Influence of Coolant on Chip Forming in Gun-Drill Based on Fluid-Solid Coupling Method

LI Liang[1,2*], *XUE Hu*[1,3], *SHAN Yicai*[4], *YANG Yinfei*[2], *HE Ning*[2]

1. College of Mechanical Engineering, Yancheng Institute of Technology, Yancheng 224051, P. R. China;
2. College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China;
3. College of Mechanical and Electrical Engineering, Jiangsu University, Zhenjiang 212013, P. R. China;
4.College of Mechanical and Electrical Engineering, Nanjing College of Information Technology, Nanjing 210046, P.R. China

(Received 10 March 2020; revised 12 May 2020; accepted 20 May 2020)

Abstract: Chip shape is one of the important factors that affect the processing quality of the deep hole. The flow field of 17 mm standard gun-drill is simulated by taking the coolant pressure as a single factor variable, and the influence of coolant pressure on chip forming is discussed by combining with experiments in this paper. The results show that at the initial stage of chip forming, the flow of cutting fluid will intensify the lateral crimp of chips, and then affect the crimp radius of the chip and the number of turns of the crimp screw. The lateral crimp degree increases first and then decreases with the increase of coolant pressure, and the crimp degree is the smallest at 3 MPa. In addition, during the chip removal process, the stream shrinking in the flow field is the main influencing factor that drive and force the chip to break again, and their influence on the chip removal and chip breaking is proportional to the coolant pressure.

Key words: gun drill; chip deformation; Ti6Al4V titanium alloy; fluid-solid coupling

CLC number: TG713; TH161 **Document code:** A **Article ID:** 1005-1120(2020)03-0434-12

0 Introduction

Ti6Al4V is a $(\alpha+\beta)$ type of titanium alloy with excellent comprehensive properties, which is a typical difficult-to-process material with high specific strength, low density and good corrosion resistance[1]. It is widely used in aerospace, health care, petrochemical and other fields[2]. At present, domestic and foreign scholars mainly focus on turning and milling of titanium alloy, while there are relatively few studies on drilling, especially deep hole drilling. However, in the machining field, deep hole processing accounts for about 1/8 of the total workload[3]. With the special needs of equipment manufacturing, the demand for drilling small-diameter deep holes in difficult-cut-to materials becomes increasingly prominent.

Deep hole machining has a typical closed or semi-closed cutting environment. During cutting, there are some problems such as blocked chips, extruded chips, cutting heat accumulation and torsional load increase caused by longer broken chips and poor chip removal. The deterioration of cutting performance will not only affect the machining quality of hole wall surface, but also distort the drill shaft and bit in serious cases[4]. The above problems are especially obvious in the drilling of small diameter deep hole with single lip gun-drill[5], because the overall structure of chip removal space is narrow and long, which is composed of V-channel and hole wall. To solve the problem of chip blocking in the deep hole, Ref.[6] analyzed the critical condition of chip blocking by establishing the mathematical model of chip force, and found that increasing the peak pressure of flow field can enhance the impact force

*Corresponding author, E-mail address: jzlliang@163.com.

How to cite this article: LI Liang, XUE Hu, SHAN Yicai, et al. Influence of coolant on chip forming in gun-drill based on fluid-solid coupling method[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(3): 434-445.

http://dx.doi.org/10.16356/j.1005-1120.2020.03.010

on chip, and then enhance the chip removal ability. Meanwhile, Ref.[7] determined that the coolant pressure in the V-channel was proportional to the inlet pressure based on the prediction model of flow rate and pressure. The establishment of the mathematical model is based on the assumption of model simplification, which cannot specifically describe the flow velocity behaviors and rheological property of the fluid during the chip movement. In addition, because the machining environment of gun drill is inaccessible, it is impossible to measure the flow and pressure distribution of cutting fluid. Therefore, some scholars use CFD simulation to study the factors affecting cutting quality. For example, Refs.[8-9] used CFD simulation to quantify the fluid rheological characteristics and chip transport behavior of high-pressure coolant, and determined the effects of the nose grind contour, coolant hole configuration and shoulder dub-off angle on the application efficiency of coolant and the service life of gun-drill. Ref.[10] found that the change of flow dead zone near the cutting edge of the drill has nothing to do with the flow rate of coolant. Combined with the test, it is found that the tool life and machining quality are significantly improved with the increase of inlet pressure.

These results enrich the research foundation of the drilling flow field, but the influence of coolant oil pressure on chip forming has not been analyzed in detail. Therefore, based on the study of chip spiral forming, this paper combined the fluid-solid simulation of coolant-chip and the inlet pressure test to carry out further research, in order to study the effect of the change of coolant pressure on chip forming. In addition, by reconstructing the flow path of coolant in the V-channel, the source of coolant that dominates chip movement and "secondary fracture" is determined, and the influence of coolant pressure change on it is analyzed. The relevant research results can provide some reference for the reasonable selection of coolant pressure in the deep hole gun-drilling, further improving the chip breaking and chip removal ability of gun-drill.

1 Analysis of Chip Forming Process

Gun-drill is a typical double-edged tool with a theoretical rake angle of 0°. According to the previous research, the chip forming process can be divided into four stages: lateral curling, spiral curling, chip forming, and root fracture.

(1) During the gun drilling process, the chips produced by the inner and outer edges will move along the direction perpendicular to the cutting edge on the front face, and generate shear slip at the junction of the chip and the edge, which causes the chips up-curl natually, as shown in Fig.1. Due to the different cutting speeds of the inner and outer edges, the lateral curl of the outer chip is larger, and it has a certain squeezing effect on the inner chip.

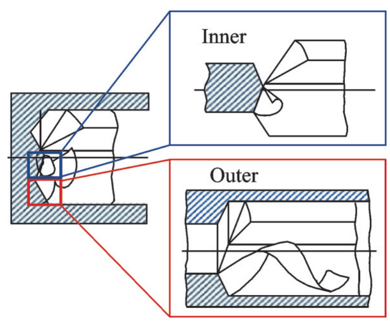


Fig.1 Chip forming process of inner and outer edges

(2) As the chip forms, it will touch point C_1 on the V-channel wall, and then it will curl up for the first time after receiving resistance from the wall. The second curl is caused by the contact between the chip and the hole wall, and C_2 is the contact point. r_c is the theoretical curling radius of a chip, which is related to the machined aperture and tool size, as shown in Fig.2.

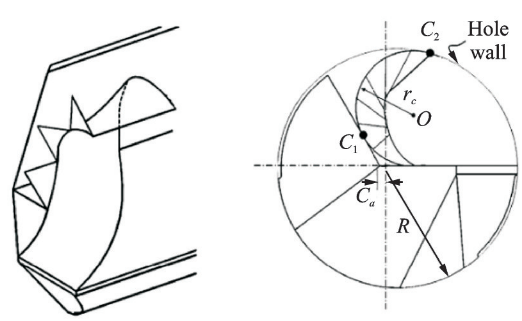


Fig.2 Sketch of up-curling of chip

(3) As the drilling process goes on, the chips continue to grow. When it reaches the rake face of gun-drill bit again, the first round of curling of the spiral chips is completed, and the chips can form multiple spiral curl cycles before it fractures.

(4) According to the existing research[7,10], the chip up-curl radius is r_{u1} in the initial stage of machining. Under the combined action of the normal force of the hole wall, V-channel and coolant pressure, the curling radius increases from r_{u1} to the critical value of fracture r_{u2}, as shown in Fig.3.

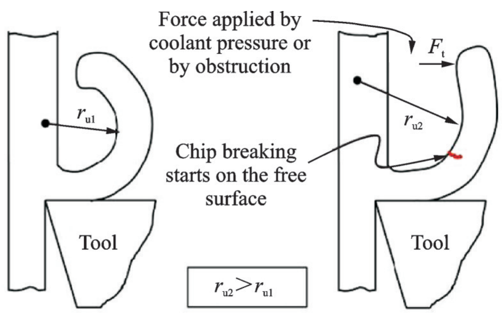


Fig.3 Increase in up-curl radius due to coolant pressure leading to chip breaking[3]

At this time, chip root will crack first. After that, with the cyclic crimping of chips, F_t will continue to increase until the ultimate tensile force F_b reached, and the crack will gradually expand until the complete fracture. Eq.(1) shows that the ultimate tensile force is mainly associated with the feed, cutting width and material characteristics.

$$F_b = \alpha \cdot s_1 \cdot f \tag{1}$$

where α is the tensile strength of chip, s_1 the cutting width, and f the feed.

During the process of chip forming, the spiral chip exerts normal forces at points C_1 and C_2 as F_{nc1} and F_{nc2} for each loop of the spiral chip due to elastic recovery inside the hole. In this paper, the chip force is simplified along the axial and radial directions of the gun drill, and the component force F_t is represented by F_Z and F_Y, as shown in Fig.4.

According to Eqs.(2)—(3), it is determined that the impact force of the cutting fluid is related to the factors such as the chip curl radius r_c, the spiral lead L, the number of turns n, the impact force of

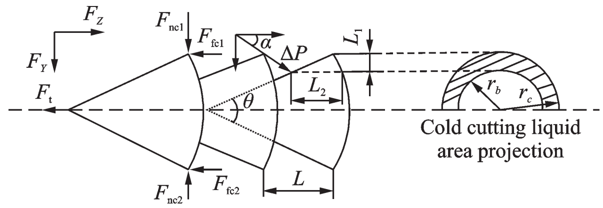


Fig.4 Impact force of coolant on spiral chip surface[6]

the fluid ΔP, the angle of the jet α, and the angle of the chip cross-section θ, among which the impact force ΔP is a controllable parameter for machining. Therefore, this paper chooses the inlet pressure as a variable to explore its influence on chip forming.

$$F_Z = \frac{\pi}{2} n \cdot \Delta P \cdot \cos\alpha \cdot L_1 [2r_c - L_1] \tag{2}$$

$$F_Y = n \cdot \Delta P \cdot \sin\alpha \cdot L_2 [2r_c - L_1] \tag{3}$$

$$L_1 = L\frac{\sin\alpha \sin\frac{\theta}{2}}{\sin\left(\alpha + \frac{\theta}{2}\right)},\ L_2 = L\frac{\sin\alpha \cos\frac{\theta}{2}}{\sin\left(\alpha + \frac{\theta}{2}\right)} \tag{4}$$

2 Experiment Design

2.1 Test setup

Through analyzing the spiral forming process and fracture mechanism of chip during the gun drill process, we find that the shape of chip is closely related to the material of the workpiece and the technological parameters. In order to analyze the influence of coolant inlet pressure on the morphology of Ti6Al4V titanium alloy chip, the following experiments are designed.

The drilling machine is NCS1600 CNC, as shown in Fig.5, with drilling depth up to 1 600 mm and rotating speed up to 6 000 r/min. SANDWIK standard single-edged gun drill is selected for the experiment, as shown in Fig.6. The material of drill

Fig.5 NCS1600 CNC deep-hole drilling machine

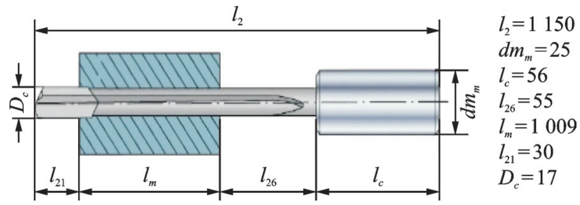


Fig.6 Φ17 mm standard gun drill

tip is cemented carbide-P20. Ti6Al4V titanium alloy is a typical difficulty processing materials, and its processing range is relatively narrow. Therefore, we design the following experimental parameters, as shown in Table 1[11].

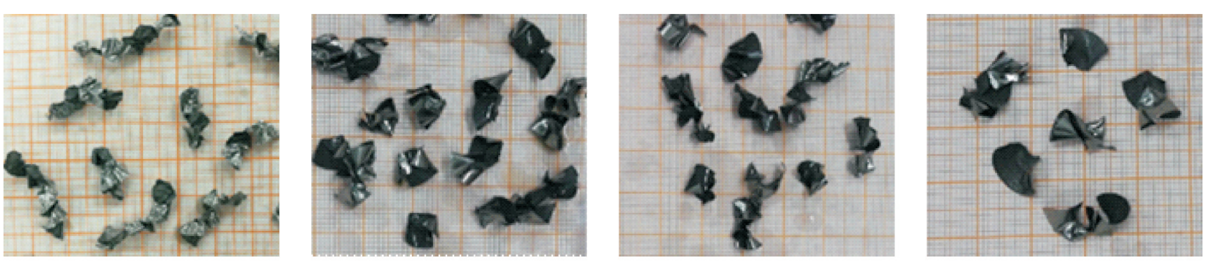
Table 1 Test parameters[11]

No.	Hole diameter/ mm	Hole depth/ mm	Cutting speed/ ($m \cdot min^{-1}$)	Feed rate/ ($mm \cdot r^{-1}$)	Coolant pressure/ MPa
1	17	80	30	0.03	1
2	17	80	30	0.03	2
3	17	80	30	0.03	3
4	17	80	30	0.03	4
5	17	80	30	0.03	5

2. 2 Analysis of test results

During the drilling process, the coolant not only plays the role of cooling lubrication, but also affects the chip breaking and chip movement. The coolant pressure has an important influence on the chip size and the machining quality. According to the traditional view, the greater the import pressure, the better the chip crushing effect and the better the processing quality, but there are some differences between the results and the conventional view. When the inlet pressure is 1 MPa, the chip will be blocked quickly, resulting in the processing cannot continue. When the pressure is 5 MPa, the chip length is the shortest, the increase of coolant pressure leads to the aggravation of chips separation between inner and outer edges, and the chip fragmentation is obvious. At the same time, the vibration of drill pipe increases and the stability decreases obviously. Therefore, we take the chip collected in the stable processing interval as the research object.

Fig.7 shows the chip morphology under different inlet pressure conditions. The comparison shows that the order of the chip curl radius is $r_{3MPa} > r_{4MPa} > r_{2MPa}$, and the length is inversely proportional to the curl radius. The crimp radius of the chip under 4 MPa oil pressure is slightly smaller than that under 3 MPa oil pressure, but the chip length is basically the same. In addition, with the increases of inlet pressure, the fluid impact and shear force on the chips increase, the tearing between chip units intensifies, and the proportion of short chips produced by the inner and outer edges separately gradually increases. Analysis from the chip morphology shows that the chip length of the Ti6Al4V decreases gradually with the increase of the pressure. When the coolant pressure is in the range of 2—4 MPa, the chip curl radius is first increased and then decreased.



(a) 2 MPa (b) 3 MPa (c) 4 MPa (d) 5 MPa

Fig.7 Effect of coolant pressure on chip morphology

3 Simulation Analysis

In order to analyze the influence of coolant on chip forming more clearly, the simulation analysis of flow field is carried out based on CFD in this paper. The model is designed referring to a real cemented carbide gun-drill used in processing. The steps of the simulation include generation of a CAD model, discretization of the CAD model, definition of boundary conditions and material properties.

3.1 CAD model

Based on the assumption that cutting fluid is an incompressible fluid and has no free surface, the geometry of gun drill and fluid are simplified as shown in Fig.8. This paper focuses on the chip forming and chip removal near the drill bit, and only the bit is selected to participate in the simulation.

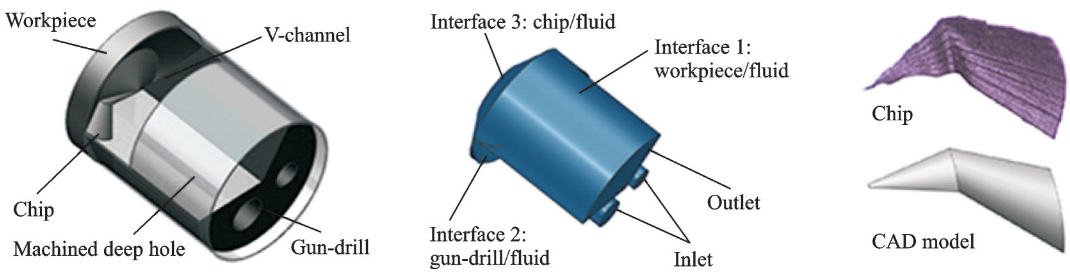


Fig.8 CAD model of gun-drill and cutting fluid

3.2 Selection of turbulence model

CFD methods can be used to calculate approximate solutions of physical quantities such as pressure and velocity of fluids[12]. ANSYS Fluent is built on the Navier-Stokes theory, which describes the properties of viscous flows. Theoretically the Navier-Stokes equations are capable to solve turbulent flows. Unfortunately, this would require extremely fine discretization levels so that the computation time would increase indefinitely[13]. Therefore, the modelling of turbulent flow problems is handled by the use of Reynolds-averaged Navier-Stokes equations (RANS) turbulence models. A basic requirement of a reliable turbulence model for industrial tasks, such as the coolant flow, is accurate and robust near-wall processing. Therefore, we choose the k-ω shear stress transport (SST) model to describe the turbulent motion in the near-wall region and the central region. In which, k is the turbulent kinetic energy, and ω the specific rate of dissipation of turbulent kinetic energy. The k-ω SST model is one of the most common turbulence models, which combines the advantageous near-wall behavior of the k-ω model with the more robust properties of the k-ω model at free flow regions (e.g. inlet and all regions far away from the walls)[14-19].

3.3 Meshing and setting of boundary conditions

The accuracy of the simulation analysis depends on the quality of the mesh. Due to the complicated structure of gun-drill bit, it is difficult to carry out accurate topology, so the tetrahedral mesh is used in the calculation models in this paper. In order to capture the flow and rheological properties of near-wall layer and the cutting edge accurately, the inflation layer mesh is divided on the wall and the local refinement of the flow field near the cutting edge is carried out, as shown in Fig.9. The boundary condition setting and machining parameter selection of CFD simulation are based on the practical parameters of drilling Ti6Al4V with gun-drill, as shown in Table 2.

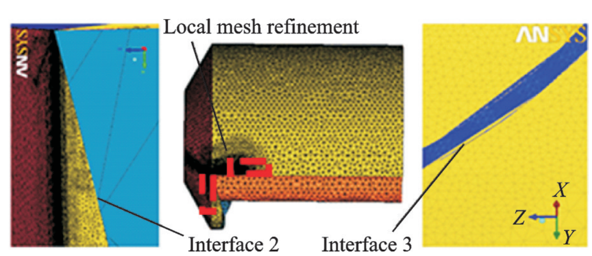


Fig.9 Meshing for fluid field

Table 2 Boundary condition settings

Boundary condition	Value
Time of transient: total time, time step/s	0.08, 0.005
Working temperature of water (measured) /K	298.15
Pressure of inlet: coolant supply (variable) /MPa	1,2,3,4,5,6
Pressure of outlet: opening-ambience	1 bar
Roughness of Interface 1: workpiece/fluid(measured)/mm	⩽0.01
Roughness of Interface 2: fluid/tool	Smooth conduit
Roughness of Interface 3: fluid/chip /mm	⩽0.01
Rotation speed of Interfaces 1 and 2 /(r•min^{-1})	12
Number of elements	3×10^6
Inflation-layer length/mm	0.005
Turbulence model type	k-ω SST

3.4 Analysis of simulation results

The cutting fluid flow in the deep hole during gun drilling belongs to a complex rotating turbulent jet in the finite space. As a typical semi-closed cutter with chip removal from the outside, the coolant hole of the gun-drill is not on the rotary axis. The first rotating jet will formed when the coolant is ejected from the hole. When the jet has pressure loss (mainly shock loss) in the bottom clearance, the high rotating turbulent jet will form again and enter the V-channel.

Under the action of shear stress and centrifugal force on the end face of the gun-drill, the coolant flows along the outer side of the end face after jetting out from Hole 1, then flows through the outer edge of Hole 2, and finally forms an inclined upward jet at the shoulder dub-off, as shown in Fig.10. The inclination of the jet entering V-channel is related to the flank angle of the shoulder dub-off. After impacting the chip, the jet will diverge at the "chip ridge", and a part flows down along the chip surface of the outer edge, forming a small diameter swirl. In the other part, a vortex with high turbulence intensity is formed near the inner chip, and gradually evolves into a large-diameter swirl after leaving the area. Hole 2 is located on the shoulder dub-off, which is far from the cutting layer. Therefore, compared with Hole 1, its jet boundary layer has a high degree of diffusion, so most of those jets enter the V-channel above the stream exiting from Hole 1. After entering the V-channel, the jet radius gradually shrinks and the flow velocity increases. The remaining coolant ejected from Hole 2 first collides with the cutting layer and then collides with the shoulder dub-off, changing the flow direction twice, finally enters the V-channel along the outer edge of the shoulder dub-off, and merges with the cutting fluid of Hole 1.

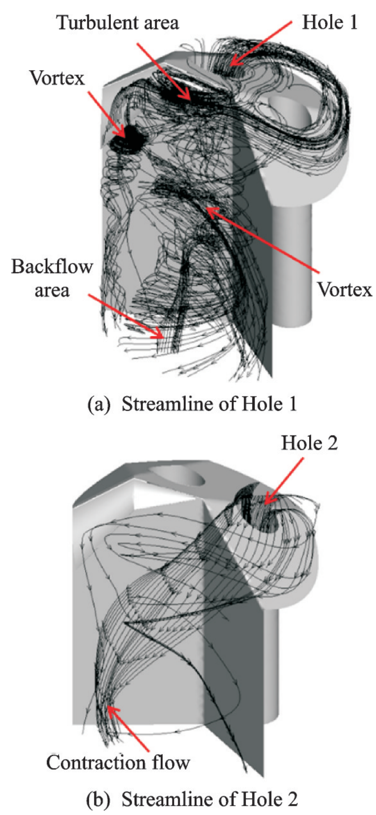


Fig.10 Streamline distribution maps in flow field

(1) Effect of inlet pressure on chip formation

Coolant mainly causes chip deformation and even fracture through the shear and impact effects.

Because the flow field on the gun-drill head is very complex[20-21] and the distribution on chip surface load is uneven, it is difficult to describe the impact of cutting fluid on chip forming intuitively and concretely. To analyze the influence of coolant pressure on chip formation, this paper uses the software Fluent and Static Structural to carry out a single fluid-solid coupling simulation analysis with the inlet pressure as the boundary condition.

According to the simulation results, in the early stage of chip forming, the chip appears "cantilever type" bending deformation under the action of coolant, as shown in Fig.11. The chip bends inwards and forwards, the peak value of curling deformation appearing at the outer edge of the chip, and the peak value of equivalent stress appearing at the root of the outer edge of the chip. The deformation of the chip decreases gradually from the outside to the inside along the radial direction, and the deformation at the drill point is minimal. The results show that the flow of coolant can enhance the lateral curling of chips. According to the analysis of the chip forming mechanism, the increase of lateral curling will change the position of contact point C_2 between chip and hole wall, making the curl degree inverse to the curl radius.

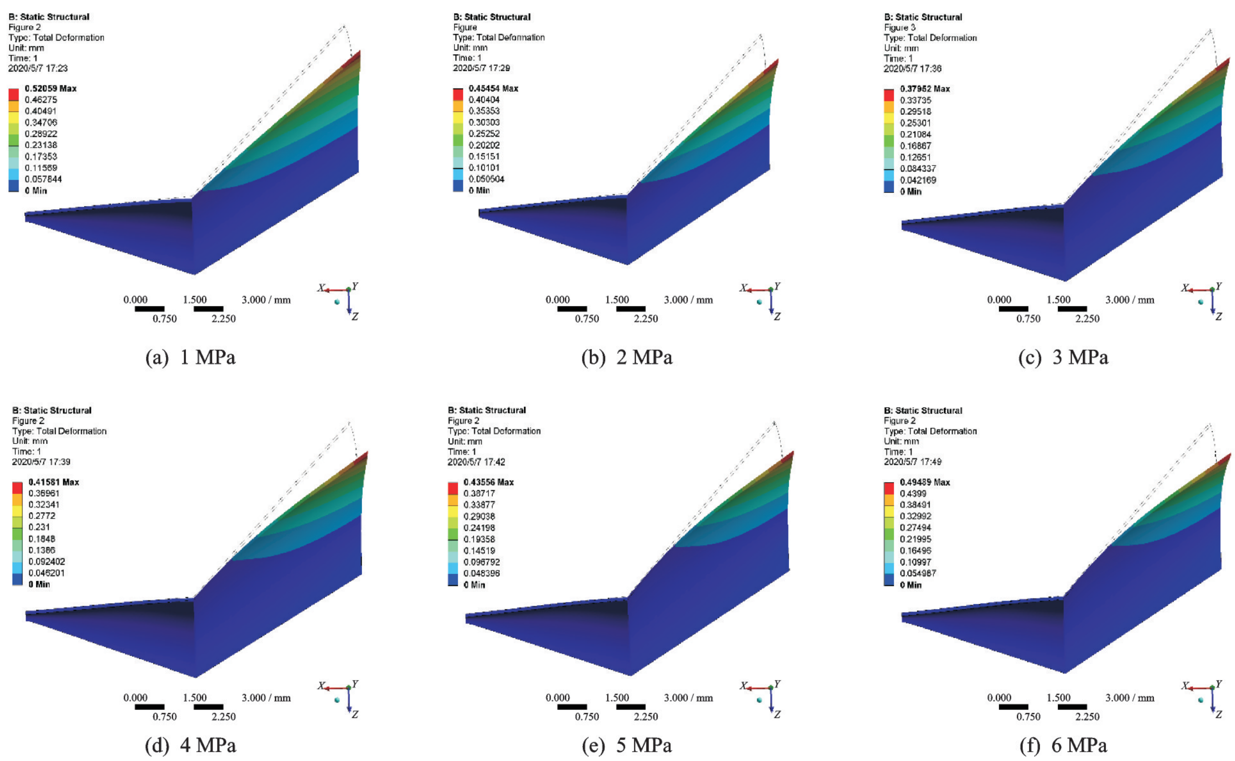


Fig.11 Deformation of lateral curl of chips under different inlet oil pressures

As shown in Fig.12, with the increase of the inlet pressure, the chip curl deformation decreases first and then increases. The maximum deformation of the chip is 0.53 mm when the oil pressure is 1 MPa, 0.38 mm at 3 MPa, and 0.495 mm at 6 MPa. The order of the curl radius is $r_{3\mathrm{MPa}} > r_{4\mathrm{MPa}} > r_{5\mathrm{MPa}} > r_{2\mathrm{MPa}} > r_{6\mathrm{MPa}} > r_{1\mathrm{MPa}}$, and the largest radius is at 3 MPa.

According to the chip forming mechanism of gun drill, the external force of chip spiral forming mainly comes from the friction force, extrusion pres-

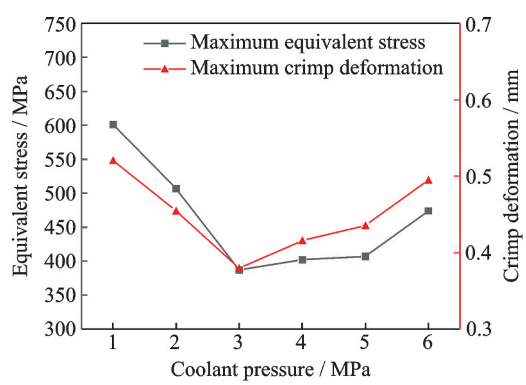


Fig.12 Curve of peak value of equivalent stress and curl deformation

sure and coolant impact force on the wall of chip removal space. The cutting fluid mainly consists of the radial force and the axial tension, which produces the bending deformation of "cantilever beam" and the tensile deformation of "pull rod". After the first spiral curling, the bending deformation amplitude of the chip is limited by the slender space of the V-channel. At the same time, the influence of the radial force of the cutting fluid acting on the spiral surface on the root strain of the chip is greatly weakened, and the axial stress area of the chip increases with chip forming. Therefore, the axial tension of the chip will increase until the chip breaks. When the coolant pressure increases from 1 MPa to 3 MPa, the radius of chip curl increases, the inlet pressure increases, and the axial length of the chip becomes shorter, because the number of helical turns needed to reach the ultimate tension is reduced. When the coolant pressure increases from 3 MPa to 6 MPa, although the coolant pressure increases, the crimp radius and the stressed area decrease. Therefore, there is no significant increase in the axial tension of chip and no significant change in the axial length of chip.

(2) Effect of coolant pressure on chip removal

As shown in Fig.13, there are different degrees of tearing on the outer edge of the spiral chip, which divides the chip into several units. In addition, there is a certain proportion of short chips in the chips during the processing of gun-drill, so it can be inferred that there is a "secondary fracture" phenomenon in the chip removal movement. The analysis of the flow field shows that the movement of chip separated from the cutting area in the flow field can be divided into the overturning movement after contraction flow impact and the torsional movement under the influence of the spiral flow. The forces applied to the chip include: the normal extrusion pressure F_{nc1} and F_{nc2} of the hole wall and the V-channel, the axial friction force F_{fa1} and F_{fa2}, the circumferential friction force F_{fr1} and F_{fr2}, the impact force of contraction flow F_w and the torsion T_s from the spiral flow. During the process of chip flow, when the axial friction force of the chip is larger than

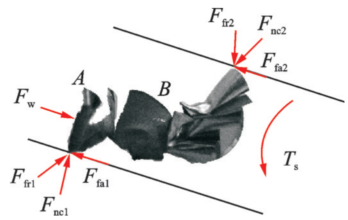


Fig.13 Force analysis of chip movement in V-channel

the axial impact force from the coolant, the chip movement speed will be reduced in the V-groove and chip clogging is easy to occur.

According to Eq.(5), it can be seen that the load distribution of chips is not uniform due to the different flow velocity of coolant in different regions. The coolant flows at the highest velocity in the contraction flow zone, so the chip is subjected to the greatest impact in this area. This shows that the contraction stream is the main external force source to promote chip movement, chip breaking, and fracture.

$$D = C_d A \frac{\rho v_0^2}{2} \tag{5}$$

where D is the flow resistance of the chip, C_d the dimensionless resistance coefficient, A the projected area of the chip, v_0 the coolant speed before interference, and ρ the Fluid density.

According to the point cloud, as shown in Fig.14, with the increase of the inlet pressure, the area of the contraction stream remains around 3.2 mm^2. Fig.15 shows the change of the average velocity diagram in the region of the contraction stream. With the increase of the inlet oil pressure, the average velocity presents a linear increasing trend. The average velocity of the coolant is 27.37 m/s at 1 MPa, 50.113 m/s at 3 MPa, and 71.96 m/s at

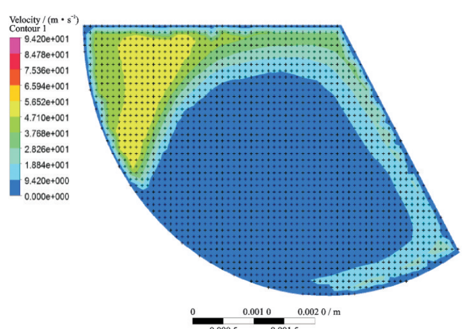


Fig.14 Schematic diagram of uniform point cloud distribution

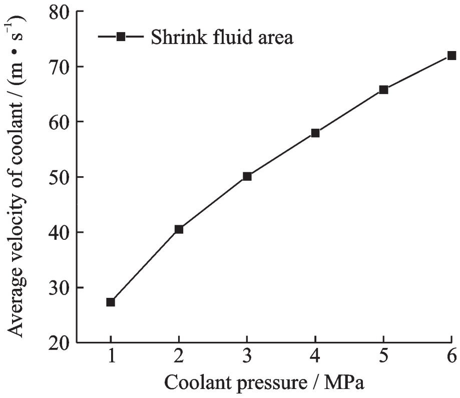
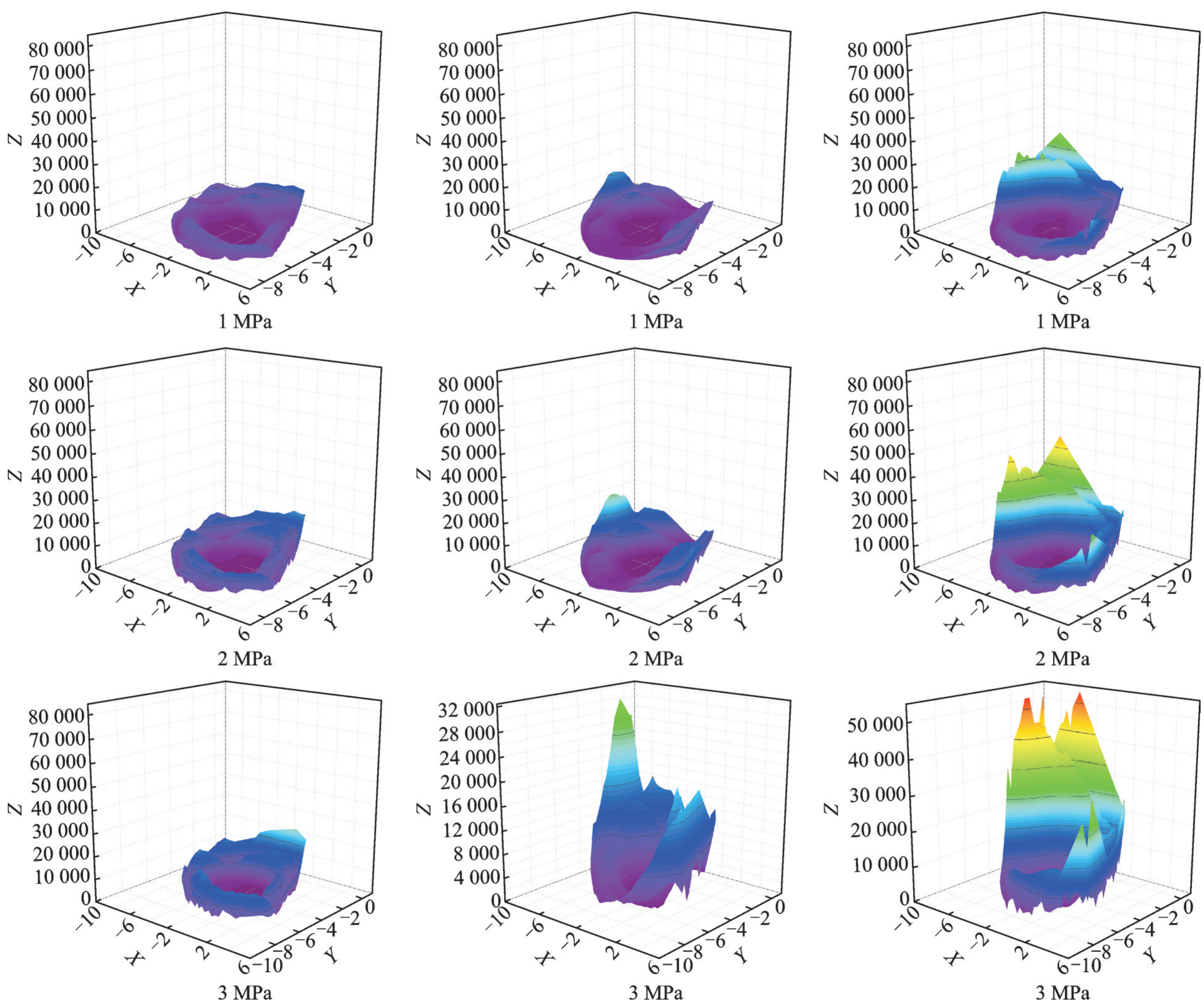


Fig.15 Average flow velocity of contracted stream area

6 MPa. Therefore, it can be inferred that with the increase of the inlet pressure, the coolant flows faster and the degree of chip breakage will be increased.

In addition to the above forces, the chip is affected by the shear stress of the fluid because of the uneven distribution of the velocity in the flow field. U, V and W are the velocity gradient components in the three coordinate directions of X, Y, Z, respectively. It can be seen from Fig.16 that under different pressure conditions, the velocity gradient near the V-channel and hole wall is larger and increases with the increase of the coolant pressure, while the gradient value of the swirl cavitation zone in the form of "sag" is generally smaller. Moreover, the change of coolant pressure has no obvious effect on the gradient distribution in this region. The velocity gradient W is larger than the components U and V in the distribution area and peak value, which indicates that the velocity gradient W is the main influencing factor of fluid shear force, and the high gradient value is mainly distributed near the contraction stream. The above analysis shows that the fluid shear stress of the chip mainly comes from the contraction stream during the chip flow process and with the increase of coolant pressure, the larger the shear force, the more obvious the secondary fracture of chip.



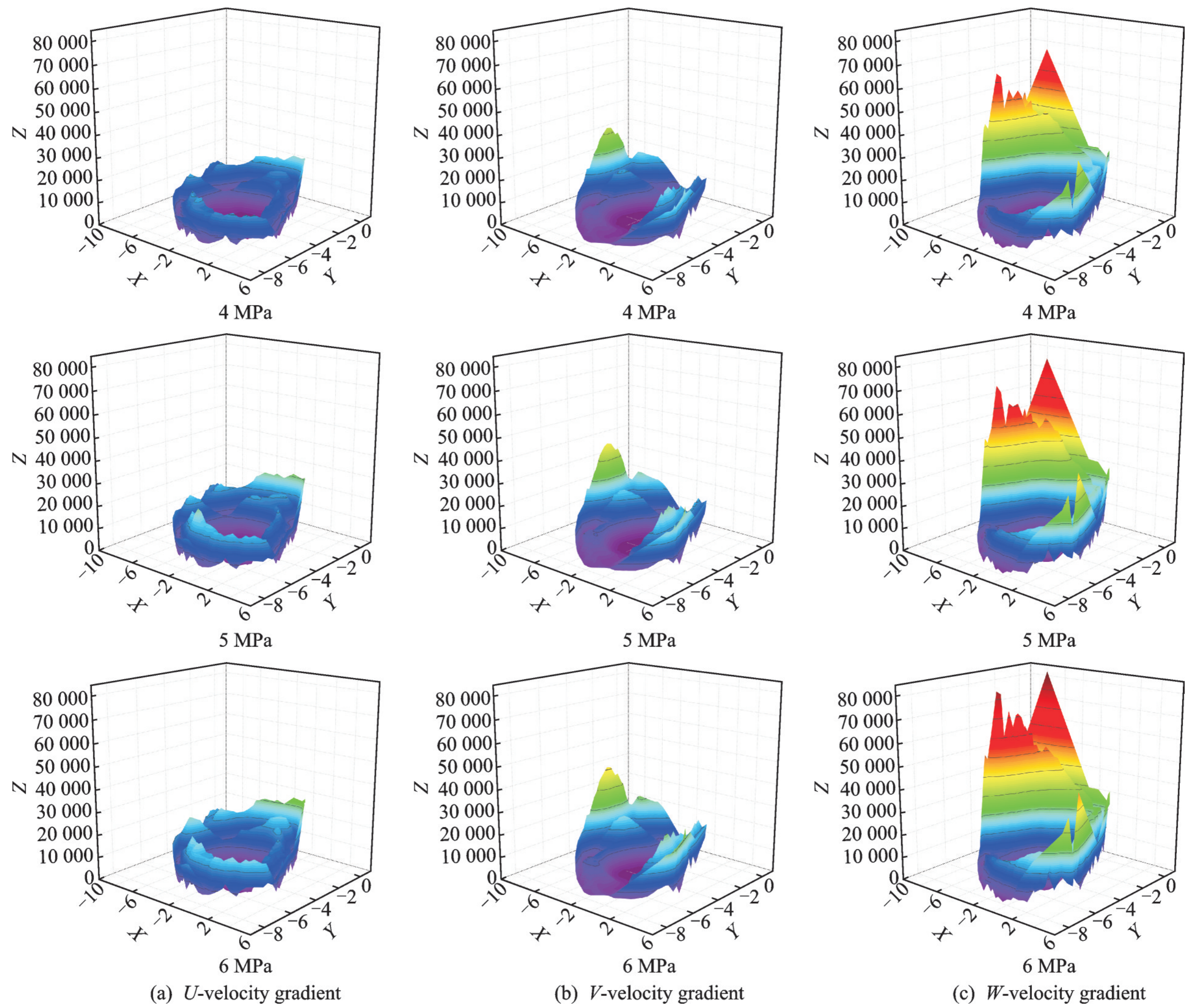


Fig.16　3-D morphologies of velocity gradient

4　Conclusions

The single fluid-solid coupling simulation adopted in this study ignores the influence of chip deformation on the flow field, and the simplification of the model also strengthens the limitations of the simulation. Therefore, the relevant analysis needs to be combined with the experimental research, and the research results are as follows:

(1) In this paper, the spiral chip forming process of the gun-drill is divided into four stages from the theoretical point of view, and the concrete influence of cutting fluid flow on-chip forming is discussed in combination with simulation and experimental research. In the early stage of chip forming, the flow of cutting fluid will affect the curl radius of the chip by strengthening the lateral curl of the chip, and then affect the length of chip breaking at the first time. The degree of lateral crimp tends to decrease at first and then increases with the increase of inlet pressure of cutting fluid, and the maximum crimp radius is at 3 MPa.

(2) Through the deconstruction of the flow path of cutting fluid, the shrinkage flow in the flow field is the main factor to push the chip and force the chip to produce "secondary fracture". With the increase of inlet pressure, the area of contraction flow unit has little change, and the average flow rate and velocity gradient increase. Therefore, the coolant oil pressure increases, and the impact force and shear stress of the fluid also increase, which is more favorable for the chip's secondary crushing and chip removal.

(3) In summary, 3—4 MPa is a better choice for deep hole gun drilling of Ti6Al4V titanium alloy with 17 mm diameter.

References

[1] EZUGWU E O, WANG Z M. Titanium alloys and their machinability—A review[J]. Journal of Materials Processing Technology, 1997, 68(3): 262-274.

[2] LIU Jingjing. Experimental study on the gun-drilling process of Ti6Al4V Titanium alloy and 15-5PH stainless steel[D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2017. (in Chinese)

[3] ZOU Jianxin. Technology actuality, outlook and advice for titanium and its alloys[J]. Aerospace Materials & Technology, 2004(1): 26-28.

[4] LI Liang, HE Ning, XUE Hu. Study on chip formation mechanism of deep hole gun drilling of Ti6Al4V titanium alloy[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(1): 164-174.

[5] ASTAKHOV V P, FRAZAO J P, OSMAN M O M. On the experimental optimization of tool geometry for uniform pressure distribution in single edge gun-drilling[J]. Journal of Engineering for Industry, 1994, 116(4): 449-456.

[6] BIERMANN D, WOLF M, AMUTH R. Cutting edge preparation to enhance the performance of single lip deep hole drills[J]. Procedia CIRP, 2012, 1: 172-177.

[7] DONG Zhen. Technology research of high efficiency chip removal based on pulsed fluid characteristics and real time monitoring for deep-hole drilling[D]. Taiyuan: North University of China, 2016. (in Chinese)

[8] JUNG Jinhyuk, NI Jun. Prediction of coolant pressure and volume flow rate in the gun drilling process[J]. Journal of Manufacturing Science and Engineering, 2003, 125: 696-702.

[9] TNAY G L, WAN S, WOON K S, et al. The effects of dub-off angle on chip evacuation in single-lip deep hole gun drilling[J]. International Journal of Machine Tools and Manufacture, 2016, 108: 66-73.

[10] WOON K S, TNAY G L, RAHMAN M, et al. A Computational fluid dynamics (CFD) model for effective coolant application in deep hole gun drilling[J]. International Journal of Machine Tools and Manufacture, 2016, 113: 10-18.

[11] Sandviken. Sandvik AB (2018)[EB/OL]. (2018-07-14). http://www.coromant.sandvik.com/cn.

[12] OEZKAYA E, BEER N, BIERMANN D. Experimental studies and CFD simulation of the internal cooling conditions when drilling Inconel 718[J]. International Journal of Machine Tools & Manufacture, 2016, 108: 52-65.

[13] NAKAYAMA K, UENOYAMA M, TAMURA K. Chip curl in metal-cutting process[J]. Journal of the Japan Society of Precision Engineering, 1961, 27(321): 681-688.

[14] AURICH J C, KIRSCH B, HERZENSTIEL P, et al. Hydraulic design of a grinding wheel with an internal cooling lubricant supply[J]. Production Engineering: Research and Development, 2011, 5(2): 119-126.

[15] CHORIN S G, MARSDEN A E. A mathematical introduction to fluid mechanics[J]. Journal of Applied Mathematics & Mechanics, 1980, 60(4): 217-217.

[16] WANG H, ZHAI Z J, LIU X. Feasibility of utilizing numerical viscosity from coarse grid CFD for fast turbulence modeling of indoor environments[J]. Building Simulation, 2014, 7(2): 155-164.

[17] ZIRKEL A, LAURIEN E. Turbulence modelling for CFD-methods for containment flows[M]. Heidelberg, Berlin: Springer, 2012.

[18] BEER N, OEZKAYA E, BIERMANN D. Drilling of inconel 718 with geometry-modified twist drills[J]. Procedia CIRP, 2014, 24: 49-55.

[19] SPRENG F, SCHNABEL D, MUELLer A, et al. A local adaptive discretization algorithm for smoothed particle hydrodynamics[J]. Computational Particle Mechanics, 2014, 1(2): 131-145.

[20] FALLENSTEIN F, AURICH J C. CFD based investigation on internal cooling of twist drills[J]. Procedia CIRP, 2014, 14: 293-298.

[21] BIERMANN D, OEZKAYA E. CFD simulation for internal coolant channel design of tapping tools to reduce tool wear[J]. CIRP Annals Manufacturing Technology, 2017, 66: 109-112.

Acknowledgements This work was supported in part by the National Natural Science Foundation of China (No. 51505409), the Six Talent Peak Project in Jiangsu Province (No. GDZB-080), and the Natural Science Research in Jiangsu Province (No.17KJB460008). The authors would like to acknowledge LIU JingJing and WU Peng for their assistance.

Author Dr. **LI Liang** received the M.S. and Ph.D. degrees in mechanical manufacturing from Nanjing University of Aeronautics and Astronautics (NUAA) in 2005 and 2019 respectively. He joined in Yancheng University of Technology in June 2005, where he is an assistant professor in the college of Mechanical Engineering. His research is focused on high speed and high performance cutting, deep hole drilling processing and relevant fields.

Author contributions Dr. LI Liang designed the study, complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Mr. XUE Hu contributed to data for the analysis of the influences of cutting speed and coolant oil pressure on chip shape through drilling experiments and fluid simulation. Dr. SHAN Yicai and Dr. YANG Yinfei conducted the analysis and interpreted the results. Prof. HE Ning contributed to the discussion and background of the relationship between chips forming mechanism. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: SUN Jing)

基于流固耦合的深孔枪钻加工冷却液对切屑成形的影响

李　亮[1,2]，薛　虎[1,3]，单以才[4]，杨吟飞[2]，何　宁[2]

（1.盐城工学院机械学院，盐城 224051，中国；2.南京航空航天大学机电学院，南京 210016，中国；
3.江苏大学机电学院，镇江 212013，中国；4.南京信息职业技术学院机电学院，南京 210046，中国）

摘要：切屑形貌是影响深孔加工质量的重要因素之一。本文以冷却液油压为单因素变量，对Φ17 mm标准枪钻加工的流场进行CFD仿真模拟和试验研究，探讨了冷却液油压对切屑成形和断裂的影响规律。结果表明：在切屑成形初期，冷却液的流动会强化切屑侧向卷曲，继而影响切屑螺旋卷曲半径和切屑的螺旋圈数，其中侧向卷曲程度随切削液进口压力增大呈先增大后减小的趋势，在3 MPa时卷曲程度最小。此外，在排屑过程中，流场内的收缩流股是排出切屑和迫使切屑发生二次断裂的主要影响因素，其对排屑和断屑的影响与进口油压呈正比。

关键词：枪钻；切屑成形；Ti6Al4V钛合金；流固耦合