Study on the burr formation process in micro-milling of high aspect ratio structures

Xinlei Zhang 1 · Ni Chen 1 · Jinming Wu 2 · Jiawei Wei 1 · Bo Yan 1 · Liang Li 1 · Ning He 1

Received: 13 January 2021 / Accepted: 3 May 2021 / Published online: 10 May 2021
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Abstract
SKD11 is widely used in manufacturing die. With the development of industrial level, the size of the die is further reduced, and the difficult processing problem of high aspect ratio (HAR) micro-structures is exposed. Micro-milling is a suitable method for machining HAR micro-structures; however, the inevitable generation of burrs deteriorates the machined surface. Previous studies have mostly focused on the burr formation process of shallow grooves but have ignored HAR grooves. This paper investigated the burr formation mechanism in HAR (2:1) grooves on harden steel (SKD11). Due to the fact that the burr formation process was difficult to be observed in the actual micro-milling process, a finite element model was established. A corresponding experimental research was conducted, which revealed a good consistency between simulation and experimental results. Moreover, a new burr type was formed on the sidewall of the HAR groove, which was transformed from top burrs and was named as side burr. The results demonstrated that the chip flow on the rake face of the micro-mill was hindered by the sidewall, which caused chip crumbling, chip accumulation, and surface scraping, seriously affecting the burr formation mechanism. This paper revealed the burr formation mechanism for HAR grooves on SKD11, which provides basic data for manufacturing die with complex structure and small size.

Keywords Micro-milling · Burr formation · High aspect ratio (HAR) micro-structures · Finite element method · Chip flow

1 Introduction
In recent years, in a range of fields including electronics, aerospace, medicine, and energy [1–3], the demand for miniaturized products, especially with high aspect ratio (HAR) features, has gradually increased. SKD11 is widely used in manufacturing die. With the development of industrial level, the size of the die is further reduced, and the difficult processing problem of high aspect ratio (HAR) micro-structures is exposed [4]. Laser machining [5, 6], electrical discharge machining (EDM) [7, 8], and wire electrical discharge machining (WEDM) [9, 10] are used to machine HAR structures. However, these methods produce metamorphic layers above the machined surface, restricting to achieve the high machining accuracy [11–13]. Micro-milling has been an effective way to prevent the generation of metamorphic layers, but some burrs may form on the structure and affect the quality of the machined surface, significantly restricting its wide application [14–21].

Recently, scholars have investigated the rule of burr formation in micro-milling, reporting valuable results. Liang et al. [22] found that there were three kinds of burrs on the micro-groove (top burr, exit burr, entrance burr) and studied the burr formation principle through finite element (FE) simulation. Entrance burr size was small, with triangle, acicular, and ribbon as the main morphology. Top burr size was the largest, with wavy, zigzag, bending, and flip as the main morphology. Exit burr to the flip, acicular, ribbon as the main morphology, when the micro-mill cut out, the material pushed out plastically to form exit burr. Chen et al. [23] studied the burr formation principle of Ti-6-Al-4V, and four kinds of burrs were found on the micro-groove (top burr, exit burr, entrance burr, bottom burr). While the
forming process of bottom burr had carried on the detailed analysis, the tearing effect between the chip and workpiece was the principal causes of bottom burr. In addition, the unsuitable feed speed and oversized edge radius exacerbate the tearing effect. The exit and entrance burrs were mainly lamellae burrs and the top burrs were mainly flip burrs. Davoudinejad et al. [24] analyzed the burr formation principle of AL6061-T6 by using FEM and found that burr started to form when the micro-mill cut in the workpiece, and the undeformed chip thickness (UCT) was the thinnest at the beginning. As the micro-mill continued to cut in, the UCT gradually increased, and finally top burr was formed at the groove top, and the curly burrs were the main morphology.

Most studies concerned micro-milling of shallow grooves, but only few studies have focused on micro-milling of HAR grooves [25, 26]. Han et al. [27] studied the formation principle of the top burr on the HAR groove. Through the method of combining experiment and FEM, they found that there was ploughing and friction phenomenon at the cut-in and cut-out positions due to the change of UCT, and the workpiece material was strongly squeezed, and finally irregular bulges formed on the sidewall. The research on burr of HAR groove was relatively deficient.

To sum up, based on a large number of scholars’ in-depth research on the burr formation mechanism of various materials, this paper has been further studied. The selected material in this paper was hardened steel (SKD11), which is a high-carbon and molybdenum steel of ledeburite class. It is a typical hard-to-cut material with excellent wear resistance, hardenability, toughness, and thermal stability, which is widely used in molds and tools. Tang et al. [28] studied the influence of technological parameters on machining quality in macro-milling process of SKD11 and introduced cutting speed, depth of cut, and edge radius to provide a reference for the selection of technological parameters. At present, most scholars have mainly investigated the machinability of SKD11, while only few scholars have studied the burr formation principle of micro SKD11 structures in micro-milling.

Above studies concerning shallow grooves provided a reference for HAR micro-structures on SKD11. The difference between HAR grooves and shallow grooves is the height of the sidewall, which limits the chip flow and has a significant effect on burrs. Generally, micro-grooves with depth-width ratio greater than 2 were defined as HAR grooves [29]; the present work investigated the law of burr formation at the edges of micro-grooves with 2:1 aspect ratio on SKD11. Since grooves are in the sub-micro scale and burr formation is very difficult to observe, the finite element method (FEM) was applied to simulate the micro-milling process.

### 2 FE model establishment and experimental verification

#### 2.1 FE model establishment

**2.1.1 Material model**

The material studied in this paper was SKD11, and its chemical composition and physical properties are presented in Tables 1 and 2, respectively [30].

In metal cutting, the material undergoes plastic deformation was developed under the combined action of high temperature, high pressure, large stress, and large strain. In FE simulations, a constitutive model was required to calculate the deformation of a material. The selection of proper constitutive models guaranteed the accuracy of the simulation results. The Johnson-Cook (J-C) model [31] was the most commonly used constitutive model in relevant FE simulations.
since it can adequately reflect the temperature rise and strain behavior of a material during the cutting process. The J-C model was calculated in Eq. 1 [31].

\[
\sigma_{J-C} = A + B(\xi)^n \left[ 1 + C \ln \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right) \right]^{\mu}
\]

where A, B, C, n, and m were the J-C constitutive model constants; \( \xi \), \( \dot{\xi} \), and \( \dot{\xi}_0 \) were, respectively, equivalent plastic strain, equivalent plastic strain rate, and reference strain rate; T, T_{melt}, and T_{room} were respectively cutting temperature, material melting point, and ambient temperature. In addition, the constitutive model parameters of SKD11 are presented in Table 3 [32].

Although J-C model was a classical constitutive model, it was not difficult to find that this constitutive model was lack of processing scale dimension, which caused the consistent prediction effect of J-C model no matter in micro scale or macro scale. Meanwhile, Fleck et al. [33] found that the behavior of materials at the micro scale was significantly different from that at the macro scale and the size effect increased with the decrease of processing scale. For the simulation of micro scale, the influence of size effect, cutter edge radius, and minimum UCT on milling should be accounted. Therefore, improving the J-C model to adapt to the change of processing scale was necessary, and Eqs. 2 and 3 were the improved constitutive model [34]:

\[
\sigma = \sigma_{J-C} \sqrt{1 + \left( \frac{18\alpha^2 G^2 b}{\sigma_{J-C}^2 L} \right)^\mu}
\]

\[
L = \frac{\arccos \left( \frac{r_e - h}{r_e} \right) \pi r_e}{180}
\]

where \( \alpha \) was the rake angle and G was the shear modulus, which was calculated in Eq. 4. E was elastic modulus, \( v \) was the Poisson’s ratio, and the values of E and \( v \) are shown in Table 2; \( b \) was the Burgers vector, which was calculated in Eq. 5. \( a \) was the lattice constant, and the value of \( a \) was 0.359 nm [35]; \( L \) was length of primary machining deformation zone; \( r_e \) and \( h \) were cutting edge radius and depth of cutting. In addition, these parameters are shown in Table 4.

\[
G = \frac{E}{2(1 + v)}
\]

\[
b = \frac{\sqrt{2}a}{2}
\]

Finally, we used secondary development subroutine of DEFORM to program and imported the improved constitutive model into the material library.
2.1.2 Friction model

There were two kinds of contact relations in FEM: workpiece to micro-mill and workpiece to workpiece; and there were stable contact relations between them. The friction coefficient between workpiece and micro-mill was 0.63 \cite{36} and that between workpiece and workpiece was 0.15.

2.1.3 FE simulation of the micro-milling process

The micro-milling process of HAR (2:1) grooves was simulated by the Deform-3D (SFTC Company) software, and the schematic diagram of shallow and HAR (2:1) grooves is shown in Fig. 1. Firstly, the tool and workpiece were modeled in SolidWorks (Dassault Systemes S.A) and then were imported into Deform-3D. Subsequently, simulation parameters were set to define the micro-milling characteristics of HAR (2:1) grooves.

The imported micro-mill was placed at the initial position. The micro-mill was set as a rigid body, because the present study did not involve the study of tool wear. The workpiece was set to move along the feed direction, while the micro-mill was set to rotate clockwise around its axis. In particular, in order to improve the calculation speed and ensure the simulation quality, the grid density of the processing area was increased, and the ratio of the grid density between the processing area and the non-processing area was 20:1 (Fig. 1). The simulated process can be seen in Fig. 2.

### Table 5

| Code No. | Dia. | Length of cut | Rank angle | Back angle | Helix angle | Edge radius |
|----------|------|---------------|------------|------------|-------------|-------------|
| MHRH230  | 0.2 mm | 0.15 mm       | 0.5°       | 6°         | 30°         | 0.0015 mm   |

2.2 Burr size measurement

2.2.1 Simulation

The height of entrance burr, exit burr, bottom burr, and the side burr of HAR (2:1) grooves were measured in the Deform-3D software. In shallow grooves, the measurement method for the top, bottom, entrance, exit, and side burrs was the same as that for the HAR (2:1) groove.

2.2.2 Experiments

This paper mainly focused on the experiments aspect of the research, and the main purpose of simulation was to explain the deformation mechanism. The measurement positions of burrs at the edges of the shallow and HAR (2:1) grooves were consistent with those described in Section 2.2.1. The size of burrs on micro-milled grooves was measured by Scanning Electron Microscope (SEM).

2.3 Experimental validation

2.3.1 Experimental set-up

The micro-milling experiments used a self-developed micro-milling machine tool (Fig. 3a). The machine tool adopted a vertical frame and a marble base with excellent shock absorption performance. The \(X\)- and \(Y\)-axes of the platform were driven by linear servomotors and integrated a Renishaw grating encoder with 0.1-\(\mu\)m resolution to achieve closed-loop
feedback control of the servomotors. The maximum spindle speed was \(4 \times 10^4\) r/min. At the highest speed of the machine, the tool runout was less than 1 \(\mu m\). The employed machine tool has the advantages of compact size, high positioning accuracy, and good system rigidity. In the experiments, a two-flute tungsten carbide micro-mill was used (Fig. 3b), and its parameters are shown in Table 5.

### 2.3.2 Comparison between experimental and simulation results

In this section, the cutting force of shallow and HAR (2:1) grooves was analyzed by comparison between simulation and experiment. The processing parameters are shown in Table 6, and the parameters in Table 6 were also used in the study of burr formation process.

Meanwhile, in order to ensure the accuracy of the results, two sets of repeatability tests were carried out, and the cutting forces of HAR groove in \(X, Y,\) and \(Z\) directions were collected by the force measuring instrument. The depth of cut of repeatability tests were 5 and 10 \(\mu m\), respectively, and the other parameters were consistent with Table 6. In addition, the process parameters in Table 6 were selected, and the size of side burr, top burr, entrance burr, exit burr, and bottom burr was measured to analyze the error between experiment and simulation. It can be seen from Fig. 4 that the change trend of cutting force and burr size in the experiment and simulation was basically the same; the average error of cutting force and burr size were 2.1% and 9.5%, respectively, which proved that FEM can be used to observe the forming process of burr.

### 3 Results and discussion

Entrance, exit, side, and bottom burrs can be observed in micro-milled HAR (2:1) grooves (Fig. 5) [37, 38]. Compared to shallow grooves, the higher aspect ratio makes it difficult to remove chips in time, which severely affects the formation of burrs [39]. In this paper, the burr formation mechanism during micro-milling of HAR (2:1) grooves was investigated and compared to that of shallow grooves [5]. Burrs were subdivided into burrs along the UM side and burrs along the DM side, based on whether the feed direction of the workpiece was consistent with the rotation direction of micromill. Figure 5 illustrates the location of burrs both along the UM and DM sides.

### Table 6 Processing parameters used in both experiments and simulation

| Groove type       | Spindle speed \(10^4\) r/min | Depth of cut (\(\mu m\)) | Feed per tooth (\(\mu m/z\)) |
|-------------------|-------------------------------|--------------------------|------------------------------|
| Shallow groove    | 2                             | 15                       | 2                            |
| HAR (2:1) groove  | 2                             | 15                       | 2                            |

Fig. 4 Cutting force/burr height of simulation and experiment
3.1 Side burr/top burr

The numerous pits and bulges observed on the sidewall of the machined HAR groove were defined as side burrs (Fig. 6c), while fish-scale burrs can be observed on the sidewall (Fig. 6d). This type of burrs was transformed from top burrs (Fig. 6a, b) of the shallow groove, seriously affecting the quality of the micro-milled groove surface. Therefore, the formation mechanism was needed to be investigated to reduce the number of side burrs.

In micro-milling, with the rotation of the micro-mill, the change trend of UCT was first increased and then decreased (Fig. 7a) [40]. A large number of studies showed that when the UCT was less than the minimum UCT of the micro-mill, the material deformation was mainly elastic-plastic deformation, and the material removal rate was significantly reduced [41]. When the milling area was close to the sidewall of the DM side, the chip flow was formed on the rake face and flowed upward gradually with the rotation of the micro-mill (Fig. 7b). When the micro-mill contacted with the sidewall, the UCT was less than the minimum UCT, while the chip root had elastic-plastic deformation, and the chip would reach the maximum deformation amount (Fig. 7c). Then two cases would occur: the chip dropped from the sidewall and formed a pit (Fig. 7d), or the chip bonded on the sidewall and formed a bulge (Fig. 7e). In addition, the number of bulge-like side burrs was less and randomly distributed on the DM side. If the micro-mill was absolutely sharp, the chips would be
completely removed in the micro-milling, and the UCT would not exist, and the chips could completely separate from the substrate. However, due to the wear and preparation technology, the micro-mill had a certain edge radius, and there was a certain probability that the chips would not separate from the substrate to form bulge-like side burr. By observing the SEM images, the probability of forming bulge-like side burr was not large, which can be inferred that the chip root was easy to reach the fatigue limit in the micro-milling.

Relatively speaking, the surface quality of the UM side was better than DM side (Fig. 8), because the micro-mill started to cut into the workpiece from the DM side, and the chip flow on the rake surface can be discharged smoothly, which was conducive to reducing the size of side burr on the groove side.

Fish-scale burrs would form on both the DM and UM side (Fig. 8), which was another manifestation of side burrs. The main cause was the UCT less than the minimum UCT, when micro-milling was completed, there were small amounts residual material along the sidewall of the DM and UM side (Fig. 9a, c). In next micro-milling, the micro-mill removed part of residual materials left by the previous milling process (Fig. 9d, e) and then formed new residual materials. In the end, continuous residual materials would form on the sidewall, which was manifested as fish-scale burrs (Fig. 9f) [40].

The burrs observed on the top of the shallow groove were defined as top burrs (Figs. 6b and 10). Large-scale bulge-like top burrs, located on the DM side, were generated due to the chip removal along the micro-mill rake face, while some chips were attached to the top of the shallow groove, forming bulge-like top burrs. On the UM side, the chips did not remove from the top but flowed along the micro-mill rake face, formed top burrs due to the extrusion between micro-mill and sidewall.

Fig. 7 Side burr formation process in the HAR groove during micro-milling: (a) milling area per tooth; (b) chip flow on the rake face; (c) chip about to reach the maximum deformation; (d) case 1, chip drop; and (e) case 2, chip bonding

Fig. 8 Contrast of side burrs on the DM and UM side of HAR groove
3.2 Exit burr

The numerous burrs at the bottom and side of the exit of the shallow and HAR grooves defined as exit burrs (Fig. 11). The exit burr is mainly bulge, but the burr morphologies were different between the UM and the DM sides due to the differences in the machining mechanism (Fig. 11a, c).

The exit burrs of the HAR groove were mainly bulges, and the burrs at the exit of the DM side were mainly short horizontal burrs, while those at the UM side were mainly long curly burrs (Fig. 11c, d). In micro-milling of the HAR groove, at the UM side, after the micro-mill tip entered the milling state, chips flowed along the cutting edge of the micro-mill, gradually forming a stable chip flow on the rake face of the micro-mill. The micro-mill was about to mill the thin wall of the workpiece at the exit (Fig. 12a); since the low structural strength of thin wall could not bear the cutting force, severe plastic deformation was induced (Fig. 12b). Therefore, the chip flow on the rake face of the micro-mill was not stable, and material on the thin wall was pushed out (Fig. 12c). When the plastic deformation reached the fatigue limit, the thin wall was broken, while the non-removed material was divided into two independent parts. Afterwards, the chip flow was no longer continuous, since there was a no-load section in the conversion process between UM and DM, which caused a large fluctuation of cutting force with a certain impact on exit burr.

Small-scale chip flow formed at the shear deformation zone with the feed of micro-mill (Fig. 13a). However, in the elastic-plastic deformation zone, the structural strength of thin wall was low, and the material deformation increased, so the chip flow cannot be formed (Fig. 13a) [41]. As a result, the upper part of the thin wall would overturn and continue until the micro-mill cut out and formed bulge-like burrs on both sides. The cutting force at the tip of micro-mill was the second major factor affecting the exit burr. The cutting force component of DM side along the feed direction was opposite to that of the UM side (Fig. 13b), resulting in the formation of the curly exit burr on the UM side and the formation of the horizontal exit burr.
burr on the DM side (Fig. 11c). The exit burr formation mechanism of shallow groove was consistent with that of HAR groove, and the exit burr size can be effectively reduced due to the smooth chip discharge of shallow groove (Fig. 11a, b).

3.3 Entrance burr

Burr at the micro-groove entrance were defined as entrance burrs. The morphology of the entrance burr and the exit burr was completely different. The long curly burr was formed on the DM side, while no burr was formed on the UM side (Fig. 14a, c). Therefore, entrance burrs have less effect on microstructure compared with exit burrs.

As it can be seen in Fig. 15a, in micro-milling of the HAR groove, the tip of the micro-mill first cut into the workpiece at the UM side, and chips were squeezed on the rake face of the micro-mill. Therefore, chips expelled along the rake face of micro-mill and formed the steady chip flow (Fig. 15b). The deforming direction of the chip was inward, and the ductile chip would not form outward, eventually forming pit-like burr on the UM side (Fig. 15c). The formation of entrance burrs on the UM side was mainly attributed to edge crumbling, all the way to the entire entrance on the UM side. In micro-milling, the micro-mill initially cut out the workpiece at the DM side of the HAR groove, and the chip removal direction was consistent with the feed direction (Fig. 15d). As the micro-mill rotated, chips broke away from the workpiece limit and turned outward (Fig. 15e). Finally, there were some bulge-like entrance burrs at the side and bottom of the HAR groove near the sidewall (Figs. 14c and 15f). The formation process of entrance burrs along the DM side was similar to that along the UM side. The entrance burr formation mechanism of shallow groove was consistent with that of HAR groove, and the entrance burr size can be effectively reduced due to the smooth chip discharge of shallow groove (Fig. 14b, d).

3.4 Bottom burr

The burrs produced at the bottom of the machined micro-grooves were defined as bottom burrs (Fig. 16a, c) [39]. Some pit-like bottom burrs were formed at the bottom, while bulge-like bottom burrs were formed at the junction of the bottom and the sidewall (Fig. 16a–d), which seriously affected the surface quality of the groove bottom.

![Fig. 12 The formation of exit burrs: (a) thin-wall formation, (b) thin-wall deformation, and (c) thin-wall overturn](image-url)
The bottom burrs of HAR grooves mainly distributed on the bottom near the sidewall, mainly bulge-like burrs (Fig. 16c). First, in the feed process of micro-mill, the cutting force was changed due to the UCT that was constantly changing, which can be seen from the FEM that the cutting force changed periodically (Fig. 17a) [1]. Moreover, the micro-mill had good toughness, so in addition to the normal motion of the micro-mill, there would be a certain degree of vibration, which would lead to the processed surface that was not smooth (Fig. 17b). There were more bulge-like burrs on the bottom near the sidewall, and the bottom burr on the UM side was messier. Because the micro-mill cut into the workpiece from the UM side, the deformation space of the chip was crowded, leading to the serious extrusion of the chip, and finally the formation of messy burr at the bottom. In contrast, the chips on the DM side had more deformation space and ultimately had less impact on the bottom of the groove.
In addition to the main factor of tool vibration, tool wear cannot be ignored. Tip wear caused the actual machining width to be narrowed, which would increase the working strength of the cutting edge (Fig. 18) [42]. As a result, there would be more residual materials on the bottom near the sidewall, further increasing the size of burr at the bottom. In the middle of the groove, there were also some small-sized bottom burrs (Fig. 16c), because a small amount of chips fell into the milling area, and as the micro-mill rotated and slid the bottom, the bottom burr was formed during the processing. The bottom burr-forming principle of shallow groove was consistent with that of HAR groove, and the vibration amplitude of the micro-mill was reduced, and the final bottom burr size was smaller due to the smooth chip discharge of the shallow groove (Fig. 16c, d).

Fig. 15 (a–c) Entrance burr formation process on the UM side of the HAR groove; (d–f) entrance burr formation process on the DM side of the HAR groove

Fig. 16 (a) Bottom burrs of shallow groove (SEM); (b) section view of shallow groove on DM side; (c) bottom burrs of HAR groove (SEM); (d) section view of HAR groove on DM side
3.5 Burr size comparison

It can be seen from the measurement of burr size of HAR groove and shallow groove that the largest burr on the HAR groove was side burr and the largest burr on the shallow groove was top burr (Fig. 19), because most chips were discharged from these positions during the micro-milling and the burr size was also significantly increased. At the same time, the top burr size of shallow grooves was much larger than the side burr size of HAR grooves (Fig. 19), because the most amount of side burr was small fish-scale burrs and bulge-like side burr was the second most. The chip root was transferred to the sidewall on the DM side with the rotation of the micro-mill, and the size of chip root was gradually reduced (Fig. 20). Under the extrusion of the micro-mill and the side wall, the chips were easier to fall off from the side wall, and the size of bulge-like side burr formed was generally smaller.

The vibration and wear of tool were the main factors affecting bottom burr (Fig. 17), because the sidewall of the HAR groove inhibited chip discharge, the chip discharge amount at the exit and entrance of the HAR groove was more than that of the shallow groove under the same depth of cut, which would lead to the larger exit burr size of the HAR groove.

The vibration and wear of tool were the main factors affecting bottom burr (Fig. 17), because the sidewall of the HAR groove limited chip discharge and increased the chance of chip falling in the milling area, and the burr size of the HAR grooves was larger (Fig. 19). At the same time, the sidewall of
the HAR groove was easy to interfere with the vibratory micro-mill, which would destroy the balance of the micro-mill and affect the bottom burr size.

4 Conclusions

Experiments were used to investigate how the sidewall affected the burr formation mechanism of HAR (2:1) and shallow grooves, which were further verified by the simulations. The detailed results can be summarized as follows:

1. When we consider the size effect of materials in the modeling process, the average error of cutting force and burr size were 2.1% and 9.5%, respectively, verifying the accuracy of the simulations.

2. Side burrs were classified into three types: fish-scale burrs, bulge-like burrs, and pit-like burrs. Among them, the number of fish-scale side burrs was the most, and the size was the smallest. Shallow grooves did not have the limitation of sidewall and can form larger-scale top burrs.

3. The factors affecting the exit burr were the low structural strength of the thin wall and the direction of the cutting force. Due to the low structural strength of the thin wall, the micro-milling process would be interrupted, the chip flow would disappear, the thin wall would be turned over, and the bulge-like burrs would be formed at the exit.

4. The direction of cutting force would affect the degree of exit burr crimping, the horizontal burr would form on the DM side, and the curly burr would form on the UM side. Compared with shallow grooves, HAR grooves eventually had a greater chance of forming large-sized exit burrs due to the single direction of chip discharge.

5. The entrance of the UM side was relatively smooth, with a small amount of pit-like entrance burrs. Large-size entrance burrs were mainly distributed on the DM side, mainly curly long burrs. Compared with shallow grooves, the entrance burr size was larger due to the difficulty of chip discharge in HAR grooves.

6. The bottom burrs were mainly distributed on the bottom near the sidewall. As chips on the UM side were severely squeezed, the burrs were relatively disorderly, while the chips on the DM side had a large deformation space, forming burrs with regular arrangement.

7. The reasons that affected the bottom burr size included the vibration of micro-mill and the interference between tool and sidewall. In addition, due to the chip falling in the milling area, a small amount of bottom burr was finally formed on the bottom.

Acknowledgements The authors would like to express their sincere gratitude to the National Natural Science Foundation of China (NSFC) (No. 51905270 and 51975288), the NSF of Jiangsu Province (No. BK20180435), and the China Postdoctoral Science Foundation (2019TQ0149 and 2019M660116) for their support.

Author contribution Xinlei Zhang: Conceptualization, methodology, software, validation, writing—Original Draft

Ni Chen: Software, formal analysis, investigation, data curation

Jinming Wu: Project administration, investigation

Jiawei Wei: Software, investigation

Bo Yan: Software, investigation

Liang Li: Resources, supervision

Ning He: Resources, supervision

Funding This study was funded by the National Natural Science Foundation of China (NSFC) (No. 51905270 and 51975288), the NSF of Jiangsu Province (No. BK20180435), and the China Postdoctoral Science Foundation (2019TQ0149 and 2019M660116). Part of this work was also funded by the Foundation of Jiangsu Key Laboratory of Precision and Micro-Manufacturing Technology.

Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable
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