Influences of linear interpolation method and cutting parameters on machined surface texture in large curvature surface milling

Hang LI*, Guosheng SU*, Mingdong YI*, Peirong ZHANG* and Chonghai XU*

*School of Mechanical & Automotive Engineering, Qilu University of Technology (Shandong Academy of Sciences), Jinan, Shandong, China, 250353
E-mail: suguo@163.com

Received: 27 November 2019; Revised: 2 February 2020; Accepted: 30 March 2020

Abstract
Large curvature surfaces are often milled by straight-line interpolation method. However the misuse of the cutting parameters may lead to checkerboard texture on the machined surface. In this paper, the effect of interpolating straight-line length and tool path on the checkerboard texture on the milled surface is studied. The checkerboard texture is measured and characterized in terms of surface micromorphology and profile shape. Influences of the interpolation line length and milling path on the appearance of the checkerboard texture are analyzed. The influences of feed per tooth and pick feed on the checkerboard texture are discussed. Results show that linear interpolation method is readily to cause formation of the checkerboard texture on the milled surface of a workpiece. With the increase of the length of the interpolation line the present of checkerboard texture on the milled surface becomes more obvious, and vice versa. The bright and dark bands of the checkerboard texture are always perpendicular to the curvature plane of the milled surface. The feed per tooth and pick feed may influence the appearance of checkerboard texture as well.

Keywords: Curved surface, Ball-end milling, Surface texture, Linear interpolation

1. Introduction
There are a large number of curved surface molds with large curvature in the automobile panel die. In the milling of such molds, variations in cutting parameter values, cutter path, and tool wear may lead to disastrous consequence in surface texture of the machined parts, which may involves appearance, application, or security problems.

Cutting parameters and tool geometry parameters are the main factors affecting surface topography. Chen et al. (2014) studied the surface generated by single factor experiment under multi-axis finishing conditions. The influence of cutting parameters on surface texture and 2D and 3D surface topography were also analyzed. The result shows that the concave-convex areas on the machined surface are distributed orderly due to the special cutting direction of the cutting edge. Toh (2003) milled AISI H13 steel using raster, single-direction raster, and offset tool pathing mode. He compared the surface topography maps under different axial cutting depths, and proposes a method to improve surface texture by selecting appropriate inlet and outlet conditions. Jasni and Lajis (2013) investigated the surface topography of AISI D2 hardened steel (58-62 HRC) under dry milling conditions. The surface roughness, surface morphology and defect analysis are studied. It is found that the milled surface is anisotropic in nature. The combination of tool motion (cutting and feed speed direction) produces a layered texture during milling. Milled surfaces are constructed of low-amplitude terrain between the peaks and valleys of the machined surface, and the surface defects are debris, grooves, cavities. Yang and Liu (2015) studied the effects of cutting parameters such as cutting speed, feed rate, and cutting radial depth on surface topography during milling of titanium alloy Ti-6Al-4V. The surface morphology after machining was characterized by surface defect, surface roughness multiple linear regression, and surface morphology autocorrelation. The experimental results show that the surface defects in Ti-6Al-4V excircle milling are mainly feed marks, scratches, adhesive material particles. Under the conditions of high cutting speed, small feed rate, and small cutting depth
high-quality surfaces can be obtained.

In addition to geometric factors, cutting force, heat, vibration, and tool wear also have influences on surface topography. Ma et al. (2014) conducted an experimentally studied the optimization of cutting parameters on cutting force in high-speed milling of Inconel 718. They analyzed the relationship between cutting force and spindle speed. They pointed out that the cutting force is related to the geometrical characteristics of the curved surface. The larger the curvature, the larger the cutting force. Wu et al. (2017) analyzed the influence of the machined surface radius and milling lead angle on cutting thickness. The influence of the machined surface curvature on cutter stability in milling process is studied by a full discretization method. Liang and Liu (2018) studied the tool wear behavior and surface morphology of Ti-6Al-4V during high-speed cutting. The influence of tool wear on the machined surface morphology is evaluated in terms of surface roughness and defects. It is concluded that high-speed machining of Ti-6Al-4V can obtain better surface morphology.

Quinsat et al. (2008) proposed a three-dimensional surface topography simulation model for three-axis ball-end tool machining based on which they obtained the three-dimensional surface roughness considering the influence of processing parameters and surface description. Chen and Wang (2018) proposed a kinematic model of ball-end milling for free-form surface based on double harmonic spline interpolation (BSI), and extended the application of BSI in point cloud. The validity and accuracy of the model were verified by comparing the computer simulation results with experimental machining results under different experimental conditions. Quinsat et al. (2011) proposed a terrain simulation model based on N-buffer method and inverse kinematics transformation for five-axis milling. The terrain simulation model was used to study the influence of processing parameters such as tool inclination angle and maximum allowable scallop height on the milling processing. The simulation results show that the Tool inclination is the decisive factor affecting the surface quality according to the selected regional parameters. Li et al. (2010) proposed an improved model to predict the three-dimensional surface topography and dynamic cutting force of the workpiece during end milling based on the Z-map representation of the workpiece. The numerical method is used to solve the differential equations that control the dynamics of the milling system. The influence of cutting parameters such as feed rate, cutting axial depth, and dynamic characteristics of milling system on surface topography were studied.

In surface milling, tool path is also important factors influencing the surface topography. Liu et al. (2012) used an equal-residual-height method to plan the tool path in surface milling. This method established a local coordinate system at the tool point on the tool path to avoid the loss of tool data. They improve the finish of the machined surface by this method. Li et al. (2018) established a tool pathing model by a piecewise interpolation function combining the distribution of tool position points. The segmentation optimization of the tool path is realized by limiting and judging the chord height error of the segmentation track, which improves the precision of milled surface. He et al. (2018) determined the position of interference point through milling convex surface experiment. The tool path is then re-planned by interpolation to eliminate interference and improve the surface quality of the workpiece.

In order to improve the machining efficiency and reduce the amount of data for NC code, straight-line interpolation is used in the machining of curved surfaces with large curvature. However the misuse of the cutting parameters may lead to checkerboard texture on the machined surface (Fig. 1). The checkerboard texture not only reduces accuracy of the machined surface but also makes the appearance of the machined surface bad. However, seldom research has been carried out on this issue. The formation mechanism of the checkerboard texture and the influences of the cutting parameters are need to be revealed.

![Checkerboard texture in the surface of a die for automobile panel](image)
2. Materials and methods

2.1 Experimental materials

QT600-3 is pearlitic ductile iron, which has the characteristics of medium and high strength, medium toughness and ductility, good wear resistance and vibration absorption, and good castability. It is often used as the die material of automobile panel. QT600-3 is adopted as the experimental material in the current study. The chemical compositions of QT600-3 are listed in Table 1. The main physical properties of QT600-3 are listed in Table 2.

| Physical properties | Tensile strength $σ_b$ (MPa) | Yield strength $σ_{0.2}$ (MPa) | Elongation $δ$ (%) | Hardness (HB) | Density $ρ$ (g/cm$^3$) |
|---------------------|-----------------------------|-------------------------------|-------------------|---------------|------------------------|
| Values              | ≥600                        | ≥370                          | ≥3                | 190-270        | 7.3                    |

Table 1 Chemical compositions of QT600-3 (wt%)

| C  | Si   | Mn  | P  | S   | Mg  | Cu  | Rare earth oxide |
|----|------|-----|----|-----|-----|-----|-----------------|
| 3.0-.5 | 2.4-2.8 | 0.3-0.5 | <0.1 | 0.03-.035 | 0.045-0.05 | 0.35-0.4 | 0.04-0.05 |

The experimental equipment is DNM-415 CNC machining center, BT40*SFC25-100 sintered shank, BNMM-250090T-S25 carbide cotter arbor, BNM-250 DH103 spherical blade (Fig. 2). The overhang of the sintered shank is 108 mm in length. The diameter of the circular blade is 25 mm (Fig. 2). Machining convex surface on blank with length × width × height of 500 × 3000 × 50mm. The radius of curvature of the convex surface is 2252.5mm. The convex surface to mill is limited in an area with 300mm in length and 250mm in width. The geometry structure and parameters of the tool and the convex surface are shown in Fig. 3.

Fig. 2 Machine tool for the milling experiments

Fig. 3 Machining surface geometry
2.2 Experimental methods

In order to investigate the influence of the interpolation line length and the tool path on the surface texture of the machined surface under the linear interpolation mode, three lengths (12000μm, 7500μm, 3750μm) of the linear interpolation line and the two milling directions are used in the milling experiment (Fig. 4).

The workpiece of QT600-3 is clamped on the workbench of the CNC machining center. The workpiece is first rough milled with a φ12mm flat end mill. NC coding is carried out by an automatic NC programming system of a software. Then the rough milled surface is finish milled with a R25mm ball end mill in linear interpolation mode with the cutting parameters listed in Table 3. A portion of the NC code of the milling with the interpolation line length of 7500μm is appended in the last of this paper.

Table 3 Cutting parameters

| Curvature radius | Pick feed | Rotation rate | Feed per tooth |
|------------------|-----------|---------------|---------------|
| r (mm)           | ae (mm)   | n (r/min)     | fz (mm/z)     |
| 2252.5           | 0.5       | 5500          | 0.182         |

3. Result and discussions

3.1 Morphology and profile of the checkerboard texture

The morphology and profile of the checkerboard texture with the length of the interpolation line 7500μm is investigated (Fig. 5). It can be seen from Fig. 5 that checkerboard texture was regenerated on the milled surface of the workpiece though the bright and dark bands are indistinct. The bright bands and dark bands are alternately arranged in the feed direction and perpendicular to the pick feed direction. It should be noted that distance between two neighboring bright bands is about 7.5mm. The width of the bright band is about 3mm and the dark about 5mm which is much higher than feed per tooth.

Marks indicating the position of the bright bands are made on the milled surface, then milled surface in the area of the bright and dark bands are observed under an optical microscope.

Fig. 5 Chessboard texture on the milled surface with the length of the interpolation line 7500μm
Fig. 6 is the microscopic topography of the milled surface in the bright band (Fig. 6 (a)) and the dark band (Fig. 6 (b)). The white arc in the figure is the feed mark left by the ball end milling tool. It shows that both the feed marks of bright band and dark band are not uniform. Microscopically, the differences in microstructure and brightness in the bright band and the dark band are not obvious.

Fig. 6 Microscopic morphology of the milled surfaces

An interval across four successive bright and dark bands in the machined surface in the feed direction are scanned for milled surface profile measuring (Fig. 7). The scanning strategy for the milled surface profile measurement is schematically shown in Fig. 7 (a). The vertical lines numbered I, II, III, IV, and V in Fig. 7 are drawn according to the marked points made at bright bands. The average distances between the two bright bands region are I-II=7800μm, II-III=7300μm, III-IV=7500μm, and IV-V=8200μm. The average value of the distances is 7700μm. The milled surface profiles of the across the four successive dark bands are shown in Fig. 8 (a)-(d). From Fig. 8 (a)-(d), the surface profile between two neighboring bright bands is a wavy shape. There is no obvious differences between the surface profiles of bright bands and dark bands. Combining the scanned profile curves at II, III, and IV points, the profile curve across the four successive bright and dark bands then is obtained (Fig. 8 (e)). In Fig. 8 (e), the overall profile curve of the specimen measured has a circular arc shape. The radius of the combined profile curve is approximately 2440μm which is close to the value of the curvature radius of the milled convex surface.

Fig. 7 Surface profile measurement in feed direction

(a) Scanning strategy

(b) Combining of the scanned curve at marked points
Feed rate variation in the bright and dark bands is investigated. Four successive feeds in the bright and dark bands are selected for the measurement (Fig. 9). The result is shown in Fig. 10. Fig. 10 (a) and (c) are the feed per tooth in the bright band. It can be seen that the value of the feed per tooth fluctuates around the feed per tooth in the milling experiments for all the cases. The large value variation of the feed per tooth occurred at the first point in Fig. 10 (a) and (c). Compared with Fig. 10 (b) and (d) the value fluctuation in Fig. 10 (a) and (c) is a little larger.
3.2 Appearance of milled surface with the variation of the length of the interpolated line

When the milling is completed, the specimens is slightly polished with whetstone and checkerboard textures appears. Fig. 11, Fig. 12, and Fig. 13 show the milled surface with interpolation line length 12000μm, 7500μm, and 3750μm, respectively.

There are bright bands and the dark bands on the milled surface of the specimen as shown in Fig. 11. The
checkerboard texture on the milled surface is not as obvious as that in Fig. 8. These bright and dark bands are perpendicular to the curvature plane. Measuring the spacing between two neighboring bright bands, the measured values are as follow: J1=11000μm, J2=12000μm, J3=11000μm, J4=12000μm. The average value is 11500μm. The measured value is consistent with the value of the length of the interpolation line used in the experiment.

Fig. 11 Chessboard texture on the milled surface with the length of the interpolation line 12000μm

In Fig. 12, the checkerboard texture in the polished area with whetstone is more pronounced. The checkerboard texture shows a regularity of light and dark in the direction of feed, and the light and dark lines alternately appear. The width of the bright band is about 3mm and the dark about 5mm which is much higher than feed per tooth. The distance between the two bright lines has a strong consistency with the corresponding length value of the interpolation line. The distances between two neighboring bright bands are K1=8000μm, K2=8000μm, K3=7000μm, K4=7000μm, K5=7000μm, K6=8000μm. The average value of the distances is 7500μm which is just value of the corresponding value of the length of the interpolation line.

Fig. 12 Chessboard texture on the milled surface with the length of the interpolation line 7500μm

Compared with the checkerboard texture in Fig. 11 and Fig. 12, the checkerboard texture at interpolation line length 3750μm is much harder to be identified (Fig. 13). After a careful observation of the spacings between two neighboring bright bands are measured: L1=3500μm, L2=3500μm, L3=4000μm, L4=3000μm. The average value of the spacings is 3500μm.
3.3 Appearance of milled surface with the variation of the milling direction

To clarify the influences of the milling direction on the appearance of the chessboard texture on the milled surface of the workpiece. Millings with feed direction in Y axis (Fig. 4) was carried out. After milling is completed, the milled surface is ground with a piece of oil stone. Chessboard texture is then can be seen (Fig. 14). The bright bands in Fig. 14 seem much wider than those in Fig. 12 which are about 5 mm, while the dark band is about 3 mm. However, the direction of the bright and dark bands in Fig. 14 are the same as that in Fig. 12. That is the milling direction has no influences on the direction of the bright and dark bands, the direction of the chessboard texture is determined by curvature direction of the surface to be milled. The spacings between two neighboring bright bands are measured: M1=8000μm, M2=7500μm, M3=7500μm. The average value of the spacings is 7666μm which is consistent with the length of the interpolation line.

3.4 Discussions

The NC code with the length of the interpolation line 7500μm is used for the discussions. According to the NC code, the tool path is drawn as Fig. 15. It can be seen that the tool path for the milling of the curvature surface of the workpiece is composed of linear interpolation segments. X-axis coordinate value shows that the space along the X axis of per interpolation segment is 7500μm, which is the control parameter to yield NC code with the length of the interpolation line 7500μm. The average value of the distance between two neighboring bright bands of the checkerboard texture measured in Section 3.1 is 7700μm. This value is consistent with the length of the interpolation line. So the checkerboard texture is caused by the milling method with the linear interpolation fitting the curved lines or surfaces in NC coding process. Because of the discontinuity of the light reflection, the brightness of the milled surface thereby varies under illumination, which leads to the checkerboard texture on the milled surface macroscopically. So the appearance of the chessboard figure is decisively dependent on the length of the interpolation lines. With shorter length of the
interpolation line, the angle deviation between two neighboring interpolation lines becomes smaller, and the tool path becomes smoother. Then the space between the bright and dark bands will be smaller and more difficult to be identified macroscopically.

Fig. 15 Tool path according to the NC code in the milling experiment

On the other hand, feed marks of cutting tool at intersection point of two neighboring interpolation lines may be uneven, and this may affect the appearance of the bright and dark bands (Fig. 16). In the case of the milling in X direction (Fig. 4), the ball-end milling tool goes along the tool path during the milling of the workpiece (Fig. 16(a)). At the beginning of a interpolation line, the value of feed per tooth is 182μm. When the tool point of the ball end mill is near the intersection of two neighboring interpolation lines, the feed mark may change in case of the length of the interpolation line being not divided evenly by the feed per tooth (Fig. 16(a) A-1). In Fig. 10 the feed per tooth in the bright band fluctuates greatly with measured values 200μm, 144μm, 144μm, and 167μm at the measured point 1 to 4, respectively. This proves that the feed per tooth has changed at the intersection of two neighboring interpolation lines. The transition area of feed mark at intersection point of two neighboring interpolation lines may influence the light reflection at the intersection area of the milled surface, which further influences the appearance of the checkerboard texture of the milled surface. However if the length of the interpolation line length can be divided evenly by the feed per tooth, the feed mark will be as Fig. 16(a) A-2 which may have no influence on the appearance of the checkerboard texture, when the appearance of the checkerboard texture depends only on the length of the interpolation line.

Similar transition marks may be caused in the case of the milling in Y direction (Fig. 16(b)) when the length of the interpolation line cannot be divided evenly by the pick feed (Fig. 16(b)). In this case, the milled intersection point will be at a different position to the corresponding theoretical position, which may further change the width of bright band and dark band. Furthermore, the transition area may straddle several cutting paths transversely (Fig. 16(b) B-1), and in most cases the pick feed is larger than the feed per tooth. This will make the transition area (the width of bright or dark band) of at the intersection point wider than that caused by feed (milling in X direction in current study). This can be validated by the experiment result shown as Fig. 14, in which the bright band is about 5 mm and the dark band is about 3 mm in case of the milling in Y direction, while the bright band is about 3 mm and the dark band is about 5 mm in case of the milling in X direction (Fig. 5, Fig. 12). The wide transition area of at the intersection point will disperse the reflected light at that area, and this may decrease the difference between the appearances of bright bands and dark bands and makes the appearance of checkerboard texture on the milled surface inapparent.

So, to improve the checkerboard texture in milling of curvature surface coding with circular interpolation instead of linear interpolation should be adopted. In addition, reducing the length of the linear interpolation line and adjusting the acceleration/deceleration behavior of the machine can also be used to improve the checkerboard texture in milling of curvature surface in condition of coding with linear interpolation.
4. Conclusions

In order to reveal the influences of the interpolating straight-line length and tool path on the texture on the milled surface, the linear interpolation method is performed on a three-axis CNC machining center with the nodular cast iron QT600-3 as the experimental material. The influences of the interpolation line length and path on the appearance of the checkerboard texture are analyzed. The influence of the feed per tooth on the checkerboard texture is also discussed. The main conclusions of the current study are as follows.

(1) The occurrence of the checkerboard texture phenomenon is mainly related to the usage of interpolation method for curved surface milling in NC coding process. Milling with linear interpolation method is readily to cause formation of the checkerboard texture on the milled surface of a workpiece. With the increase of the length of the interpolation line the appearance of checkerboard texture on the milled surface becomes more obvious, and vice versa.

(2) In addition, transition marks of cutting tool at intersection point of two neighboring interpolation lines appears and may influence the appearance of checkerboard texture in case that the length of the interpolation line cannot be divided evenly by the feed per tooth. In milling along the direction perpendicular to the plane of interpolation lines (milling in Y direction in the current study) the uneven division of the length of interpolation line to pick feed may influence the width of bright and dark bands of checkerboard texture.

(3) The bright and dark lines of the checkerboard texture are always perpendicular to the curvature plane of the milled surface, and has nothing to do with the feeding direction in cutting.

(4) The texture of checkerboard pattern in drilling of curved surface can be improved by using of coding with
circular interpolation instead of linear interpolation method or reducing the length of the linear interpolation line and adjusting the acceleration/deceleration behavior of the machine tool in condition of coding with linear interpolation.

Acknowledgments

The authors would like to acknowledge the financial support by the Innovation Team Project of Colleges and Institutions in Jinan City (2018GXRC005), Key Research and Development Plan of Shandong Province (2018GGX103023), National Natural Science Foundation of China (51675289, 51775285)

References

Chen, X.X., Zhao, J., Dong, Y.W., LIU, S., Zhao, J.B. Study on the machined surface geometry generated by multi-axis ball end milling process. Advances in Materials Manufacturing Science and Technology XV, Vol. 770, (2014), pp. 370-375.

Chen, H.Q., Wang, Q.H. Modeling and simulation of the surface topography in ball-end milling based on biharmonic spline interpolation. International Journal of Advanced Manufacturing Technology, Vol. 99, No.9-12, (2018), pp. 2451-2466.

He, C.S., Zheng, M.L., Yang, S.C., Xin, T. Tool path planning without interference for convex surfaces based on the optimal cutter orientation of the annular cutter. International Journal of Interactive Design and Manufacturing, Vol. 12, No.3, (2018), pp. 787-800.

Jasni, N. A. H., Lajis, M.A. Surface topography in machining of AISI D2 hardened steel. Applied Mechanics and Materials, Vol. 315, (2013), pp. 660-664.

Liang, X.L., Liu, Z.Q. Tool wear behaviors and corresponding machined surface topography during high-speed machining of Ti-6Al-4V with fine grain tools. Tribology International, Vol. 121, (2018), pp. 321-332.

Li, Z.Q., Li, S., Zhou, M. Surface Topography Predication in High-speed End Milling of Flexible Milling System.Advanced Materials Research, vol. 29-32, (2010), pp. 1832-1837.

Liu, W., Zhou, L.S., An, L.L. Constant scallop-height tool path generation for three-axis discrete data points machining. International Journal of Advanced Manufacturing Technology, Vol. 63, No. 1-4, (2012), pp. 137-146.

Li, J., Li, H.B., Zhang, H.T., Zhang, P. Research on the effect of cutter position points distribution optimization on surface milling accuracy. Key Engineering Materials, Vol. 764, (2018), pp. 323-332.

Ma, J.W., Wang, F.J., Jia, Z.Y., Xu, Q., Yang, Y.Y. Study of machining parameter optimization in high speed milling of Inconel 718 curved surface based on cutting force. International Journal of Advanced Manufacturing Technology, vol. 75, No.1-4, (2014), pp. 269-277.

Quinsat, Y., Sabourin, L., Lartigue, C. Surface topography in ball end milling process: Description of a 3D surface roughness parameter. Journal of Materials Processing Technology, Vol. 195, No.1-3, (2008), pp.135-143.

Quinsat, Y., Lavernhe, S., Lartigue, C. Characterization of 3D surface topography in 5-axis milling. Wear, Vol. 271, No.3-4, (2011), pp. 590-595.

Toh, C. K. Surface topography analysis when high-speed rough milling hardened steel. Advanced Manufacturing Processes, Vol. 18, No. 6, (2003), pp. 849-862.

Wu, S., Yang, L., Liu, X.L., Zheng, M.L., Li, R.Y. Effects of curvature characteristics of sculptured surface on chatter stability for die milling. International Journal of Advanced Manufacturing Technology, Vol. 89, No. 9-12, (2017), pp. 2649-2662.

Yang, D., Liu, Z.Q. Surface topography analysis and cutting parameters optimization for peripheral milling titanium alloy Ti-6Al-4V. International Journal of Refractory Metals and Hard Materials, Vol. 51, (2015), pp. 192-200.
Partial NC code used in the milled experiments

```
% X-12.5 Z-2.987
O2019
G17 G40 G49 G80 G90
G00 G90 G54 X-119.555 Y59.5 S5500 M03
Z20
G01 Z6.318 F2000 X-134.521 Z-6.948 F2000
X-132.5 Z-6.83
X-125. Z-6.404
X-117.5 Z-6.
X-110. Z-5.625
X-102.5 Z-5.273
X-95 Z-4.945
X-87.5 Z-4.642
X-80. Z-4.364
X-72.5 Z-4.111
X-65. Z-3.883
X-57.5 Z-3.681
X-50. Z-3.503
X-42.5 Z-3.351
X-35. Z-3.223
X-27.5 Z-3.12
X-20. Z-3.041
```