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Research Article

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Posted Date: August 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10040335/v1>

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Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on October 14th, 2026. See the published version at <https://doi.org/10.1007/s00170-026-19321-w>.

Formation Mechanism and Parameter Influence of Multi-type Burrs on 6061-T6 Aluminum Alloy from Micro-milling to Precision Milling

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This work was supported by Project number: Aeronautical Science Foundation of China (No:2023Z045012001); ChongqingMunicipal Education Commission of Science and Technology Research Project (No:KJQN202402614);

Abstract: 6061-T6 aluminum alloy is widely applied in precision components for 3C electronics and aerospace, and prone to entry, top and exit burrs under the cutting depth of 0.2–1.4 mm, which impairs machining accuracy and surface integrity. In this work, thermo-mechanical coupled finite element simulation combined with $L_{16}(4^3)$ orthogonal tests was adopted. A milling model was established based on the Johnson-Cook constitutive model and Hillerborg fracture energy model, and validated with a milling force relative error below 9%. The formation mechanisms of three burr types and the influences of processing parameters were investigated. The results reveal that up-milling burr size is 22% higher than down-milling; feed rate and spindle speed dominate burr formation, and cutting force peak-to-peak value is positively correlated with burr thickness. This study clarifies the burr formation mechanism of 6061-T6 aluminum alloy under wide-cut-depth precision milling, providing theoretical support for burr suppression and process optimization.

Keywords: Micro-precision milling; 6061-T6 aluminum alloy; hermo-mechanical coupled simulation

1 Introduction

6061-T6 aluminum alloy has become a core lightweight structural material for microstructures and high-precision components in high-end manufacturing fields such as aerospace and 3C electronics due to its excellent strength and toughness, corrosion resistance and cutting performance^[1]. Micro-to-precision milling can realize efficient integrated forming of micro-features and precision structures, and satisfy the material removal demand within the wide cutting depth range of 0.2~1.4 mm, which has become the mainstream processing technology scheme for precision parts of 6061-T6 aluminum alloy^[2]. Nevertheless, affected jointly by the high plasticity of aluminum alloy and thermo-mechanical coupling behavior in cutting process, multiple types of burr defects are easily formed at the cutting entry, groove top and cutting exit during micro-precision milling. These defects significantly reduce the dimensional accuracy and surface integrity of parts, increase the subsequent deburring cost, and affect the service reliability of components^[3]. Therefore, it is necessary to systematically explore the dynamic formation mechanism of multi-position burrs under wide-cut-depth micro-precision milling, and clarify the coupling law among process parameters, cutting force and burr characteristics, so as to realize the effective suppression of burr defects and the improvement of machining quality in precision processing of 6061-T6 aluminum alloy.

To improve the machining stability and achieve accurate regulation of machining quality for aluminum alloy microstructures, existing studies have carried out systematic exploration on the process adaptability, forming capacity and parameter optimization of micro-to-precision milling. Ji et al.^[4] explored the chatter suppression method in micro-milling under different working conditions, and effectively improved the dynamic stiffness of the cutting system and the machining integrity of aluminum alloy microstructures at small cutting depths by optimizing the matching strategy of tool overhang length and cutting parameters. In addition, they completed the forming of high-precision micro-groove structures with low chatter marks and high dimensional accuracy by adopting stable cutting processes optimized based on stability lobe diagrams. Gao et al.^[5] focused on the micro-milling processing performance of 6061-T6 aluminum alloy with commercial cemented carbide micro-milling cutters, formulated adaptive milling parameters and tool path schemes, and carried out experimental verification by adopting thin-walled structures with different characteristic sizes. Han et al.^[6] investigated the influences of micro-milling parameters and processing technologies on dimensional error and surface quality of aluminum alloy thin-walled components, and determined the reasonable axial feed scheme for micro thin-walled structures with different specifications. Saha et al.^[7] conducted research on micro-groove structures, explored the influences of tool wear and cutting depth on machining surface quality as well as the generation of cracks and burr defects, clarified the action mechanism of key process factors, and realized stable machining of microstructures with high surface integrity under optimized process conditions. Li et al.^[8] carried out multi-factor orthogonal experiments on the precision milling process of 6061-T6 aluminum alloy, quantitatively analyzed the influence weight of spindle speed, feed rate and cutting depth on machined surface roughness, and optimized the optimal parameter combination for low-roughness machining. Li et al.^[9] systematically compared the effects of different tool coatings and edge radii on the micro-milling performance of 6061 aluminum alloy, and confirmed that tool geometric parameters exert a significant regulatory effect on machining stability and forming accuracy. Aiming at the machining deformation problem in precision milling of aluminum alloy, Jiang et al.^[10] established a mapping relationship model between cutting force and machining deformation, and effectively suppressed the machining deformation of thin-walled structures through process parameter optimization. Zaidi et al.^[11] carried out multi-objective process optimization for milling of 6061-T6 aluminum alloy. Based on Taguchi L9 orthogonal tests, they explored the influences of cutting parameters and insert number on surface roughness, burr width and specific cutting energy. The optimal process scheme and parameter influence weight were determined through grey relational analysis and ANOVA, which provided experimental support for process optimization in precision machining of aluminum alloy. Lee et al.^[12] systematically studied the differences between up-milling and down-milling working conditions in micro-milling, compared the differences in cutting force fluctuation, material plastic deformation characteristics and machined surface quality under up-milling and down-milling conditions, and confirmed that up-milling process possesses better forming stability in the machining of micro-structures. Zhang et al.^[13] analyzed and predicted the size-effect-based burr formation mechanism in micro-milling, and found that the width and height of burrs initially decreased with the increase of feed per tooth, and Aiming at the burr defect problem in micro-milling of aluminum alloy, existing studies have carried out multi-dimensional analysis on burr formation mechanism and morphology evolution law. In terms of numerical simulation of burr formation, Özel et al.^[14] conducted simulations based on the three-dimensional finite element method (FEM), investigated the formation of top burrs and built-up edges (BUEs), as well as chip adhesion

and three-dimensional chip flow during micro-milling. It was concluded that tool wear, top burr size and chip curl increase with the reduction of tool edge sharpness. Wu et al.^[15] established a finite element constitutive model for micro-milling of aluminum alloy, systematically explored the influence law of the combination of cutting depth and feed rate on burr initiation and evolution combined with the Johnson-Cook damage criterion, and realized high-precision prediction of burr characteristic size through simulation. Wolf et al.^[16] constructed a three-dimensional drilling simulation model combining CFD numerical simulation and finite element method, explored the influence mechanism of machining thermal load and chip forming process on tool heat flow and wear evolution, and improved the numerical simulation model system of cutting considering thermo-mechanical coupling effect. Davoudinejad et al.^[17] established a finite element model for micro-groove milling of aluminum alloy, systematically analyzed the evolution process of burr morphology under different cutting conditions, and confirmed that plastic side flow of cutting material is the core inducement for the formation of groove top burrs. Cao et al.^[18] constructed a joint simulation model for multiple types of burrs in micro-groove milling of aerospace soft aluminum alloy, synchronously simulated the whole dynamic initiation and evolution process of inner curved and aggregated burrs, quantitatively analyzed the growth rate and size difference of various burrs under different process parameters combined with experiments, and provided dual support of simulation and experiment for the research on burr formation mechanism and machining quality improvement in micro-groove milling of aerospace soft metals. Wu et al.^[19] established a defect evolution analysis model for CFRP composite milling considering real-time tool wear, explored the influence of edge morphology evolution on fiber burr morphology, distribution and matrix crack initiation during tool wear, revealed the fiber orientation-dependent burr generation mechanism, and confirmed that burr growth induced by tool wear is an important inducement for the initiation and directional propagation of fishbone cracks on machined surfaces.

In addition, many scholars have realized quantitative prediction of burr size by constructing theoretical models. Li et al.^[20] established an analytical prediction model for Poisson burr size in micro-milling of aluminum alloy considering the interface constraint effect, verified the model under different cutting parameters and constraint intensities, and confirmed that the model can accurately predict burr height and thickness combined with finite element simulation and experimental verification. N et al.^[21] established a mathematical model for exit burr height in micro-end milling of Inconel 718 alloy by combining micro-cutting size effect, material microstructure and cutting temperature, and predicted its formation mechanism analytically. The results showed that the exit burr height first decreased and then increased with the rise of feed per tooth. The burr height was higher when the feed per tooth was lower than the tool edge radius, and increased with the feed per tooth exceeding the edge radius, while the burr size reached the minimum in the transition zone, with a maximum model prediction error of only 6.4%. Jiang et al.^[22] constructed a thermo-mechanical coupling theoretical model for PLLA micro-milling considering the size effects of minimum cutting thickness and edge radius, revealed the plastic flow law of polymer materials during machining, clarified the quantitative correlation between burr width on both milling sides and micro-cutting parameters, and provided a theoretical method for mechanism analysis and size prediction of burrs in micro-milling of medical polymer materials. Yadav et al.^[23] established a correlation model among cutting force, residual stress and burr characteristics in titanium alloy micro-milling, revealed the regulation mechanism of residual stress and cutting force on burr generation, and realized accurate prediction of burr morphology and cutting force characteristics relying on simulation and

experiments. Combined with the coexistence characteristics of plowing and shearing in micro-milling and considering the influences of helix angle and tool wear, Gao et al.^[24] established a mathematical model of micro-milling force for single-crystal nickel-based alloy, clarified the influence law of cutting parameters on milling force combined with finite element simulation and experiments, and provided a theoretical basis for accurate prediction of micro-milling force and process optimization.

Apart from numerical simulation and theoretical model research, most existing studies analyzed the burr formation mechanism and regulation methods in micro-milling through systematic cutting experiments, focusing on clarifying the coupling correlation mechanism among process parameters, cutting force and burr characteristics. Dos et al.^[25] experimentally explored the formation law of top burrs in dry micro-milling of pure titanium, analyzed the influences of the ratio of feed per tooth to edge radius, axial cutting depth and milling path strategy on top burr size and milling force, clarified that the ratio of edge radius to feed per tooth and axial cutting depth are the key parameters for regulating top burrs, and different machining paths and up-down milling modes have significant effects on burr morphology and size. Yabo et al.^[26] systematically analyzed the influence law of cutting parameters on micro-milling burrs by combining theoretical simulation and cutting experiments, and concluded that burr size increases with the rise of feed rate, cutting speed and tool edge radius. Zhao et al.^[27] investigated the influences of cubic boron nitride coated and uncoated micro-milling cutters on burr formation in aluminum alloy machining combined with finite element simulation and experiments. The results showed that cubic boron nitride coated micro-milling cutters can significantly alleviate tool wear, thus obtaining smaller burr size and better workpiece surface quality. Based on the elastic-plastic deformation mechanism of materials, Jing et al.^[28] established a three-dimensional finite element simulation model, explored the influence law of tool wear on burr formation in aluminum alloy micro-milling, and found that tool wear leads to the increase of edge radius, which further raises cutting force and cutting temperature, and ultimately promotes the formation of more and larger-sized burrs.

Although increasing studies have focused on burr formation mechanism, size effect and burr types, most previous researches are limited to single working condition with small cutting depth and only focus on burrs at a single position. Few studies have systematically explored the synergistic mechanism of multiple burrs covering a wide cutting depth range. Therefore, taking 6061-T6 aluminum alloy within the wide cutting depth range of 0.2~1.4 mm as the research object, this paper adopts the combined method of orthogonal test and thermo-mechanical coupled finite element simulation. The accuracy of the simulation model is verified through milling force experimental data. The dynamic formation and evolution mechanisms of three types of burrs including entry burr, top burr and exit burr in micro-to-precision milling are systematically revealed, and the coupling influence law of three key process parameters (axial cutting depth, feed rate and spindle speed) on cutting force and burr morphological characteristics is clarified. The research results can provide theoretical basis and data support for burr defect suppression and process parameter optimization of 6061-T6 aluminum alloy in wide-cut-depth micro-precision milling.

2 Establishment of the finite element model and experimental set up

Axial cutting depth (a_p), feed speed (v_f) and spindle speed (n) are the core process parameters that dominate material deformation, cutting force and burr formation during micro-milling of 6061-T6 aluminum alloy. To fully clarify their influence laws on entry, exit and top burrs concerned in this study, and balance experimental efficiency and data integrity, the $L_{16}(4^3)$ orthogonal experimental

design was adopted to set up a total of 16 working conditions from A1 to D4. The parameter levels were determined based on micro-milling feasibility and equipment performance limits: a_p ranges from 0.2 to 1.4 mm, v_f from 100 to 220 mm/min, and n from 9000 to 20000 r/min. To systematically reveal the burr formation mechanism, the Johnson-Cook constitutive model was employed in the finite element modeling to accurately describe the plastic flow behavior of 6061-T6 aluminum alloy under high strain rate and thermo-mechanical coupling conditions. Coulomb's friction law was used to define the tool-chip interface friction for simulating the contact interaction between the tool and workpiece/chip. The geometric model dimensions, cutting parameters and boundary conditions were strictly consistent with the orthogonal experiments, ensuring the reliability and comparability of simulation results.

2.1 Material analysis

In this study, 6061-T6, a heat-treatable strengthened Al-Mg-Si aluminum alloy widely used in precision manufacturing, was selected as the experimental material. After complete heat treatment consisting of solution treatment, quenching and artificial aging, the alloy possesses moderate strength, excellent corrosion resistance, and favorable machinability and weldability. Its chemical composition and physical properties are presented in Table 1 and Table 2.

Table 1 6061-T6 Aluminium alloy chemical composition table

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other
rest	0.4- 0.8%	0.7%	0.15- 0.4%	0.15%	0.8- 1.2%	0.04- 0.4%	0.15%	0.15%	0.15%

Table 2 6061-T6 Aluminium mechanical properties parameter table

Performance parameter	Value
Tensile strength (UTS)	310 – 345 MPa
Yield strength (YS)	275–310 MPa
Elongation (δ , %)	8%–12%
Hardness (HB)	90–100 HB
Elastic modulus (E)	68.9 – 70 GPa
Density	2.70 g/cm ³
Thermal conductivity	167 W/(m·K)

In this study, a two-flute flat-end milling cutter with a diameter of 1.5 mm was used as the experimental tool. Fig. 1(a) presents the overall macroscopic appearance and structural dimensions of the cutter, and Fig. 1(b) shows the locally magnified morphology of the cutting edge. It can be clearly observed that the tool edge is treated by mirror precision grinding, which features a smooth, sharp profile and superior anti-wear performance. Fig. 1(c) illustrates the cross-sectional view of the tool end face, clearly demonstrating the core tooth structure of the two-flute flat-end design. The cutter is manufactured from a novel tungsten steel base material, possessing high overall structural strength and excellent wear resistance. The detailed material and mechanical performance parameters of the milling cutter are summarized in Table 3.

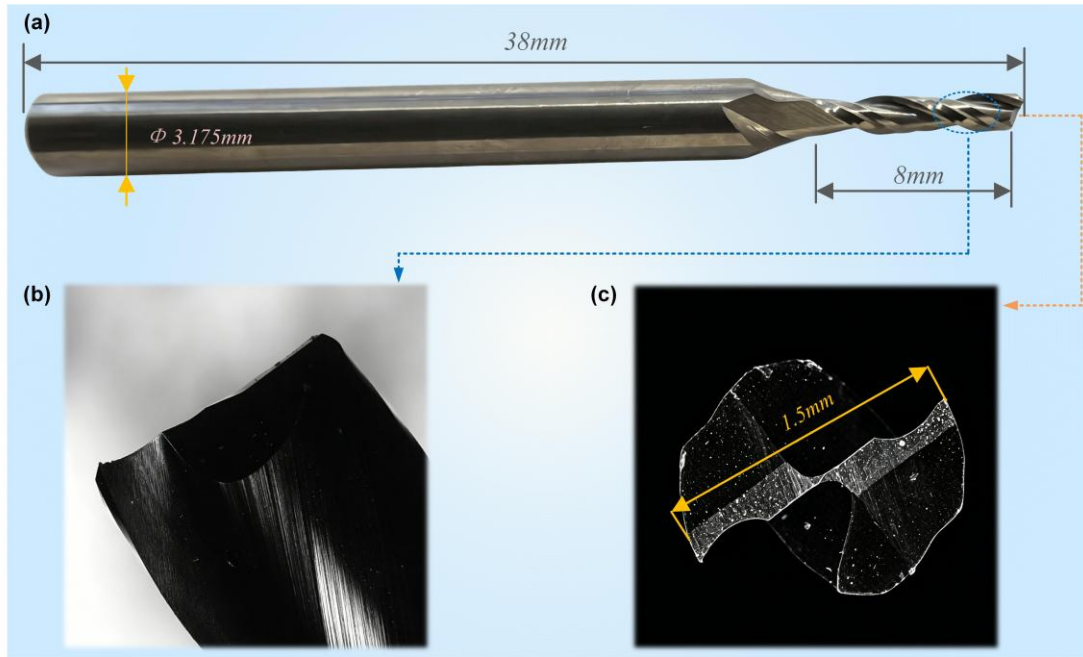


Fig. 1. Geometric properties of cutting tool.

Table 3 Micro milling cutter parameter table

Property	Value
Material	Hard alloy
Type of cutter	Flat-ended helical micro-mill
Blade diameter(mm)	1.5
Handle diameter(mm)	3.175
Blade length (mm)	8
Overall length(mm)	38
Blade number	2
Helix angle	35°
Hardness	45C

2.2. Experimental design and planning

This experiment mainly investigates the effects of process parameters and milling force on burr size control and morphology evolution to explore the burr formation mechanism, so no cutting fluid was used throughout the experiment to avoid the interference of its high-speed flushing on burr formation; based on preliminary process exploration, literature research, CNC machining center characteristics and practical experience, an orthogonal experiment was designed (Table 4) with detailed grouping shown in Table 5, where the axial cutting depth was set at 0.2–1.4 mm (covering micro and conventional milling ranges) to avoid cutting force surge, tool breakage and elastic-plastic deformation-induced burrs, the feed rate at 100–220 mm/min (optimal for 6061-T6 micro-milling) to reveal its influence on burr size while avoiding built-up edges at low speed and high cutting temperature at high speed, and the spindle speed in a 9000–20000 r/min gradient to keep the cutting edge linear velocity in the optimal processing window and avoid burrs caused by excessive cutting force, tool wear and thermal deformation.

Table 4 .Milling process parameters

Process parameters	Level			
	1	2	3	4
a_p/mm	0.2	0.6	1	1.4
$v_f/\text{mm}\cdot\text{min}^{-1}$	100	140	180	220
$n/\text{r}\cdot\text{min}^{-1}$	9000	12000	16000	20000

Table 5 Milling Group

No	Process parameters		
	a_p/mm	$v_f/\text{mm}\cdot\text{min}^{-1}$	$n/\text{r}\cdot\text{min}^{-1}$
A1	0.2	100	9000
A2	0.2	140	12000
A3	0.2	180	16000
A4	0.2	220	20000
B1	0.6	100	12000
B2	0.6	140	9000
B3	0.6	180	20000
B4	0.6	220	16000
C1	1	100	16000
C2	1	140	20000
C3	1	180	9000
C4	1	220	12000
D1	1.4	100	20000
D2	1.4	140	16000
D3	1.4	180	12000
D4	1.4	220	9000

The raw blank specimen with dimensions of 90×100×30 mm was evenly divided into 16 small machined specimens of 10×15×10 mm by laser cutting. Laser cutting ensures cutting accuracy and avoids interference from additional burrs on experimental results. After cutting, all specimens were polished and cleaned to maintain a consistent initial surface state. Subsequently, each specimen was firmly mounted on a Kistler 9119AA1 dynamometer via bolts to restrain displacement and vibration during milling, thereby guaranteeing the acquisition accuracy of milling force signals. The actual installation layout of the test specimens is shown in Fig. 2(a).

For subsequent observation and characterization, burrs generated during micro-groove milling were classified into three categories according to their positions: entry burr, top burr and exit burr. Independent measurement and statistical analysis were performed separately for burrs on the down-milling and up-milling sides. The burr height was selected as the evaluation index for entry burrs, which directly reflects the degree of material extrusion and accumulation during tool cutting-in. The burr thickness was adopted to evaluate top burrs, characterizing the lateral extension induced by chip backflow and edge stretching. Both burr height and root thickness were used for exit burrs to characterize the overall protrusion degree as well as the root plastic deformation and tearing strength. The specific positions and measurement criteria of various burrs are illustrated in Fig. 2(b).

On this basis, the average burr thickness was further introduced as a comprehensive global evaluation index to systematically clarify the internal coupling relationships among milling force, burr morphology, cutting process parameters and overall burr formation. This index overcomes the limitation that single-position indicators are difficult for global horizontal comparison and correlation

analysis. It enables unified quantitative statistics on the overall burr thickness of micro-groove edges, and supports the rule analysis and mechanism discussion of overall burr severity under multiple machining conditions.

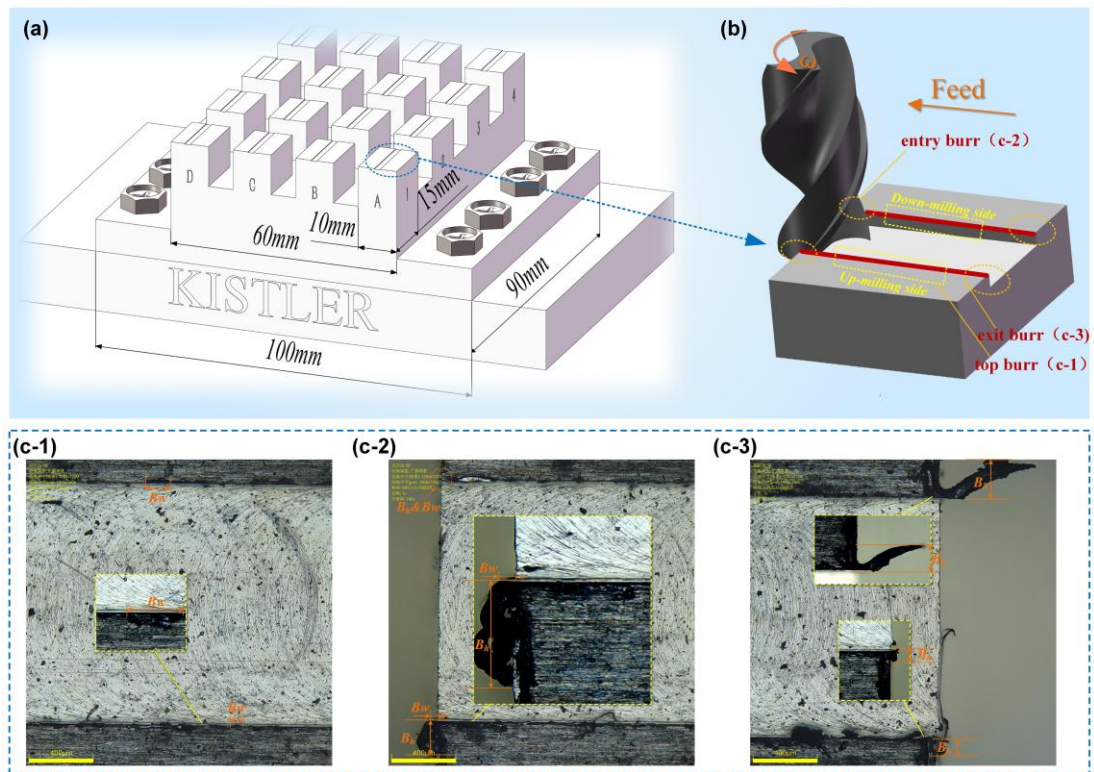


Fig. 2. Experimental setup of specimens and characterization scheme for burrs.

All milling tests were conducted on a DX 650 engraving and milling machine, which features X/Y/Z axis travels of 650×500×400 mm, a maximum spindle speed of 24000 rpm and a positioning accuracy of ± 0.05 mm, fully satisfying the high-precision micro-milling requirements of this study, as shown in Fig. 3(a). Milling force signals were acquired using a Kistler 9129A dynamometer at a sampling frequency of 6.3 kHz, and the raw force data were extracted and waveform-processed via DynoWare software on a PC; low-pass filtering was further applied to eliminate high-frequency interference induced by spindle dynamic characteristics and retain real cutting force characteristics, with the original and filtered force waveforms presented in Fig. 3(c) and Fig. 3(d), respectively. The peak-to-peak values of transverse force F_x and feed force F_y were adopted to evaluate cutting force characteristics, which can well reflect dynamic cutting variations that cannot be captured by average force. All peak-to-peak values were obtained by averaging the cutting force signals of 100 continuous tool revolutions under each condition, and each test was repeated twice with a new cutter to ensure stable and consistent experimental results.

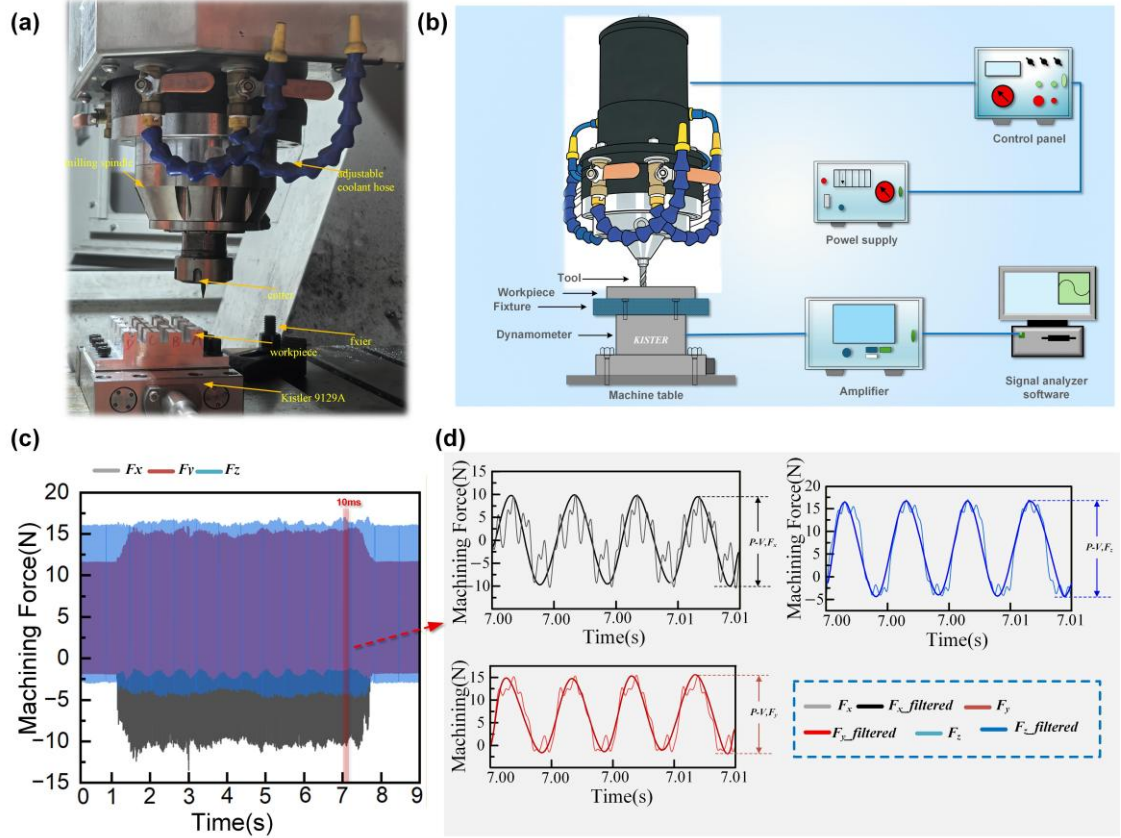


Fig. 3. Micro-milling experimental setup and milling force signal processing procedure.

2.3 Finite element modeling

To explore the burr formation mechanism in the milling process, the micro-milling simulation in this study was carried out based on the Abaqus/Explicit solver. The analysis step was set to Dynamic, Explicit, and the Thermomechanical Coupling function was enabled. This configuration can simultaneously calculate the displacement, stress evolution and temperature field distribution during cutting, accurately couple the heat generation induced by plastic deformation, interfacial friction heat generation and material thermal softening effect, and meet the simulation requirements of dynamic fracture under high strain rate.

Fig. 4 presents the initial state and boundary conditions of the finite element model. According to the measured geometric parameters of the cutter, three-dimensional solid models of the micro-diameter two-flute end mill and the workpiece were established by SolidWorks CAD software, as shown in Fig. 4(a).

In the simulation, the cutter was defined as a rigid body and meshed with R3D4 elements, while the workpiece was discretized by EC3D8RT elements. In this study, the cutter is made of cemented carbide, whose hardness and stiffness are much higher than those of the 6061-T6 aluminum alloy workpiece. The deformation of the cutter itself during micro-milling is extremely small and can be ignored. Therefore, simplifying the cutter as a rigid body can greatly improve the computational efficiency of dynamic explicit simulation, without significantly affecting the core results such as cutting force distribution, material plastic flow and burr formation. This simplification is fully reasonable and universally applicable in micro-milling simulation.

Combined with References^[29, 30], which took Ti6Al4V as the research object but proposed

general criteria for cutting simulation mesh design applicable to this study and pre-simulation analysis, the influences of mesh size and morphology on simulation accuracy were comprehensively considered. A fine square mesh of 1 μm was adopted for the cutting area of the workpiece with a mesh orientation angle of 90°. Meanwhile, a mesh size of 1 μm was also used for refined modeling of the cutter edge area to ensure the simulation accuracy of deformation and fracture behavior in the cutting region. The mesh generation results are shown in Fig. 4(b) and Fig. 4(c).

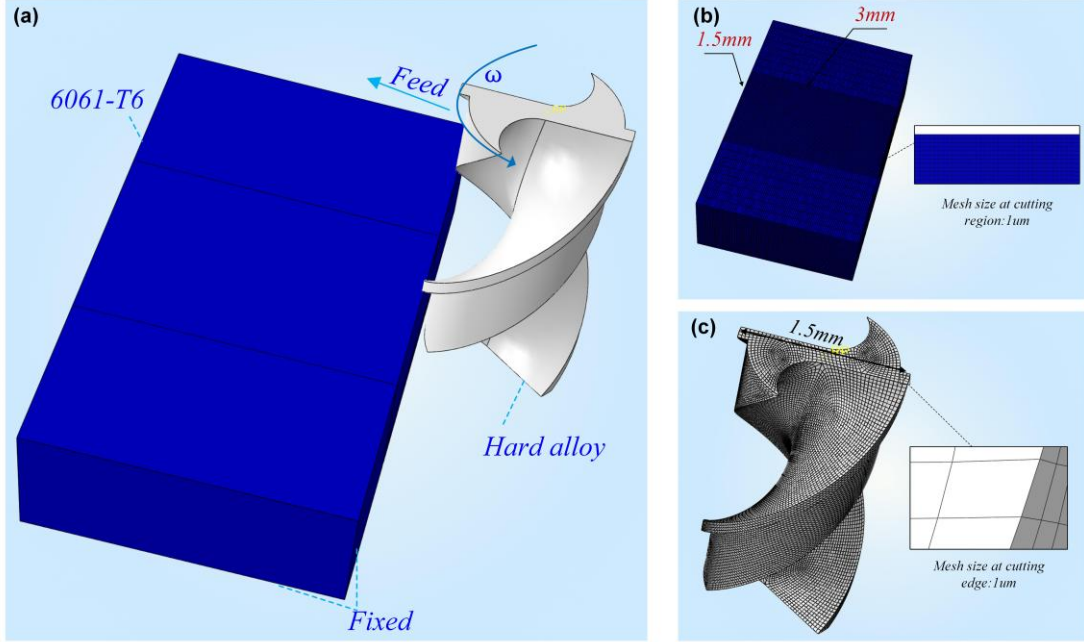


Fig. 4. 3D micro-milling model.

The Johnson-Cook (J-C) constitutive model^[31] can accurately characterize the plastic flow behavior of 6061-T6 aluminum alloy under high strain rate and thermo-mechanical coupling conditions in micro-milling, and is suitable for describing the evolution law of thermodynamic and mechanical properties of the workpiece material. The physical properties of the simulated material and the relevant J-C constitutive model parameters are listed in Table 6. According to this model, the equivalent stress of the material is defined as:

$$\sigma = (A_{JC} + B_{JC}\varepsilon^{n_{JC}})(1 + C_{JC}\ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})[1 - (\frac{T - T_r}{T_m - T_r})^{m_{JC}}] \quad (1)$$

In this equation, A_{JC} represents the yield stress of the material. B_{JC} and n_{JC} describe the strain hardening effect, while C_{JC} is the strain rate constant and m_{JC} characterizes the thermal softening effect. T , T_m and T_r denote the material temperature, melting temperature and room temperature, respectively. ε refers to the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, and $\dot{\varepsilon}_0$ is the reference strain rate.

o accurately simulate the dynamic separation behavior between chips and workpiece during micro-milling and fully reveal the fracture mechanism of burr formation, the Johnson-Cook (J-C) damage model^[31] and Hillerborg fracture energy (G_f) model were adopted in this study to define the damage initiation response and damage evolution response of the material successively, realizing the whole-process simulation from crack initiation to complete material failure and fracture.

In the J-C damage model, the failure strain of the material is defined as a coupled function of stress triaxiality, strain rate and temperature, which serves as the core criterion for judging the

initiation of initial material cracks. The corresponding material parameters are listed in Table 7, and its expression is given as:

$$\varepsilon_f = \left[D_1 + D_2 \exp(D_3 \sigma^*) \right] (1 + D_4 \ln \dot{\varepsilon}^*) (1 + D_5 T^*) \quad (2)$$

In this equation, ε_f is the equivalent plastic failure strain of the material, and D_1, D_2, D_3, D_4, D_5 are the J-C damage constants of 6061-T6 aluminum alloy. $\sigma^* = \frac{\sigma_{eq}}{\sigma_m}$ is the stress triaxiality, σ_m is

the average stress (MPa), σ_{eq} is equivalent stress (MPa); $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$ is a dimensionless strain

rate, The parameter definition is consistent with the formula (1). $T^* = \frac{T - T_r}{T_m - T_r}$ is a dimensionless

temperature, whose value range is $0 \sim 1$, and the parameter definition is consistent with formula (1).

Damage initiation is quantitatively described by the damage index ω , and its expression is defined as:

$$\omega = \sum \left(\frac{\Delta \varepsilon^{pl}}{\varepsilon_0^{pl}} \right) \quad (3)$$

During plastic deformation, the scalar damage parameter ω increases continuously with the accumulation of equivalent plastic strain. In the formula, the term $\Delta \varepsilon^{pl}$ represents the increment of equivalent plastic strain, while the critical equivalent plastic failure strain ε_0^{pl} is calculated by the J-C damage model (Equation (2)) under the instantaneous stress triaxiality, strain rate and temperature field. When ω accumulates to the critical value of 1, the material satisfies the damage initiation criterion, indicating the occurrence of initial crack initiation and subsequently entering the damage evolution stage.

After damage initiation, the mechanical properties of the material degrade significantly. Its stress-strain response can no longer be directly characterized by the original J-C plastic constitutive model (Equation (1)). Instead, the degradation parameter D is adopted to control the attenuation rate of material stiffness, which accurately describes the softening behavior of the material during crack propagation until the element fails completely.

Following damage initiation, the material enters the damage evaluation and evolution stage dominated by the Hillerborg fracture energy (G_f) model. In this model, fracture energy G_f is defined as a core material parameter, which physically represents the energy required to form a new crack surface per unit area. The corresponding expression is as follows:

$$G_f = \int_{\varepsilon_0^{pl}}^{\varepsilon_f^{pl}} L \bar{\sigma} d\varepsilon^{pl} = \int_0^{\bar{u}_f^{pl}} \bar{\sigma} d\bar{u}^{pl} \quad (4)$$

In this formula, L is the characteristic length, ε_f^{pl} is the equivalent plastic strain at failure, and

$\bar{u}_f^{pl}$ is the equivalent plastic displacement at failure. By adopting stress-displacement responses

instead of stress-strain responses, the Hillerborg fracture energy model effectively reduces mesh dependency in finite element simulation and remarkably improves the stability and accuracy of fracture simulation. Based on the energy dissipation theory of brittle fracture, this model defines G_f as an intrinsic material parameter. It has been verified in Reference [32] that the model can be well applied to the simulation of metal cutting processes, and can accurately describe the fracture behavior of chip formation and separation under large plastic deformation and high-temperature conditions.

In this study, the Hillerborg fracture energy G_f was selected by referring to the systematic investigation on the ductile fracture behavior of 6061-T6 aluminum alloy conducted by Zhu et al.[33]. Through experimental and simulation verification, it was confirmed that 6061-T6 is a high-toughness ductile metal, and its fracture energy G_f needs to consider both linear elastic fracture energy and energy dissipation from large plastic deformation. Combined with the measured fracture toughness of 6061-T6 and its elastic modulus $E \approx 69$ GPa, the linear elastic fracture energy was calculated to be about $9.8 \sim 12.2$ kJ/m² via the classical fracture mechanics formula $G_f = K_{IC}^2 / E$. However, the micro-milling process involves severe plastic deformation and high strain rate loading, and the energy dissipated by crack propagation is far higher than the linear elastic fracture energy. Following the general practice of similar metal cutting simulations[34], $G_f = 20$ kJ/m² was adopted in this study. This value lies within the reasonable range of ductile fracture energy dissipation for 6061-T6 aluminum alloy, and can accurately characterize the crack propagation and energy consumption behavior during chip separation.

The stiffness degradation of materials during damage evolution is quantitatively calculated based on the exponential evolution law of the degradation parameter D , and the expression is given as:

$$D = 1 - \exp \left(- \int_0^{\bar{u}^{pl}} \frac{\bar{\sigma}}{G_f} d\bar{u}^p \right) \quad (5)$$

In this equation, $\bar{u}^{pl}$ represents the equivalent plastic displacement. In the Abaqus/Explicit solver, when the degradation parameter D gradually accumulates from 0 to 0.99, the solver automatically sets D to 1. At this moment, the material stiffness is completely degraded and the corresponding element fails thoroughly, achieving smooth separation between the chip and the workpiece.

Table 6 Simulation of physical properties and constitutive model parameters

Parameter	Value	Physical Significance
ρ	2700 kg/m ³	Density
E	68.9 GPa	Young's Modulus
ν	0.33	Poisson's Ratio
k	167 W/(m·K)	Thermal Conductivity
C_p	896 J/(kg·K)	Specific Heat
T_m	652°C	Melting Temperature
$\dot{\epsilon}_0$	1.0 s ⁻¹	Reference Strain Rate
A	276 MPa	Yield Stress
B	114 MPa	Hardening Modulus
n	0.05	Hardening Exponent
C	0.008	Strain Rate Coefficient

m	1.30	Thermal Softening Exponent
T_r	25°C	Room Temperature

Table 7 Plastic strain model and thermal expansion parameters

Parameter	Value	Physical Significance
D_1	0.071	Initial Damage Threshold
D_2	1.248	Damage Growth Exponent
D_3	-1.515	Stress Triaxiality Sensitivity
D_4	0.011	Strain Rate Sensitivity
D_5	0.635	Temperature Sensitivity
$\bar{\epsilon}_f$	0.8	Failure Strain
α	$23.6 \times 10^{-6} / ^\circ\text{C}$	Coeff of Thermal Expansion

In this study, two contact types are considered, namely tool-workpiece and chip-workpiece, both adopting the shear friction model. Under the assumption of constant shear stress, the friction coefficient remains constant. The friction coefficient for tool-workpiece contact is set to 0.7, and that for chip-workpiece contact is set to 0.1.

3 Results and discussion

This chapter conducts systematic simulation verification, mechanism analysis and quantitative correlation research on burr formation in 6061-T6 aluminum alloy micro-milling. Firstly, experimentally measured milling forces are compared with finite element simulation results to verify the accuracy and reliability of the thermo-mechanical coupled model, which can accurately reproduce actual micro-milling material deformation and cutting behavior. Secondly, based on the validated model, the formation mechanisms of entry, top and exit burrs are elaborated from the perspectives of material plastic flow, stress-strain evolution and edge material accumulation. Finally, multi-dimensional analysis is performed: it quantitatively explores the effects of spindle speed, feed rate and cutting depth on the characteristic dimensions of the three burr types, and introduces average burr thickness as a comprehensive index to analyze the global correlation among milling force, cutting parameters and overall burr formation.

3.1 Milling Force Verification

The experimental and simulated peak-to-peak (PV) values of F_x and F_y are presented in Fig. 5 and Table 8. The two sets of results show identical variation trends and good numerical consistency. For the micro-milling of 6061-T6 aluminum alloy, the simulation-experiment error of F_x peak-to-peak values ranges from 4.10% to 6.76% under different cutting parameters, while that of F_y ranges from 4.25% to 8.27%. The overall error is steadily controlled within 9%.

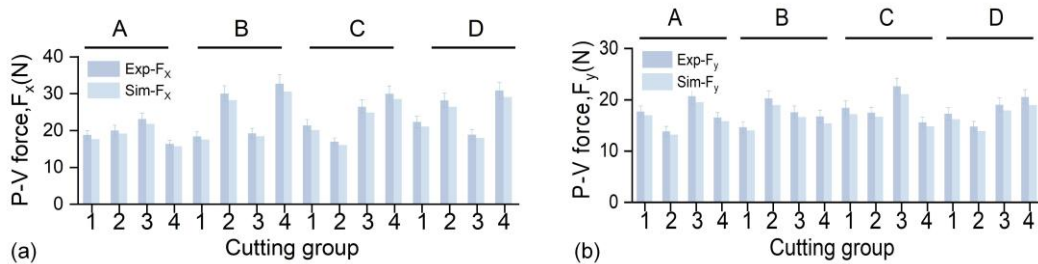


Fig. 5. Comparison between simulated and measured a) F_x and b) F_y forces in micro-milling.

Table 8 Measured and simulated force values.

Cutting condition				P-V $F_x(N)$			P-V $F_y(N)$		
group	a_p/mm	$v_f/mm \cdot min^{-1}$	$n/r \cdot min^{-1}$	Exp	Sim	Error%	Exp	Sim	Error%
A1	0.2	100	9000	18.71513	17.601	5.96	17.65095	16.938	4.25
A2	0.2	140	12000	19.94697	19.125	4.25	13.79459	13.127	5.04
A3	0.2	180	16000	23.0584	21.789	6.54	20.62444	19.456	6.04
A4	0.2	220	20000	16.2887	15.645	4.21	16.4514	15.778	4.57
B1	0.6	100	12000	18.34847	17.523	4.63	14.60811	13.963	4.84
B2	0.6	140	9000	29.9892	28.225	5.97	20.20508	18.988	6.46
B3	0.6	180	20000	19.18576	18.465	4.1	17.4969	16.545	5.7
B4	0.6	220	16000	32.65884	30.558	6.61	16.68058	15.312	8.27
C1	1	100	16000	21.34927	20.147	5.85	18.37199	17.147	6.92
C2	1	140	20000	16.89458	16.000	5.29	17.42706	16.689	4.74
C3	1	180	9000	26.42643	24.845	6.15	22.55295	21.058	6.89
C4	1	220	12000	29.93319	28.525	4.79	15.5305	14.756	5.35
D1	1.4	100	20000	22.25801	21.78	5.65	17.18774	16.125	6.33
D2	1.4	140	16000	28.1353	26.4	6.17	14.69613	13.869	6.09
D3	1.4	180	12000	18.82978	17.958	4.94	18.98322	17.845	6.23
D4	1.4	220	9000	30.78549	29.993	5.8	20.46292	18.963	7.64

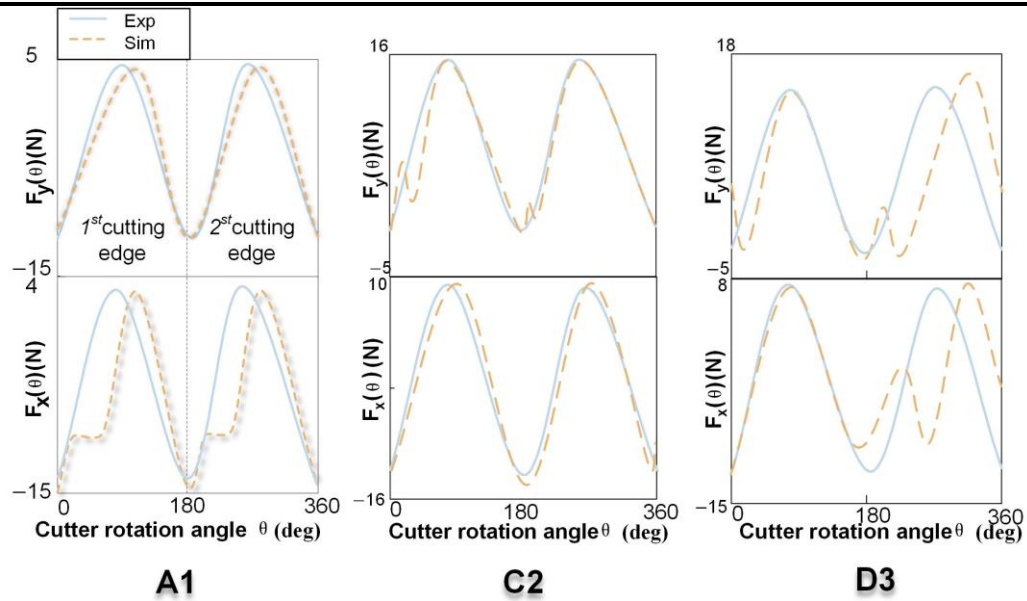
**Fig. 6.** The variation of measured and simulated forces with tool rotation in micro-milling.

Fig. 6 compares the dynamic evolution of experimental and simulated milling forces with tool rotation angle under three typical cutting conditions: A1 (low parameters), C2 (medium parameters) and D3 (high parameters). The simulated and measured forces share highly consistent variation trends with periodic fluctuations corresponding to the cutting cycle of the two-flute end mill.

Under condition A1 with small cutting depth, low feed and low spindle speed, the cutting load is low and the size effect is prominent. For F_x , the simulated curve shows a slight leading fluctuation at the initial rotation stage ($\theta \approx 0^\circ \sim 30^\circ$) with minor phase misalignment but close peak and valley amplitudes. For F_y , the simulated and experimental curves match well in periodicity, peak position and amplitude. Under condition C2 with moderate cutting depth, medium feed and high spindle speed,

the simulated F_x curve is highly consistent with the experimental one without obvious deviation. For F_y , only a slight leading fluctuation appears at the initial stage ($\theta \approx 0^\circ \sim 45^\circ$), followed by good agreement in subsequent cycles.

The local fluctuation and phase misalignment at the initial cutting stage of A1- F_x and C2- F_y are mainly attributed to the ideal rigid instantaneous contact adopted in the simulation. In practice, the tool edge cuts into the workpiece gradually with changing contact stiffness. Besides, the finite element model ignores practical disturbances such as tool setting deviation and workpiece surface asperities, resulting in time difference of force activation.

Under high-load condition D3 with large cutting depth, medium feed and moderate spindle speed, plastic deformation and cumulative effect are significant. In the first cutting interval ($\theta \approx 0^\circ \sim 180^\circ$), simulated F_x and F_y agree perfectly with experimental results. In the second interval ($\theta \approx 180^\circ \sim 360^\circ$), slight local fluctuations and minor deviations occur in the simulated curves. Such deviations stem from residual stress, work hardening and chip discharge interference induced by the first cutting pass in actual machining, which are neglected in the ideal steady-state finite element model.

All local deviations do not alter the periodic characteristics of milling forces. The relative error of peak-to-peak forces is within the allowable engineering accuracy for micro-milling simulation. The developed finite element model can accurately reflect the mechanical behavior in 6061-T6 aluminum alloy micro-milling with high reliability, which provides a valid basis for analyzing the formation and evolution mechanism of burrs.

3. 2 Analysis of Burr Formation Mechanism

Entry burrs emerge at the initial tool workpiece engagement stage. Extrusion and squeezing of the uncut material by the cutting edge drive plastic flow and material accumulation at the entry edge, directly reflecting material deformation characteristics during cutting entry.

Fig. 7(a) shows the chip formation stage. As the tool edge initially cuts into the workpiece entry zone, extrusion and shear effects induce local Mises stress concentration (maximum stress ~ 805 MPa) at the entry edge, triggering initial plastic deformation and chip initiation. Only slight material bulging occurs without obvious burr formation. Fig. 7(b) presents the chip curling stage. With continuous tool feed, chips curl under edge friction. The entry edge material is subjected to chip pulling and persistent edge extrusion, expanding the stress concentration zone. Mild upward bulging appears, forming an embryonic burr with insignificant deformation. Fig. 7(c) corresponds to the chip separation stage. After chip curling and separation from the workpiece substrate, the unrestrained entry edge material rebounds and folds slightly under residual stress, forming a preliminary entry burr with small height and thickness and no obvious root tearing. Fig. 7(d) illustrates the final burr morphology. After the tool fully passes the entry zone, the entry burr stabilizes into a low and thin profile with regular edges on both up-milling and down-milling sides, without evident curling or tearing.

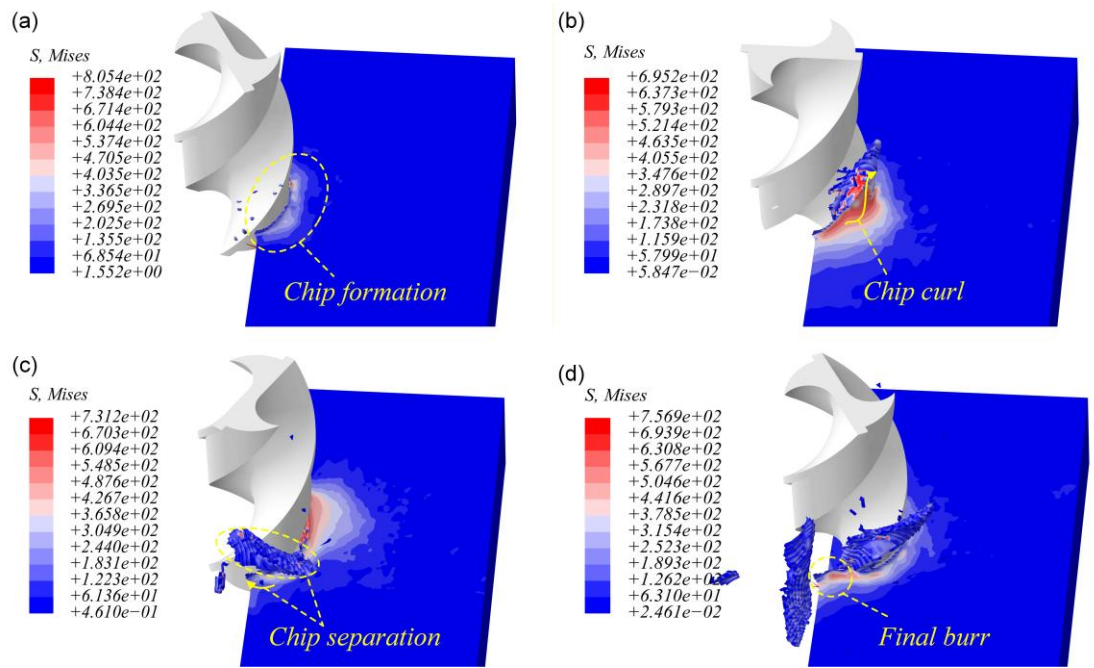


Fig. 7. Simulation cloud maps of four-stage dynamic formation process of entry burr in micro-milling under A1 group

Top burrs form during the stable cutting stage. Pulling action on the cutting edge caused by chip backflow induces lateral plastic flow and extension of edge material, and its formation process reflects the material flow behavior under stable cutting conditions.

Fig. 8(a) shows the initial stable cutting stage. The tool edge enters steady cutting, with local Mises stress concentration generated at the tool-workpiece contact region (maximum stress about 755 MPa). Chips initiate and discharge preliminarily. The cutting edge is only subjected to uniform shear without obvious lateral extension, and no top burr is formed yet. Fig. 8(b) presents the stage of chip backflow and edge pulling. With continuous tool feed, chips curl and flow backward under edge friction, exerting sustained pulling on the cutting edge. The stress field expands outward, triggering weak lateral plastic flow of edge material and gradual edge bulging, with the embryonic top burr emerging initially. Fig. 8(c) is the edge plastic extension stage. The pulling effect of chip backflow continues to intensify the plastic flow of edge material and increase edge bulging, forming a distinct embryonic top burr with tiny thickness and well-arranged edge profile. Fig. 8(d) shows the final formation stage of top burrs. As stable cutting proceeds, the plastic flow at the cutting edge tends to stabilize, eventually forming thin, small and regular top burrs. The edges on up-milling and down-milling sides are relatively flat without obvious curling or tearing.

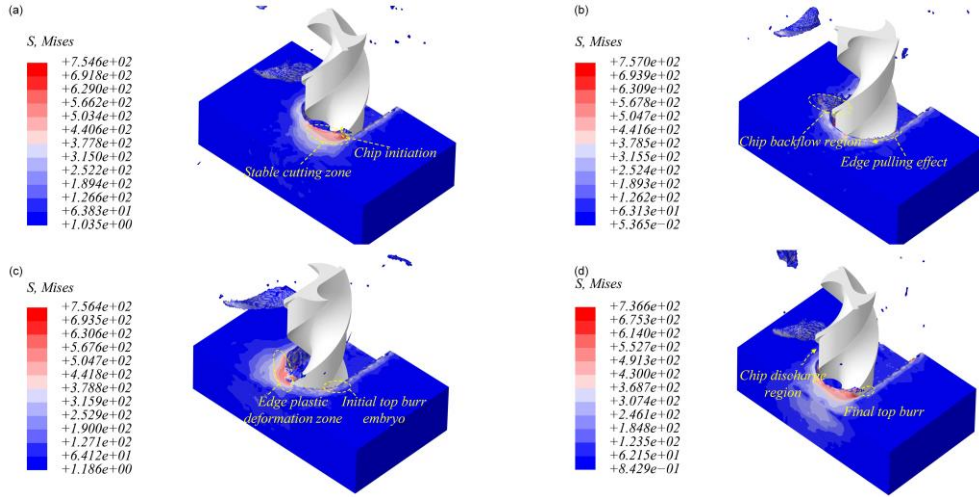


Fig. 8. Simulation cloud maps of four-stage dynamic formation process of top burr in micro-milling under A1 group

Exit burrs form at the stage when the tool is about to exit the workpiece. They are induced by the extrusion of thin residual uncut edge material from the cutting edge, as well as the plastic instability, folding and tearing of the material after losing support from the workpiece matrix. The formation process directly reflects the material instability behavior in the tool exiting stage.

As shown in Fig. 9(a), it corresponds to the stage of thin residual uncut material. When the tool approaches the workpiece exit edge, the thickness of the remaining uncut material decreases remarkably and forms a thin uncut layer. Mises stress concentration occurs at the tool-workpiece contact region with a maximum stress of approximately 760 MPa, and the material generates an initial plastic response, which lays a foundation for subsequent unstable deformation; as shown in Fig. 9(b), it is the plastic deformation stage. The cutting edge continuously squeezes the thin uncut material, the stress concentration zone expands toward the edge, obvious plastic flow and deformation take place in the material, the stress gradient of the edge region increases, and the unsupported material begins to deflect outward; as shown in Fig. 9(c), it refers to the burr nucleation stage. With the continuous accumulation of plastic deformation, local instability occurs in the edge material under stress to form initial burr nuclei, and tiny protrusions appear on the edge, marking the initiation of exit burrs; as shown in Fig. 9(d), it is the burr growth stage. With the continuous feed of the tool, the burr nuclei grow continuously under the extrusion of the cutting edge and the plastic flow of material, the height and thickness of the burr increase gradually, and the deformation range of the edge expands further; as shown in Fig. 9(e), it represents the burr extension stage. When the tool is about to completely cut out of the workpiece, the burr extends outward greatly under the action of residual stress and edge pulling, presenting obvious folding characteristics, and the plastic deformation area at the edge is further enlarged; as shown in Fig. 9(f), it is the final burr formation stage. After the tool completely exits the workpiece, the morphology of the exit burr becomes stable, ultimately forming a low and thin exit burr with relatively regular edges on both the up-milling and down-milling sides, without obvious tearing or curling.

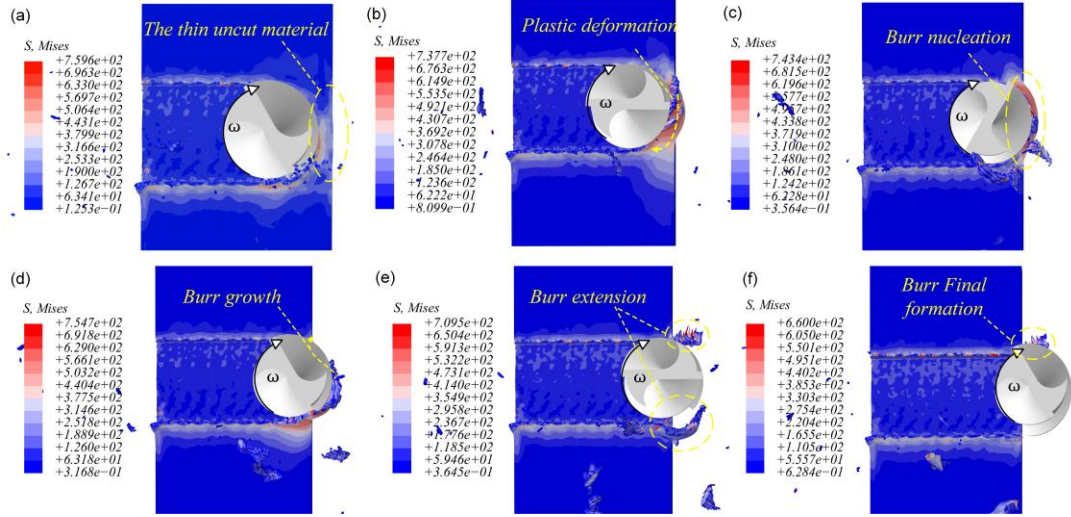


Fig. 9. Simulation cloud maps of six-stage dynamic formation process of exit burr in micro-milling under A1 group

The core mechanical mechanism of burr formation for Group C2 and Group D3 is consistent with that of Group A1, both following the evolutionary path of ‘tool extrusion → material plastic flow → edge instability accumulation’. Nevertheless, affected by cutting parameters, especially cutting depth, remarkable differences exist in stress distribution, severity of material deformation and burr morphological characteristics under different working conditions.

Fig. 10 shows the formation of entry, top and exit burrs for Group C2 ($a_p=1.0$ mm, $v_f=140$ mm/min, $n=20000$ rpm). At the entry burr stage (Fig. 10(a)), compared with Group A1’s local weak stress concentration under small cutting depth, Group C2’s $a_p=1.0$ mm significantly widens the Mises stress concentration area during tool cutting-in. The maximum stress is similar to Group A1, but its influence range is about 3 times larger, leading to stronger upward material extrusion and a thicker plastic accumulation layer at the entry edge, reflecting cutting depth’s amplification effect on entry burr deformation.

At the top burr stage (Fig. 10(b)), Group A1’s low load causes weak chip backflow and only thin, small laterally extended burrs. Group C2’s increased v_f raises cutting load, strengthens chip backflow and plastic pulling on the cutting edge, resulting in more sufficient lateral material flow and larger top burr height and thickness, showing feed rate’s strengthening effect on top burr extension.

At the exit burr stage (Fig. 10(c)), Group A1’s low load leads to slight material instability and low, gentle exit burrs. Group C2’s combined increase in a_p and v_f enhances material plastic flow, increasing instability amplitude and folding angle of unsupported edges, which raises exit burr height and root plastic deformation, with more prominent stress concentration and folding on the down-milling side, demonstrating cutting parameters’ synergistic strengthening effect on exit burr generation.

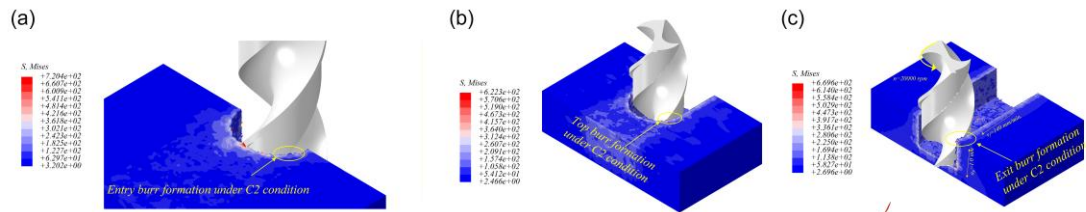


Fig. 10. Mises stress simulation cloud maps of three types of burr formation states in micro-milling under C2 condition

Fig. 11 shows the formation states of entry, top, and exit burrs in Group D3 ($a_p=1.4$ mm, $v_f=180$ mm/min, $n=12000$ rpm). However, the larger cutting depth and feed rate lead to essential differences in stress distribution, material deformation intensity, and burr morphology.

At the entry burr formation stage (Fig. 11(a)), compared with the local weak extrusion deformation under the small cutting depth of Group A1, the large cutting depth of Group D3 significantly increases the volume of material involved in deformation during tool cutting-in. The Mises stress concentration area covers the entire entry edge, the range of the extrusion effect of the cutting edge on the material is greatly expanded, the upward extrusion amplitude of the material is enhanced, a thicker plastic accumulation layer is formed at the entry edge, and slight plastic tearing characteristics are accompanied at the root. This reflects the amplification effect of cutting depth on the forming scale of entry burrs by expanding the deformation volume.

At the top burr formation stage (Fig. 11(b)), the chip backflow of Group A1 is weak under low load, only generating thin and small laterally extended burrs; the coupling effect of high feed rate and large cutting depth in Group D3 increases the resistance during chip evacuation, further enhances the pulling effect of chip backflow on the workpiece edge, causes significant lateral accumulation and curling of edge material, significantly increases the thickness of top burrs, reduces edge regularity and causes local plastic fracture traces. This reveals that the feed rate, as a core regulatory factor, plays a key strengthening role in the extension and accumulation characteristics of top burrs.

At the exit burr formation stage (Fig. 11(c)), the material exit instability of Group A1 is weak under low load, only forming low and gentle exit burrs; the large cutting depth of Group D3 increases the residual stress accumulation and material work hardening degree in the cutting area. Combined with the strong plastic flow trend brought by high feed rate, the workpiece edge undergoes severe instability and significant folding at the moment of cutting out, accompanied by obvious plastic tearing. The size of exit burrs increases significantly, and severe plastic accumulation and fracture characteristics appear at the root. This reveals that the synergistic effect of cutting depth and feed rate can jointly drive the significant growth of exit burrs by strengthening material deformation, residual stress accumulation and edge instability behavior.

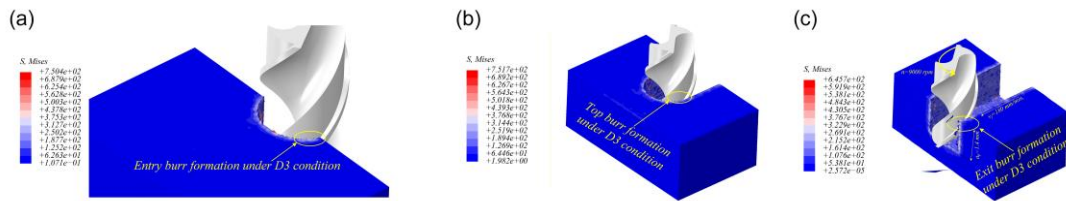


Fig. 11. Mises stress simulation cloud maps of three types of burr formation states in micro-milling under D3 condition

3.3 Relationship between Cutting Parameters and Burrs

Fig. 12(a) and Table 9 illustrate the variation trends of peak-to-peak (PV) values of F_x and F_y as well as the burr thickness on up-milling and down-milling sides under 16 orthogonal cutting conditions. The X-axis represents four cutting groups A–D with gradually increased cutting depth a_p and four working conditions in each group. The left Y-axis denotes the PV magnitudes of F_x and F_y in N, and the right Y-axis stands for the burr thickness of up-milling and down-milling sides in μm .

The figure can intuitively reflect the comprehensive correlation among cutting parameters, F_x/F_y PV forces and burr thickness on both milling sides.

From the overall variation trend, the fluctuation of F_x and F_y peak-to-peak (PV) forces shows a significant synergistic tendency with the changes in burr thickness on the up-milling and down-milling sides. Under most cutting conditions, higher F_x or F_y PV forces correspond to an overall increase in burr thickness on both sides. At peak force conditions such as A3 ($F_x=23.06$ N, $F_y=20.62$ N), B4 ($F_x=32.66$ N, $F_y=16.68$ N) and C3 ($F_x=26.43$ N, $F_y=22.55$ N), the up-milling burr thickness reaches $41.4\text{ }\mu\text{m}$, $44.6\text{ }\mu\text{m}$ and $77.5\text{ }\mu\text{m}$, while the down-milling burr thickness is $50.7\text{ }\mu\text{m}$, $54.5\text{ }\mu\text{m}$ and $95.0\text{ }\mu\text{m}$ respectively, all ranking the maximum within each group. Compared with the low-force condition in the same group (A4: $F_x=16.29$ N, $F_y=16.45$ N), the up-milling and down-milling burr thickness of A3 increases by approximately 250.8% and 249.7% respectively, which verifies the driving effect of milling force fluctuation on burr formation.

Meanwhile, the burr thickness on the down-milling side is generally larger than that on the up-milling side under all conditions. On average, the down-milling burr thickness is about 22% higher, with a maximum difference of 25.1% in Group A3. This indicates a remarkable influence of cutting direction on burr formation. During down-milling, the cutting edge extrudes materials upward to induce sufficient plastic flow, making it easier to form prominent top burrs. In contrast, up-milling presses materials toward the machined surface and restricts plastic deformation, resulting in weaker burr generation.

Within the same cutting group (e.g., A1–A4 in Group A, B1–B4 in Group B), the burr thickness at peak F_x/F_y PV conditions (A3, B4) increases by more than 190% compared with low-force conditions in the same group. For instance, the up-milling and down-milling burr thickness of B4 rises by 195.4% and 194.6% relative to B3, which quantitatively confirms the driving role of milling force fluctuation in burr formation.

Table 9 Data of burr and force under test.

group	Burr Thickness on Down-milling	Burr Thickness on Up-milling	P-V	P-V
	Side(μm)	Side(μm)	$F_x(\text{N})$	$F_y(\text{N})$
A1	10.5	12.6	18.71513	17.65095
A2	20	24.5	19.94697	13.79459
A3	41.4	50.7	23.0584	20.62444
A4	11.8	14.5	16.2887	16.4514
B1	37.2	45.4	18.34847	14.60811
B2	13	15.7	29.9892	20.20508
B3	15.1	18.5	19.18576	17.4969
B4	44.6	54.5	32.65884	16.68058
C1	16.6	20.2	21.34927	18.37199
C2	17.9	22	16.89458	17.42706
C3	77.5	95	26.42643	22.55295
C4	56	68.4	29.93319	15.5305
D1	26.4	32.2	22.25801	17.18774
D2	18	21.8	28.1353	14.69613
D3	96.9	118.3	18.82978	18.98322
D4	70.3	86.3	30.78549	20.46292

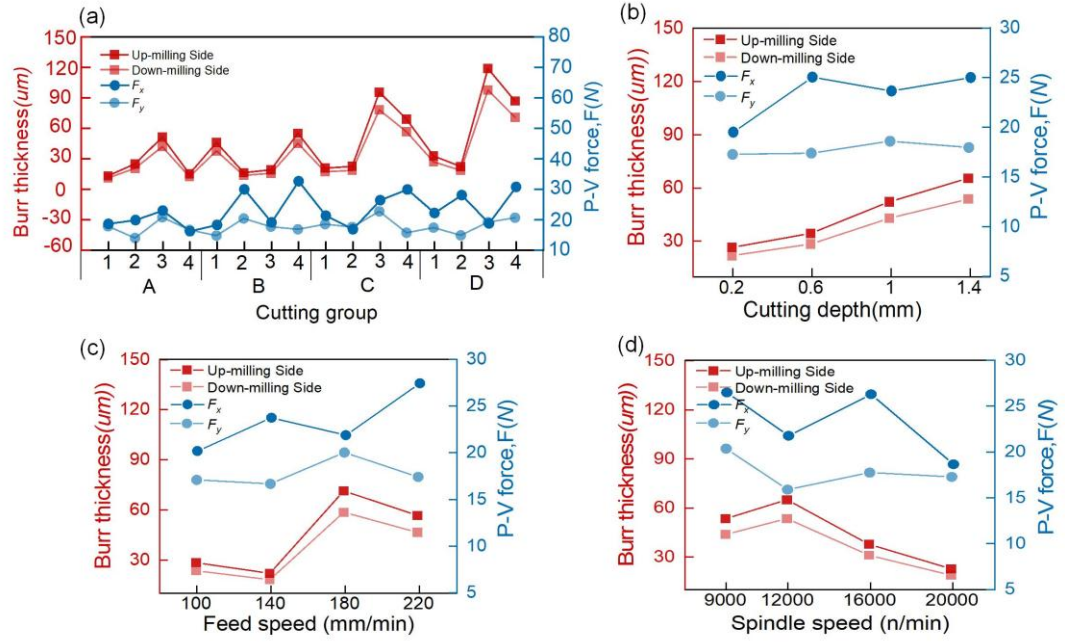


Fig. 12. Variation Laws of P-V Force and Up-/Down-milling Side Burr Thicknesses under Different Cutting Groups

Dependent Variable	Factor	df	MS	F	P-value	Significance
Down-milling burr	a_p	3	828.56	4.6	0.054	Marginally significant
	v_f	3	1460.69	8.1	0.016	Significant
	n	3	913.33	5.07	0.044	significant
Up-milling burr	a_p	3	1240.28	4.56	0.054	Marginally significant
	v_f	3	2198.5	8.08	0.016	significant
	n	3	1361.44	5.01	0.045	significant
F_x	a_p	3	27.32	1.94	0.224	N.S.
	v_f	3	38.64	2.75	0.135	N.S.
	n	3	57.37	4.08	0.068	Marginally significant
F_y	a_p	3	1.52	0.61	0.632	N.S.
	v_f	3	9.33	3.76	0.079	Marginally significant
	n	3	14.06	5.66	0.035	significant

From the mean analysis results, cutting depth a_p , feed rate v_f and spindle speed n exert differentiated influences on the burr thickness at up-milling and down-milling sides, as well as the peak-to-peak milling forces. As shown in Fig. 12(b), when the cutting depth a_p increases from 0.2 mm to 1.4 mm, the up-milling side burr thickness rises from 20.93 μm to 52.90 μm , and the down-

milling side burr thickness increases from $25.58 \mu\text{m}$ to $64.65 \mu\text{m}$, presenting a monotonically increasing trend on both sides. The ANOVA results in Table 10 show that a_p has a marginally significant effect on the burr thickness of both sides ($P=0.054$). As shown in Fig. 12(c), when the feed rate v_f increases from 100 mm/min to 220 mm/min , the up-milling side burr thickness reaches a peak of $57.73 \mu\text{m}$ at 180 mm/min , and the down-milling side burr thickness synchronously peaks at $70.63 \mu\text{m}$. The feed rate v_f has a significant effect on the burr thickness of both sides ($P<0.05$). As shown in Fig. 12(d), as the spindle speed n increases from 9000 rpm to 20000 rpm , the up-milling side burr thickness decreases from $42.83 \mu\text{m}$ to $17.80 \mu\text{m}$, and the down-milling side burr thickness drops from $52.40 \mu\text{m}$ to $21.80 \mu\text{m}$, showing a monotonically decreasing trend on both sides. The spindle speed n also exerts a significant effect on bilateral burr thickness ($P<0.05$).

In terms of milling force, cutting depth a_p has no significant influence on the peak-to-peak values of F_x and F_y ($P>0.05$) with small numerical fluctuation amplitude. The feed rate v_f only has a marginally significant effect on F_y ($P=0.079$) and no significant effect on F_x . The spindle speed n shows a significant effect on F_y ($P<0.05$) and a marginally significant effect on F_x ($P=0.068$). Overall, spindle speed exhibits a better regulating effect on milling force than cutting depth and feed rate.

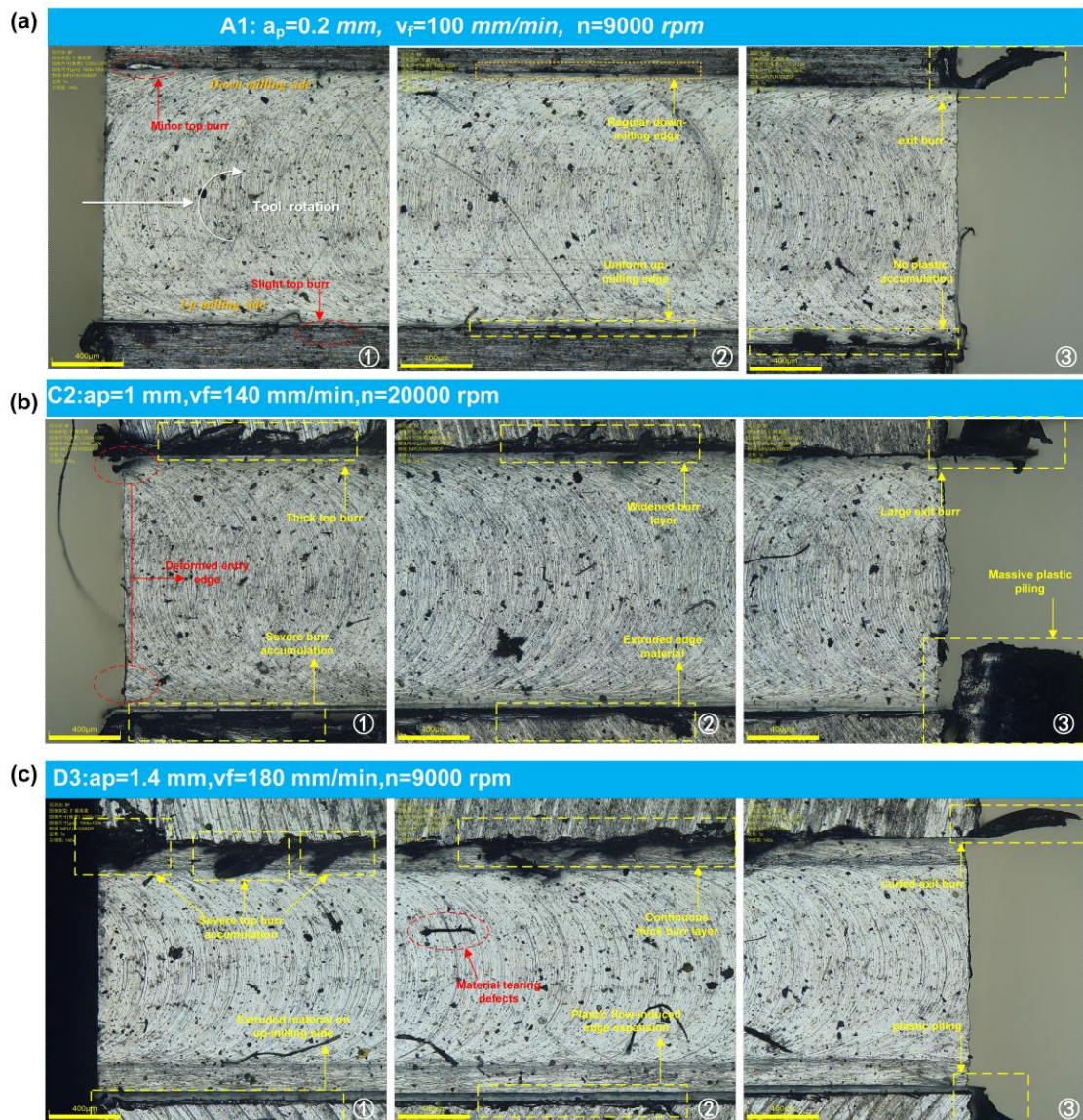


Fig. 13. Micro-morphologies of burrs on down-milling and up-milling sides under typical micro-

milling conditions

To further reveal the mechanistic differences in burr formation under various cutting conditions, three representative groups, namely A1 (low parameters with minor burrs), C2 (moderate parameters with severe burrs), and D3 (large cutting depth with extreme burrs), were selected to observe and analyze the micro-morphology of cutting edges, as presented in Fig. 11.

Fig. 13(a) corresponds to Group A1 ($a_p=0.2$ mm, $v_f=100$ mm/min, $n=9000$ rpm). With a combination of low cutting parameters, this condition yields a low cutting load. The peak-to-peak values of F_x and F_y are 18.72 N and 17.65 N, respectively. The corresponding burr thickness is 10.5 μm on the up-milling side and 12.6 μm on the down-milling side, both the minimum values among all tested conditions. Microscopic observations show only tiny top burrs are formed on both sides with small size and regular edges, without obvious plastic accumulation or tearing. Under the combined effect of small cutting depth and low feed rate, the material deformation and plastic flow in the cutting zone are slight, chips are discharged smoothly, and the residual stress at the edge remains low, which effectively restrains burr formation.

Fig. 13(b) shows Group C2 ($a_p=1.0$ mm, $v_f=140$ mm/min, $n=20000$ rpm). Characterized by high feed rate and low spindle speed, this condition produces a remarkably increased cutting load. The peak-to-peak values of F_x and F_y reach 26.43 N and 22.55 N, rising by 41.2% and 27.8% compared with Group A1. Accordingly, the burr thickness is 77.5 μm on the up-milling side and 95.0 μm on the down-milling side, an increase of 638.1% and 653.9% relative to Group A1. Microscopically, the down-milling side presents larger burrs with thicker roots and obvious traces of material plastic flow, while the up-milling burrs remain relatively regular but increase greatly in thickness. The results are consistent with the ANOVA conclusion that feed rate and spindle speed exert significant effects on burr thickness. A high feed rate increases the uncut chip thickness, while a low spindle speed prolongs the material deformation time. Their combined action aggravates plastic accumulation at the edge and eventually forms large and thick burrs.

Fig. 13(c) depicts Group D3 ($a_p=1.4$ mm, $v_f=180$ mm/min, $n=12000$ rpm) with the maximum cutting depth in the experiment. The peak-to-peak values of F_x and F_y are 18.83 N and 18.98 N, which are basically equivalent to those of Group A1. Nevertheless, the burr thickness reaches 96.9 μm on the up-milling side and 118.3 μm on the down-milling side, increasing by 823.8% and 838.9% to the peak values of all conditions. Microscopic morphology shows oversized burrs form at the cutting edge with obvious curling and local fracture, and the deformation on the down-milling side is more drastic. Combined with statistical analysis, axial cutting depth has a marginally significant effect on burr thickness. By greatly expanding the material deformation volume and intensifying work hardening and residual stress accumulation, it significantly amplifies plastic instability and edge accumulation even without obvious growth in milling force. Together with feed rate and spindle speed, cutting depth jointly determines the final burr morphology.

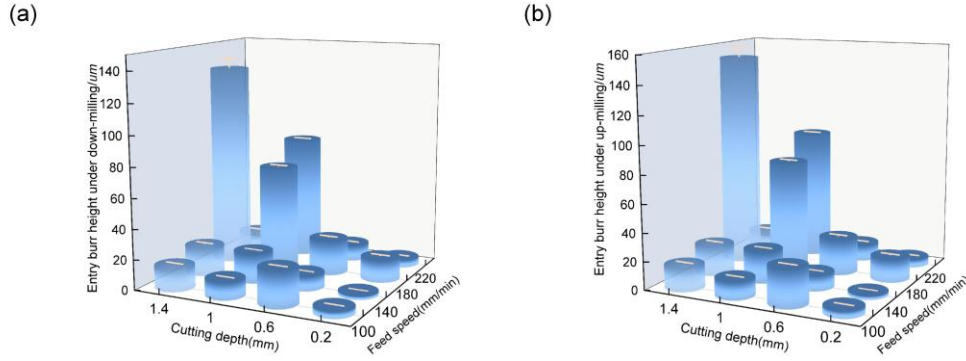


Fig. 14. Effects of cutting depth and feed rate on entry burr height in down-milling and up-milling

Fig. 14 presents the distribution characteristics of entry burr height under different cutting parameters in micro-milling, where Fig. 12(a) and (b) correspond to the quantitative measured results on the up-milling and down-milling sides, respectively. The entry burr height shows an obvious response to cutting parameters, and the burr dimension on the down-milling side is generally larger than that on the up-milling side. Its evolutionary law is highly consistent with the plastic deformation induced by material extrusion during tool cutting-in.

In terms of the quantitative characteristics of entry burr height on the up-milling side (Fig. 14(a)), the burr size fluctuates in the range of 2.2–134 μm , with the minimum value under condition A2 and the peak value under condition D3. Feed rate exerts the most prominent regulatory effect on burr size. At the feed rate of 180 mm/min, the entry burr height increases significantly under all cutting depths, with an increment of 20%–85% compared with low-feed conditions in the same group. The increase of spindle speed inhibits burr growth; under high spindle speed, the extrusion and accumulation effect of materials during cutting-in is weakened, leading to an obvious reduction in burr size. The increase of cutting depth only broadens the material deformation range and has no decisive driving effect on burr height, merely playing an auxiliary role in enlarging the overall deformation scale.

The variation trend of entry burr height on the down-milling side (Fig. 14(b)) is completely consistent with that on the up-milling side. Under the same parameters, the burr size on the down-milling side is 8%–13% higher. Its minimum value is 2.49 μm (Condition A2) and the maximum reaches 151 μm (Condition D3), which is the peak across all parameter ranges. The contact form of the cutting edge during down-milling cutting-in is more likely to induce local stress concentration and further aggravate the plastic accumulation of edge materials, which is the fundamental reason for its larger burr size. Feed rate and spindle speed remain the key factors regulating burr size, while cutting depth only imposes a limited auxiliary influence by changing the volume of deformed materials.

Combining the quantitative results of both up-milling and down-milling sides, feed rate and spindle speed are the dominant process parameters controlling entry burr height. They directly determine the nucleation and growth scale of burrs by changing the cutting-in rate, strain rate and stress distribution. Cutting depth only assists in expanding the deformation volume with relatively limited influence. Affected by the mechanical characteristics of cutting direction, the plastic deformation and material accumulation of entry burrs on the down-milling side are more severe, resulting in consistently larger dimensions than those on the up-milling side under identical parameters.

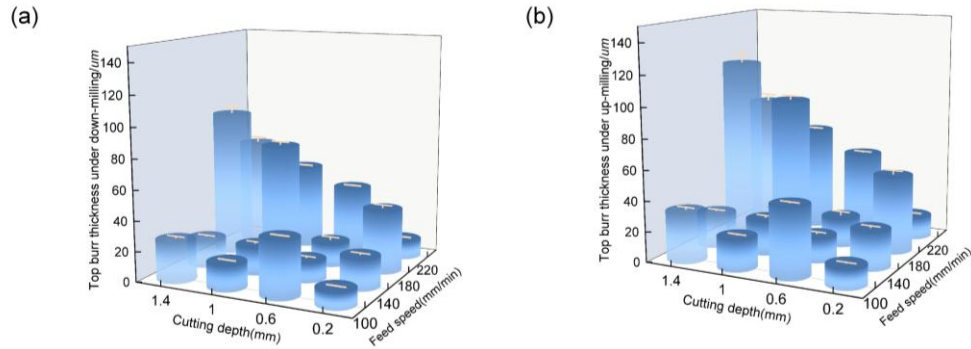


Fig. 15. Effects of cutting depth and feed rate on top burr thickness in down-milling and up-milling

Fig. 15 illustrates the quantitative distribution of top burr thickness in micro-milling under different cutting parameters, where Fig. 15(a) and (b) present the column characterization results for the up-milling and down-milling sides, respectively. Top burrs are formed by the lateral flow of chips and plastic interaction at the workpiece edge during stable cutting. Their parametric response trend is similar to that of entry burrs but follows an independent formation mechanism. Meanwhile, the top burr thickness on the down-milling side is always greater than that on the up-milling side, which is consistent with the plastic extension characteristics of materials in the stable cutting stage.

In terms of the top burr thickness on the up-milling side (Fig. 15(a)), the burr size fluctuates within the range of 10.5–96.9 μm , with the minimum value obtained under condition A1 and the peak value under condition D3, representing an overall increase of more than 8 times. Feed rate plays the most dominant role in regulating burr thickness. In the medium feed range, chip flow is hindered with sufficient lateral extension, leading to a sharp rise in burr thickness. At an ultra-high feed rate, material removal efficiency is improved and the contact duration between chips and the cutting edge is shortened, resulting in a slight drop in burr thickness. Increasing cutting depth expands the deformation volume of the cutting layer and exerts an auxiliary amplification effect on burr size, rather than acting as the leading driving factor.

The variation trend of top burr thickness on the down-milling side (Fig. 15(b)) is consistent with that on the up-milling side. Under identical parameters, the burr thickness is 10%–15% higher, reaching a peak of 118.3 μm under condition D3, the maximum among all parameter groups. The cutting edge contact mode in down-milling is more prone to inducing local stress concentration and intensifying the dragging effect of chip backflow on the edge, which triggers more severe plastic deformation and fundamentally accounts for its larger burr dimension. Feed rate dominates burr growth by altering chip motion state, while cutting depth only produces a limited auxiliary effect on the deformation scale.

Comprehensive analysis of data from both sides indicates that feed rate is the core process parameter for controlling top burr thickness, and spindle speed also has a significant regulatory effect. Together, they determine the degree of chip backflow and edge plastic accumulation. Cutting depth only imposes a marginal auxiliary influence by enlarging the deformation volume. Formed relying on the lateral extension of chips, top burrs differ distinctly from entry burrs governed by cutting-in extrusion. Both types of burrs jointly reflect the differentiated regulation law of cutting parameters on burr evolution.

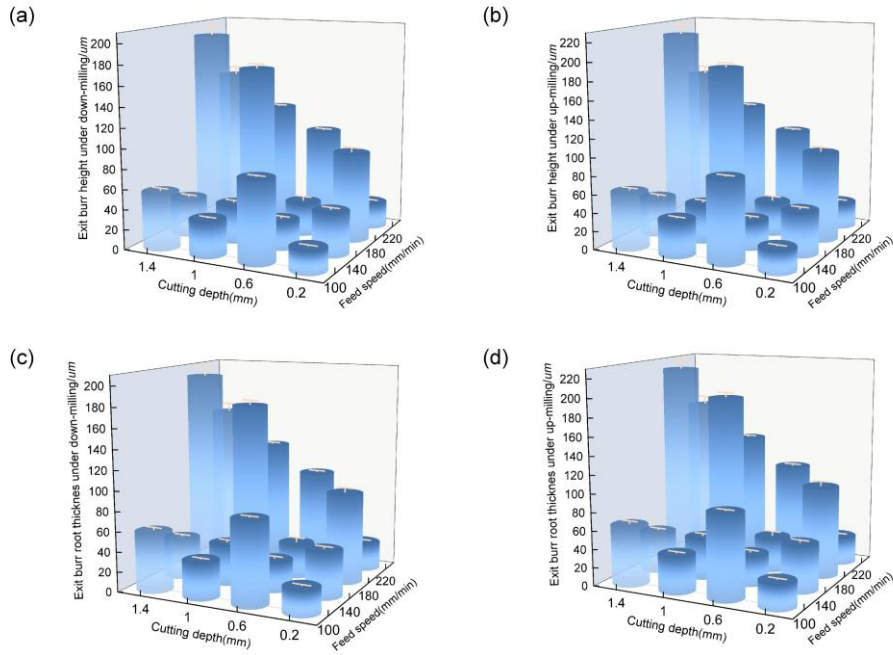


Fig. 16. Effects of cutting depth and feed rate on exit burr height and root thickness in down-milling and up-milling

Fig. 16 demonstrates the size evolution of exit burrs via four subgraphs. Among them, Fig. 16(a) and (b) display the exit burr height on the up-milling and down-milling sides, while Fig. 16(c) and (d) correspond to the root thickness, which intuitively reflects the regulating effect of cutting parameters on burr formation in the unconstrained region at the cutting exit. As the burr type with the most remarkable deformation features in micro-milling, exit burrs on the down-milling side are always larger than those on the up-milling side, which is consistent with the formation mechanism of free material instability and plastic accumulation at the tool exiting stage.

The exit burr height shows an evident gradient change with cutting parameters. The up-milling burr height increases from $22.1 \mu\text{m}$ to $198 \mu\text{m}$, and the down-milling height rises from $24.3 \mu\text{m}$ to $218 \mu\text{m}$. Feed rate plays a dominant role in regulating burr height. In the medium feed range, the unstable bulging of edge material is aggravated, leading to a substantial rise in burr height. At a high feed rate, the tool cuts out rapidly and shortens the stress acting time of the edge, alleviating the excessive growth of burrs. Increasing cutting depth merely expands the volume of deformed material and produces an auxiliary amplification effect on burr height instead of acting as the core driving factor. The interaction between the cutting edge and workpiece edge is more intense on the down-milling side, resulting in greater burr height than the up-milling side under identical parameters, and the dimensional difference expands slightly as the cutting parameters increase.

The variation trend of exit burr root thickness is consistent with that of burr height and presents higher sensitivity to parameter changes. The root thickness increases from $24.5 \mu\text{m}$ to $200 \mu\text{m}$ on the up-milling side and from $27 \mu\text{m}$ to $220 \mu\text{m}$ on the down-milling side. Under all working conditions, the root thickness is slightly larger than the burr height in the same group, which reflects the severe plastic accumulation feature at the root of the cutting exit. The regulating rule of feed rate on root thickness is similar to that on burr height, with an obvious promoting effect only in the medium feed range. The root thickness on the down-milling side is also higher than that on the up-milling side, and the discrepancy becomes more prominent under high-parameter conditions.

Combining the data of two evaluation indicators and two cutting directions, feed rate and spindle speed are the core parameters governing exit burrs, which dominate the growth degree of burrs through cutting dynamic behaviors. Cutting depth only exerts a marginal auxiliary effect by changing the deformation volume of materials. Without matrix support at the exit end, exit burrs are considerably more sensitive to process parameters than entry and top burrs. The coordinated variation of their height and root thickness fully reveals the unique evolution law of unconstrained instability-type burrs.

Conclusion

6061-T6 aluminum alloy is a key structural material for micro-milling and precision milling of components in 3C electronics, aerospace precision parts, micro molds, and precision mechanical parts. However, machining within the wide cutting depth range of 0.2~1.4 mm easily induces burr defects at entry, top and exit positions, which seriously restrict the machining accuracy, surface integrity and service performance of parts. Aiming at the key problems of unclear dynamic evolution mechanism of burrs and undefined coupling relationship among process parameters, milling forces and burr characteristics within this scale range, this study takes 6061-T6 aluminum alloy under wide-depth micro-precision milling as the research object. By combining thermo-mechanical coupling finite element modeling with the $L_{16}(4^3)$ orthogonal test, the simulation and experimental verification of milling forces are completed. The dynamic formation mechanisms of three types of burrs are systematically revealed, and the coupling influences of axial cutting depth, feed rate and spindle speed on milling forces and burr morphology are clarified. The main conclusions are summarized as follows:

(1) The established micro-precision milling thermo-mechanical coupling finite element model based on the Johnson-Cook constitutive and damage model as well as the Hillerborg fracture energy model can accurately reproduce the plastic deformation and chip separation process of materials under high strain rate. The relative errors of peak-to-peak values of simulated and experimental F_x and F_y are all within 9%, and the periodic variation trends of forces with tool rotation are highly consistent. The model possesses reliable engineering simulation accuracy and can support the quantitative analysis of burr formation mechanism.

(2) Three types of burrs of 6061-T6 aluminum alloy under micro-precision milling present differentiated dynamic formation mechanisms. Entry burrs are generated by material extrusion and accumulation during tool cutting-in with concentrated deformation and small scale; top burrs originate from plastic pulling of the edge induced by chip backflow in the stable cutting stage, featuring lateral extension as the core characteristic; exit burrs form due to plastic instability, folding and tearing of edge materials losing matrix support at the cutting exit, which exhibit the most prominent size and deformation degree. Under all working conditions, the burr size on the down-milling side is larger than that on the up-milling side, with an average increase of approximately 22%.

(3) Process parameters exert significantly different effects on burr formation. Feed rate (v_f) and spindle speed (n) have significant influences on burr thickness of both up-milling and down-milling sides. The burr size reaches the peak at a feed rate of 180 mm/min, and increasing spindle speed can effectively inhibit burr growth. Axial cutting depth (a_p) presents a marginally significant effect on burr size; the burr scale increases monotonically with the rise of cutting depth, which amplifies the burr formation effect by expanding the volume of deformed material.

(4) There is a strong coupling correlation between milling forces and burr formation. The peak-

to-peak values of F_x and F_y are significantly positively correlated with burr thickness, and the burr size reaches the maximum value in each group under peak milling force conditions. Spindle speed shows a better regulation effect on milling forces than cutting depth and feed rate, serving as the core process parameter for synergistically optimizing cutting load and suppressing burr defects.

Statement of originality

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CRedit authorship contribution statement

Chunjin Li: Writing – original draft, Validation, Formal analysis, Conceptualization. Yuhang Liu: Writing – review & editing, Methodology, Formal analysis. Bo Deng: Visualization, Supervision, Formal analysis. Cong Zhao: Formal analysis, Data curation, Resources. Liping Wang: Supervision, Resources. Chao Kang: Visualization, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This work was supported by Project number: Aeronautical Science Foundation of China (No: 2023Z045012001) ;ChongqingMunicipal Education Commission of Science and Technology Research Project (No:KJQN202402614);

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