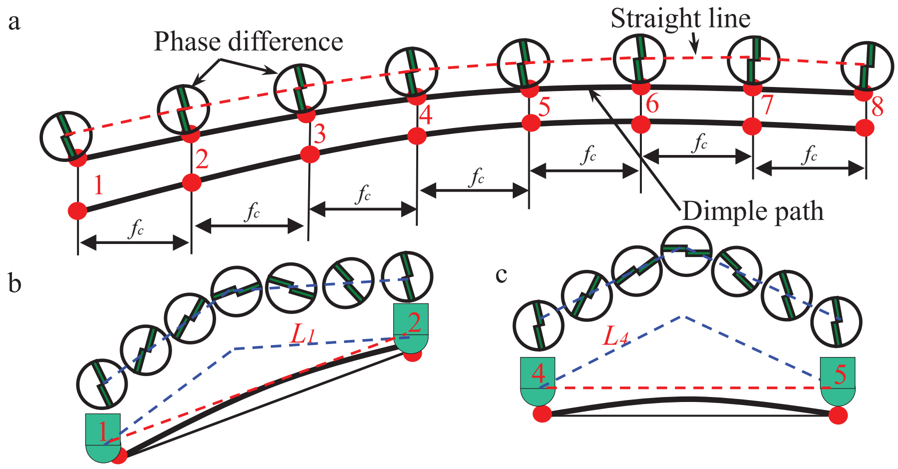

Fig. 5. (a) Cutter orientation for curved dimple path (b, c) Polygonal-line tool paths for adjacent dimples.

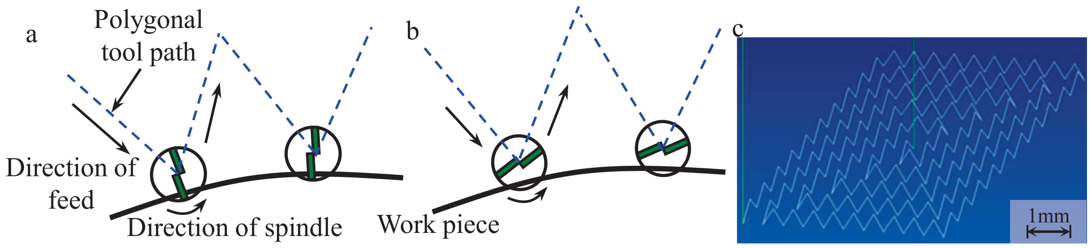

Fig. 6. Method of controlling the cutter orientation (a) Cutting work piece with expected cutter orientation (b) Non-cutting work piece with wrong cutter orientation (c) Tool path for the first patch.

4. Generation of Patterns on the Entire Bezier Surface

A Bezier surface, which is one type of curved surface whose mathematical expression is known, was used for this research. The calculation of the tool path for generating uniformly aligned dimples on the Bezier surface is complicated since Bezier surfaces can form concavo-convex shapes by changing the position of the reference points.

4.1. Non-Cutting Tool Path for Patches

A method for controlling the non-cutting travel distance between two patches was developed to generate the desired alignment of the dimples over the entire surface. Since the tool leaves the work piece after a patch is machined, a tool path is considered a bridge-shaped structure used to connect the centers of two cutter orientations at the end of one machined patch and the start of the next patch. The distance L, defined as the non-cutting tool path, can be calculated by Eq. (3); where λ is the phase difference between two cutter orientations which can be selected freely according to the length of the non-cutting travel distance:

$$\lambda = L\frac{2\pi S}{F} + 2\pi i. \qquad (i = 1, 2, 3 \ldots) \quad . \ . \ . \ . \quad (3)$$

Table 1. Coordinate values (x, y, z) of 16 control points of Bezier surface (mm).

(-30,30,24)	(-14,32,32)	(16,29,20)	(30,29,30)
(-31,14,15)	(-15,13,20)	(15,16,30)	(29,14,19)
(-32,-10,24)	(-16,-12,35)	(16,-15,21)	(32,-14,32)
(-30,-30,14)	(-14,-29,23)	(14,-30,18)	(30,-30,21)

4.2. Result of the Experiments

A Bezier surface, whose expression is known, was first selected as the targeted curved surface with 16 control points as shown in **Table 1**. The Bezier surface was divided into 8×8 curved surface patches using the method described above. The anticipated result was that the dimples on the curved surface patches were expected to align uniformly for this experiment.

Before the experiment, the alignment of the dimples and the tool positions for cutting the dimples were visualized by using 3D-CAD software (Pro/E). Finally, comparing the results of the experiment and the result of 3D-CAD software, it is ensured the machined dimples align uniformly on a curved surface patch. **Fig. 7a** shows the distribution of the entire dimple pattern on the Bezier surface, and the entire pattern of projected dimples on a smooth curved surface. The distance between two adjacent dimples can be accurately measured using the CAD software. Each projection dimple maintains a constant distance from adjacent dimples in the XY plane. Thus, the

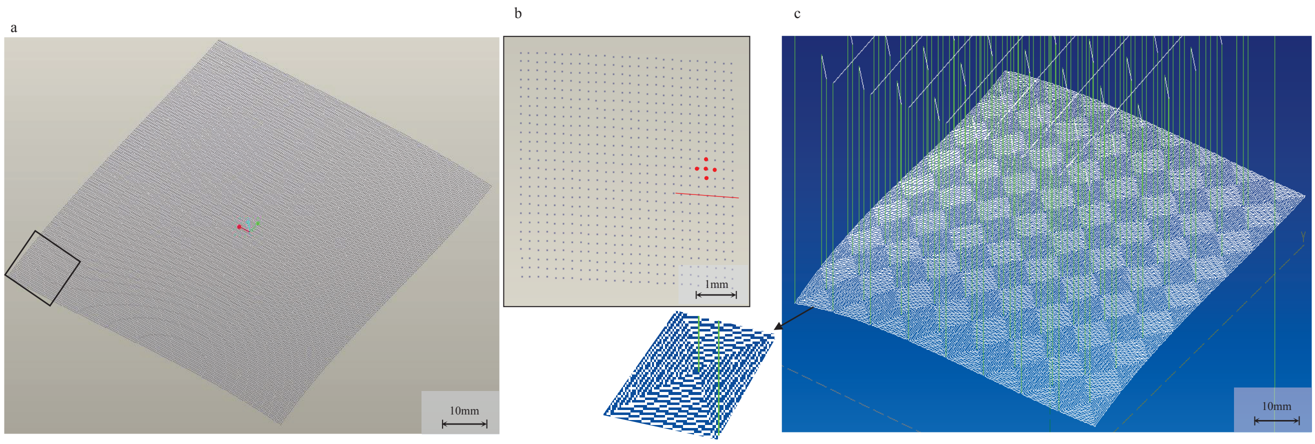

Fig. 7. Geometrical pattern of patches and dimples (a) Visualization of the whole dimples using CAD software (b) Alignment of dimples on a patch (c) Visualization of tool path.

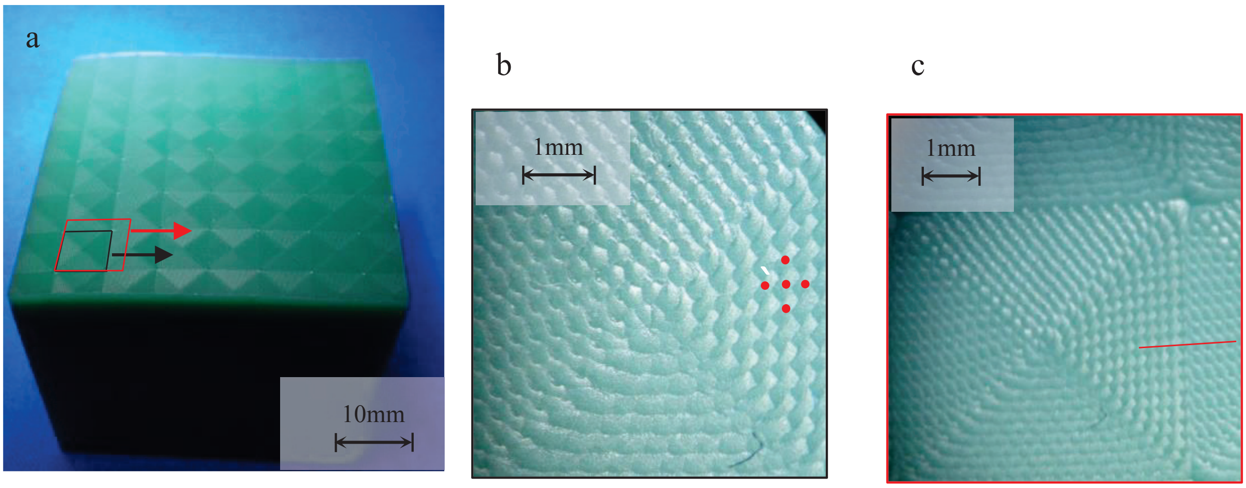

Fig. 8. Result of practical machining using curved surface patch milling (a) View of the entire surface (b) Dimples on a patch (c) Dimples on adjacent patches.

projected dimples on the Bezier surface uniformly align as can be viewed from the direction that is perpendicular to the XY plane. It is difficult to display the alignment of the projection dimples since the number of dimples is very large. **Fig. 7b** shows the location of a projected dimple on one patch of the curved surface. The distance between one dimple and an adjacent dimple (up, down, left and right) is equal in the XY plane while the dimples which are on different patches can form a line as indicated by the red line. Based on the projected dimples, the tool path can be calculated using the method described previously. **Fig. 7c** shows the trajectory of the center of a ball end-mill. After one patch was machined, the z position of the tool goes high to control the tool orientation at the entry of the next path as discussed in the previous section.

Employing the calculated tool path and cutter orientation, a work piece was machined with the curved-surface, patch-division milling technique. **Fig. 8** shows the results of the machining experiment while the cutting conditions are shown in **Table 2**. Since the control points of the Bezier surface of **Fig. 8** are as same as these of **Fig. 7**, the profile of the machined surface is the same as the results

Table 2. Cutting condition for square curved-surface patch.

Number of flutes N	2
Tool diameter D mm	2.0
Spindle speed S r/min	1000
Feed rate F mm/min	434.413
Cross feed f_c mm	0.5

of the visualization. Five red points show the center of each of the dimples and we know that each point aligns regularly and the distance between adjacent dimples is constant. In addition, the machined dimples, which are on different patches, can align on the straight line shown in red as shown in **Fig. 8c**. If the dimples were machined without using the curved-surface, patch-division milling technique, the alignment of the machined dimples form an irregular pattern as discussed in the preceding study [23]. The data indicates that a curved-surface, patch-division milling method can be applied to concave-convex curved surfaces.

5. Conclusions

In this paper, we proposed the use of curvedsurface patches whose shapes are in accord with the shape of a Bezier surface. The dimples on each patch are uniformly aligned by employing a zigzag tool path based on a calculated cutting condition. By comparing the results of the experiment with the 3D-CAD models, we know that the curved-surface patch method can generate uniformly aligned dimples on a smooth curved surface.

However, the Bezier surface that was machined in this research was a simple surface whose expression was known. A future report will focus on a method for generating regularly aligned dimples on free-form surfaces without mathematical expressions.

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