Chip Formation Mechanism of Deep-Hole Gun Drilling of Ti6Al4V Titanium Alloy

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Abstract: During the process of deep-hole gun drilling, the shape of the chip is a significant factor affecting the final quality. The relationship between chip forming mechanism and process parameters has always been a complicated problem in deep-hole drilling. This paper investigates Ti6Al4V titanium alloy to address this issue. First, the four processes and influencing factors of forming spiral chips are analyzed theoretically. Second, the fracture mechanism of chips in drilling Ti6Al4V titanium alloy is analyzed by scanning electron microscopy. Finally, the influences of cutting speed, feed rate and coolant oil pressure on chip shape are analyzed through drilling experiments and fluid simulation. The relationship between chip compression ratio and surface roughness is obtained through chip thickness measurement. This research can provide a guide for optimizing parameters of deep-hole gun drilling on Ti6Al4V titanium alloy.

Key words: gun drill; titanium alloy; chip deformation; surface roughness

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0 Introduction

Mechanical manufacturing has increasingly demanded techniques of small-diameter deep-hole processing, especially deep-hole processing on titanium alloy materials, given its broad applications in aerospace, weaponry, and rail transit[1]. Gun drilling is the key technique in deep-hole machining, but it still struggles in multi-obstacles, like low processing efficiency, poor quality and difficulty in chip removal during the processing, due to the small pore size and the long depth of the holes to be machined, the complicated structure and the relative weak rigidity of the gun drill. Plus, poor machinability of titanium alloys, tool wear and severe process hardening, also bring challenges to deep-hole gun drilling[2-3].

Deep-hole gun drilling is performed in a closed environment, and it is impossible to monitor the processing conditions directly. The chip deformation, vibration and drilling force are important for machining stability and can only be monitored through the changes of sound, the chip shape, the vibration of the tool bar and the drilling force during the process. Therefore, some studies on deep-hole drilling have been focusing on drilling mechanics mold, influence of different workpiece materials and process parameters on the drilling force. Some studies also noticed that chip morphologies for different materials and process parameters can be completely different and during deep-hole gun drilling, which also directly affect the processing quality of gun drill[4-5]. This paper considers both the forming mechanism of chip morphology and chip breaking.

During the process of gun drilling, the chips are extracted from the V-shaped groove of the drill

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pipe by coolant. Chip is not easy to be discharged when the length is too long, leading to the phenomenon of chip blocking. A longer chip not only affects the surface machining quality, but also causes torsion of the drill bit in some serious cases (as shown in Fig. 1). When the length is too short, the chip will collide and scratch the surface of the machined hole with the flow of the high-pressured cutting fluid. In some serious cases, the too short chips interposed between the outer guide strip of the drill rod and the inner bore wall will scratch the machined surface (as shown in Fig.2).

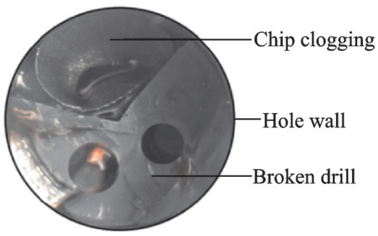


Fig.1 Broken drill due to chip clogging

Fig.2 Micro scratches on machined surface

Few studies have investigated chip formation in deep-hole drilling of Ti6Al4V. The studies are mostly experimental in nature and report few observations based on the chip in hand. Biermann et al.[6-7] studied the single-lip drilling of Inconel-718 and chip formation using high-speed camera for 1.5 and 2 mm diameter holes. They observed that Inconel-718 chip were difficult to break and chip curling played a major role in chip breaking. Pawade et al.[8] studied the effect of chip deformation on processing quality through experiments. However, these studies were conducted at smaller diameters with microscopic feed rates, and the results could not apply to the drills with a bigger diameter like 17 mm. They neither analyzed the mechanism of chip crimp and fracture theoretically.

We has been engaged in the research on the technology of deep-hole gun drilling for a long time. Through research, it was found that the gun drilling is completed once, unlike the twist drilling, there is no "drill-retract" machining process. The chip formation and fracture are only related to the workpiece material, tool size and process parameters. Therefore, this study focuses on the following issues:

(1) Theoretical analysis of the spiral chip forming process.

(2) Analysis of the chip breaking mechanism of Ti6Al4V titanium alloy during gun drill processing.

(3) Study on the influence of process parameters on chip morphology and chip thickness, the relationship between processing quality and chip deformation rate, and the effect of coolant oil pressure on chip formation.

1 Mechanics of Spiral Chip Formation

Gun drilling is a typical double-edged cutting process, and the inner and outer edges of the drill are participated in processing. The drill bit of the gun drill has no chip breaker groove, and its theoretical rake angle is 0°. Chips move on the rake face in a direction perpendicular to the cutting edge (as shown in Fig.3), and produce a shear slip at the junction of the chip and the edge, which causes the chip to "naturally curl up". At the same time, since the cutting speed of the outer blade is greater than the speed of the inner blade, the flow speed of the chip on the outer blade is greater than the flow speed of the inner blade chip, there are signs of squeezing and wrinkles on the chip surface.

The spiral chip formation is divided into four steps as follows.

Step 1 Side-curling of the chip

The mechanics of chip formation changes as the feed rate increases. The chip up-curl is not guaranteed without the chip breaker when the uncut chip thickness is higher than the innovative radius of the

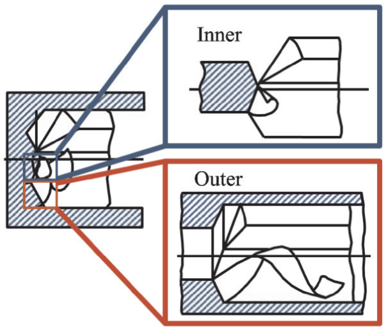


Fig.3 Chip forming process of inner and outer edges

drill cutting edge. The chip formation starts when the drill engages with the workpiece and the chip then continues to move on the rake face as the drill is fed. Unlike the chip formation at a lower feed rate, the chip shape is dominated by the side-curling and the up-curling is latent in this region. The chip continues to be in contact with the rake face until it reaches the wall of the V-flute on the drill. The chip flow angle on the outer edge is significantly larger than the inner blade. The chip flow angles on the inner and outer cutting edges change significantly as shown in Fig.4. Therefore, the degree of lateral curl of the chip is determined by the chip flow angle on the outer blade and the geometric angle of the inner and outer blades of the gun drill.

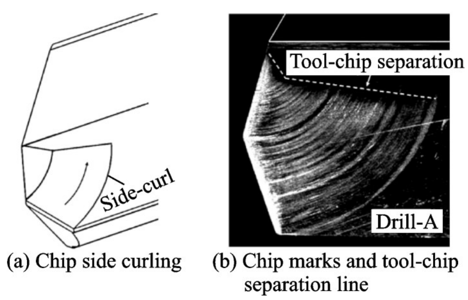


Fig.4 Sketch of side-curling of the chip

Step 2 Up-curling of the chip

The chip starts to up-curl when the chip reaches the wall of V-flute. The chip continues to curl as it comes in contact with hole wall as shown in Fig.5. The combined effect of side-curl and up-curl leads to spiral chip formation. r_c is the theoretical crimp radius of the chip, which is related to the hole diameter and tool size.

Step 3 Spiral chip formation

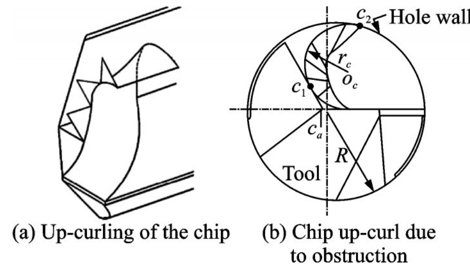


Fig.5 Sketch of up-curling of the chip

As the chip continues to form, it reaches the rake face of the drill and completes a loop of the spiral. The subsequent loops are formed as the chip continues to form before breaking.

Step 4 Elemental chip breaking

According to Nakayama et al.[9], the chip breaking starts when the maximum strain ($\varepsilon_{\max}$) on the free side of the chip crosses a threshold strain of material ($\varepsilon_{\text{crit}}$) which depends on the chip up-curl radius. Initially, the chip has an up-curl radius of r_{u1}, however, the up-curl radius increases and reaches r_{u2} when the chip is obstructed before reaching the critical strain threshold (Fig. 6). The inner curling surface of the chip near the rake face will first cause cracks, and the crack gradually expands and causes chip breakage.

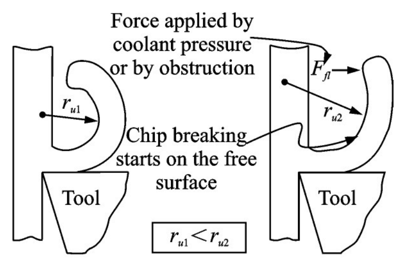


Fig.6 Increase in up-curl radius due to coolant pressure leading to chip breaking

During the process of chip forming, the spiral chip exerts normal forces at points c_1, c_2 and c_3 as F_{nc_1}, F_{nc_2} and F_{nc_3} for each loop of the spiral chip due to elastic recovery inside the hole. The magnitude of these forces depends on the extent of elastic recovery, which is defined by the thickness of the chip. Moreover, the chip is obstructed by the corresponding frictional forces (F_{fc_1}, F_{fc_2} and F_{fc_3}) acting at the contact points as shown in Fig. 7. The increase in the number of spiral turns of the chip causes the axial friction to increase, the axial tensile force at the root of the chip increases, and the axial velocity decreases.

According to Feng et al.[10], the generation rate of spiral chip can be expressed as

$$v_{cf}=\frac{R\omega}{2\zeta_a \pi r_c}p_c \tag{1}$$

where R is the radius of the bit, ω the spindle speed, p_c the pitch, and ζ_a the chip thickness compression ratio.

$$\tan\left(\frac{\theta_t}{2}\right)\left(c_a+\sqrt{(R-r_c)^2-r_c^{\ 2}}\right)=r_c \tag{2}$$

where θ_t is the angle between the V slots and c_a the distance of drill apex point from drill center.

Through the above analysis, the chip forming process in the gun drilling process is related to the angle of the gun drill bit, the material of workpiece, the cutting speed, the feed amount, and the coolant oil pressure.

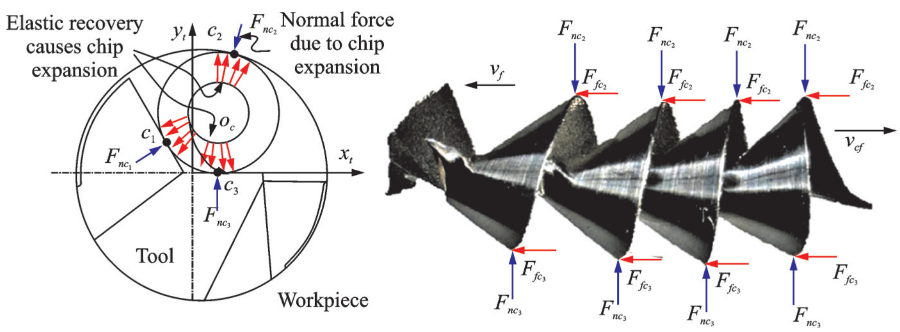


Fig.7 Normal and frictional forces acting on spiral chip due to elastic recovery

2 Chip Fracture Mechanism Analysis

Ti6Al4V titanium alloy is a typical difficulty processing materials, and the surface of the chip has a fan-shaped curled pattern (shown in Fig.8). According to Jawahir[11], the generation of serrated chip generation is caused by the combination of adiabatic shear and periodic fracture. In order to analyze the fracture mechanism, scanning electron microscope (SEM) is used to measure chip morphology (Φ17 mm, f=0.02 mm, v_c=40 m/min).

As shown in Fig.8, seven measuring points are selected on the chip section sequentially. Through analysis, there are both river pattern and dimple on the section. The cleavage crack nuclei appears in different regions of the cross section, which extend into cleavage facets, and finally tear in a plastic way. The river pattern is short and curved, with fewer branches and smaller cleavage surfaces, and more tearing edges around it. According to the fracture properties, it belongs to plastic-brittle fracture. Chip fracture morphology includes not only the fiber breakage and dimple of plastic fracture, but also the "cleavage facet" of brittle fracture. Therefore, the fracture mechanism of Ti6Al4V titanium alloy chips processed by gun drilling belongs to quasi-cleavage fracture, which is between the cleavage facet and the dimple fracture.

Due to the different cutting speeds of the inner and outer edges, there are more river patterns in the inner edge processing area and more dimples in the outer edge processing area. The reason is that with the increase of cutting speed, the failure mode of materials changes from adiabatic shear to ductile fracture with the increase of temperature.

3 Experiment Validation

By analyzing the forming process and fracture mechanism of the spiral chips, we find that the morphology of the chip relates to the material of the workpiece and the processing parameters. In order to analyze the influence of process parameters on chip morphology, we design the following experiment.

The drilling machine is NCS1600 CNC, with drilling depth up to 1 600 mm and rotating speed up to 6 000 r/min. SANDWIK standard single-edged

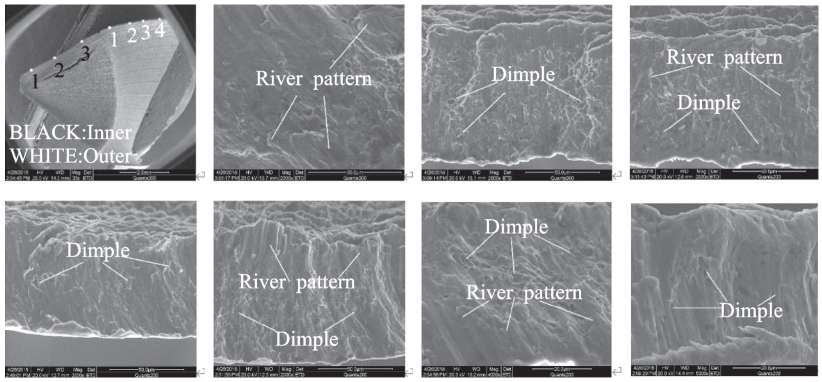


Fig.8 Electron microscopy of chip fractur

gun drill is selected for the experiment as shown in Fig.9, where l_2 is the total length of gun drill; l_c the length of the drill shank; l_{26} the support length; l_{21} the length of the bit; l_m the machined length; d_m the drill shank diameter; and D_c the bit diameter. The material of 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 .

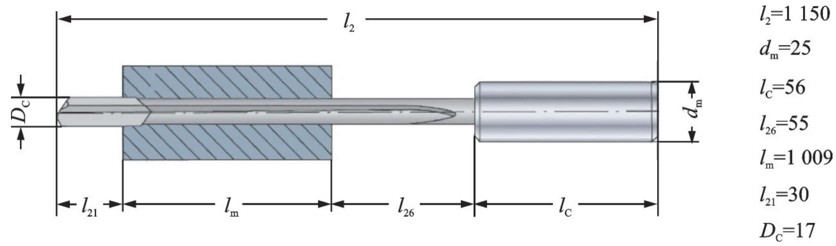


Fig.9 ø17mm standard gun drill (unit: mm)

Table 1 Test parameters

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	20	0.03	4
2	17	80	30	0.03	4
3	17	80	40	0.03	4
4	17	80	50	0.03	4
5	17	80	40	0.01	4
6	17	80	40	0.02	4
7	17	80	40	0.04	4
8	17	80	40	0.06	4
9	17	80	30	0.03	1
10	17	80	30	0.03	2
11	17	80	30	0.03	3
12	17	80	30	0.03	5

3.1 Effect of cutting speed on chip deformation

Fig.10 shows the effect of cutting speed on chip deformation in ø17 mm aperture machining. Through experimental analysis, the chips are torn and separated when v_c=20 m/min. The chips on the inner and outer edges grow at different speeds and curl in opposite directions, which cause the chips to squeeze each other. When the stress is greater than the ultimate strength of the material, the chips crushed and separated in the drill tip area and curled along the vertical direction of the two edges, respectively. As the bending stress on the chip root decreases, the chip is relatively long. If the chips are not separated, the bending stress on the chips is large. When the yield limit is reached, the fracture length of the chips is relatively small.

When the cutting speed v_c is greater than 30 m/min, the chip edge produces cracks. With the increase of cutting speed, the chip deformation increases, and some chips are deformed by extrusion severely. With the increase of cutting speed, the curling speed of chips cannot match the cutting generating speed, the internal tension of chips increases and the external edge speed is higher, so there will be a phenomenon of edge extrusion and tearing. With the further increase of cutting speed, the chip generation speed is too fast, and the chips squeeze and fold each other, resulting in serious deformation, which will also lead to the instability of drilling process.

The increase of cutting speed leads to the increase of cutting heat, and the failure mode of the material changes from adiabatic shear to ductile fracture, and the force required for chip fracture increases correspondingly. Under the condition of constant coolant oil pressure, the chips are spirally curled, and the length of chips becomes longer gradually.

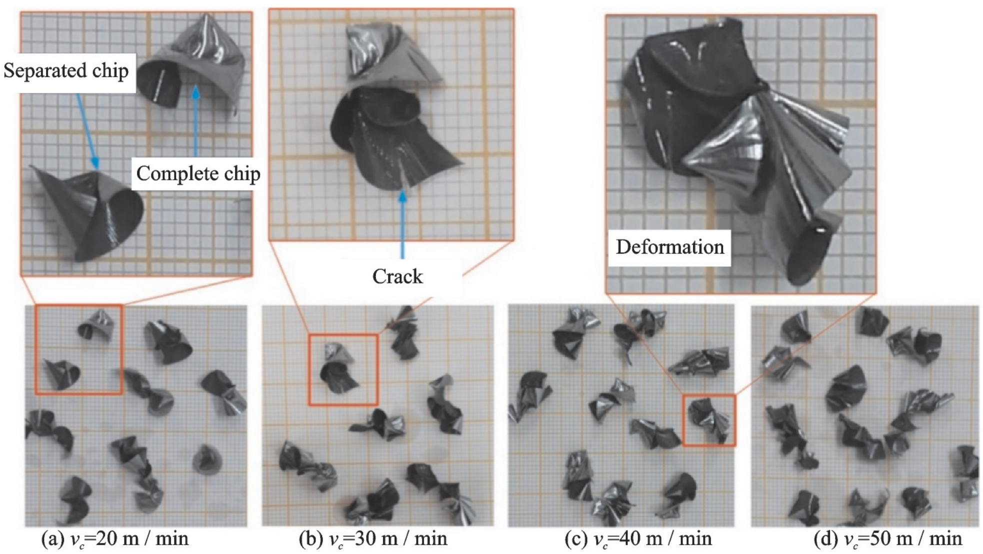


Fig.10 Effect of cutting speed on chip deformation

3.2 Effect of feed speed on chip deformation

In the process of drilling, with the increase of feed, the chip thickness increases, the strength against bending deformation increases, the deformation coefficient of chips decreases, and the curvature radius increases. With the decrease of feed, the chip thickness decreases, the strength decreases, and the chip deformation coefficient increases. The rounded edge of the cutter leads to hardening of chips, which makes it hard and brittle. It is easy to break under the impact of cutting fluid, so the chip size is small.

Fig. 11 shows the effect of feed on chip deformation. When the feed is small (f=0.01 mm/r), the chip shape is mainly short conical spiral shape with small size and stable shape. With the increase of feed rate (f=0.03 mm/r), chip thickness and chip curling radius increase, and the surface scratches of machined holes are serious. When feed reaches 0.08 mm/r, the crimp radius is approximately 5 times than 0.01 mm/r. The increase of feed leads to the increase of chip cutting thickness and crimp radius.

3.3 Chip thickness measurement

Analysis from the above experiments, we cannot measure the curling radius, length and thread pitch of the chips because of its severe extrusion deformation. The change trend of chip length and curling radius can be analyzed from the macroscopic perspective. Therefore, in order to analyze the chip morphology, we put chips into the epoxy resin mold

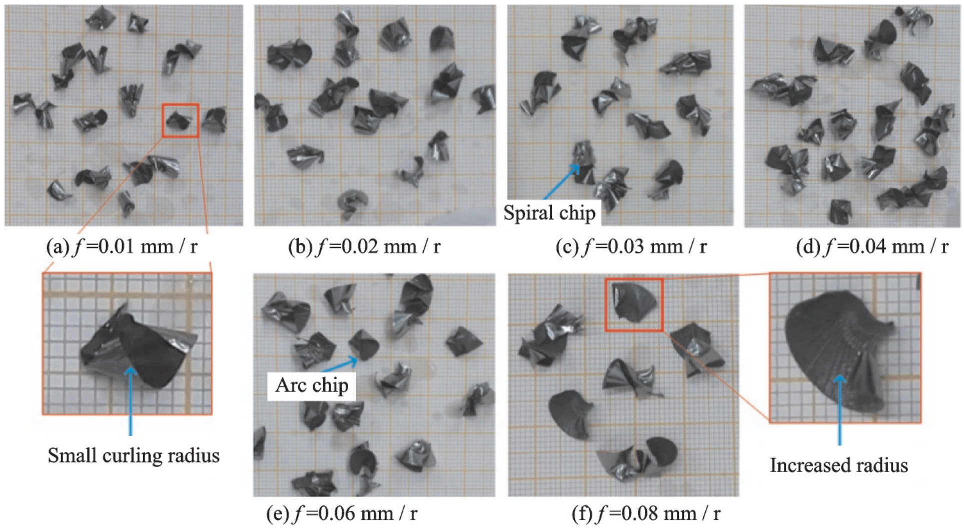


Fig.11 Effect of feed on chip deformation

and measure the multi-point thickness using the VHX-1000 microscope to obtain the average value.

As shown in Fig.12(a), the chip thickness increases with the cutting speed when the cutting speed is less than 30 m/min. With the cutting speed increases further, the chip thickness decreases gradually. The reason is that the cutting speed increases, the cutting heat increases, the friction angle decreases, the shear angle increases, and eventually the thickness decreases. As shown in Fig. 12(b), with the increase of feed rate, the chip thickness increases linearly due to the increase of instantaneous cutting thickness.

Chip thickness is an important basis for evaluating the thickness deformation coefficient, which quantifies the plastic deformation degree of chips and the power consumption of the cutting edge[12]. The machined surface roughness relates to the plastic deformation of the surface metal. Since gun drill processing belongs to the external chip removal processing system, under the same working conditions, the smaller the plastic deformation of the chip, the more serious the chip scratch on the machined surface of the hole. Therefore, the surface roughness can be indirectly reflected by the plastic deformation degree of chips.

The deformation coefficient of the chip thickness is as follows

$$\xi_a = \frac{h_{ch}}{h_d} > 1 \tag{3}$$

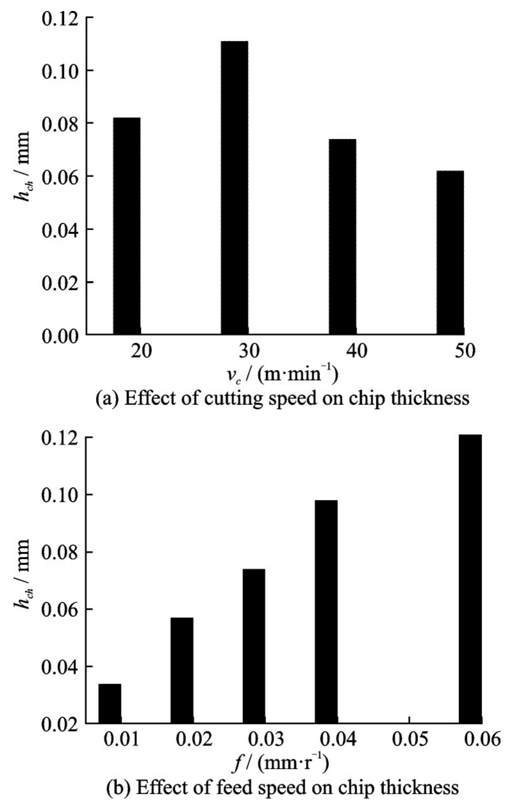


Fig.12 Effect of cutting parameters on chip thickness

where h_{ch} is the chip thickness; h_d is the theoretical thickness and is related to the feed f and β; $h_d = f\cos\beta$, here β is the inclination angle of the inner and outer edges.

The relationship between chip compressibility (CCR) and surface roughness (Ra) can be seen from Fig.13(a). With the increase of cutting speed, the chip compression rate increases first and then decreases, while the roughness is opposite. The point

(v_c=30 m/min) is the inflection point. The descending tend of the chip compressibility is obviously at low speed and gently at high speed.

Fig.13(b) shows that with the increase of feed rate, the chip compressibility decreases and the roughness increases first and then decreases. During high cutting speed and large feed speed processing, the chip plastic deformation is small and the chip compressibility is lower, and the scratch of the machined surface increase, resulting in a large surface roughness of the inner wall.

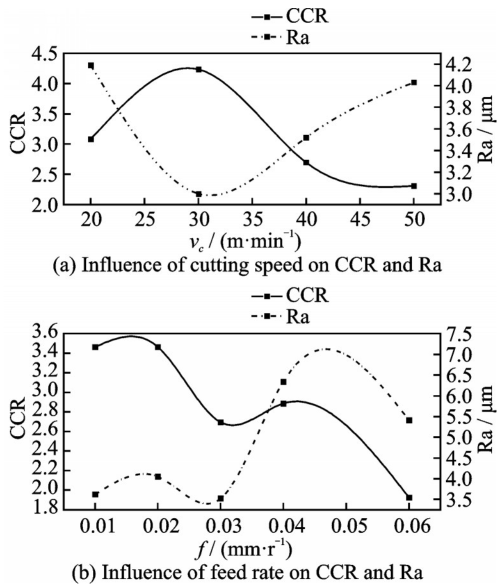


Fig.13 Influence on chip compressibility (CCR) and roughness

3.4 Effect of coolant pressure on chip morphology

During the gun drilling process, the coolant not only plays the role of cooling and lubrication, but also affects the chip breakage and chip flow in the borehole[13-14]. Coolant oil pressure has an important influence on the chip size and processing quality. The traditional view is that the larger coolant pressure, the small the chip size and the better processing quality. Analysis from the experiments, we find that when the coolant pressure is 1 MPa, the chip clogging occurs and the processing cannot continue. When the coolant pressure is 2 MPa, the chip is longer and the surface of the machining hole is scratched seriously. When the coolant pressure is 5 MPa, the chip length is the shortest, and the increase of coolant pressure leads to the aggravation of separation between inner and outer edges. Fig.14 shows the effect of coolant pressure on the chip deformation. With the increase of coolant pressure, the chip length of Ti6Al4V titanium alloy decreases gradually.

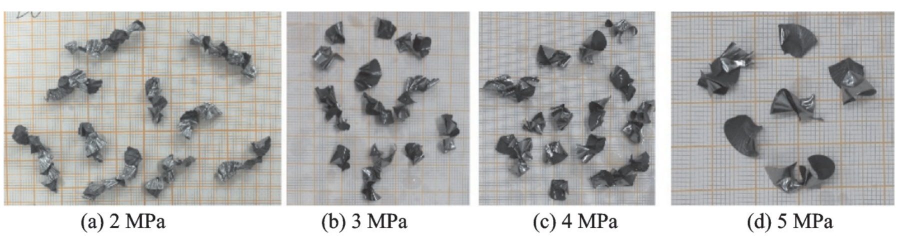


Fig.14 Effect of coolant pressure on chip morphology

As shown in Fig.15, when the oil pressure is 2 MPa, the chips are longer and wrinkle on the surface is obviously, and chips flow out slowly, which results in chip blocking. At the same time, the friction between the chips and the processed surface intensify, which increases the roughness during the processing. When the coolant pressure is 5 MPa, although the chip length is the shortest, the chatter of drill shaft is obvious and accompanied by the harsh sound during the processing, and the roughness increases instead. When the coolant pressure is 3 MPa and 4 MPa, the chip length is shorter and the roughness decreases. The results show that the coolant pressure is the major factor of chip fracture.

To study the effect of coolant on the chip forming more clearly, ANSYS-Fluent is used to analyze the variation of coolant pressure and the kinetic energy near the cutting edge of gun drill under different inlet pressures in this paper. As shown in Fig.16, the flow field simulation is carried out under different inlet pressures.

According to the probed pressure near the edge

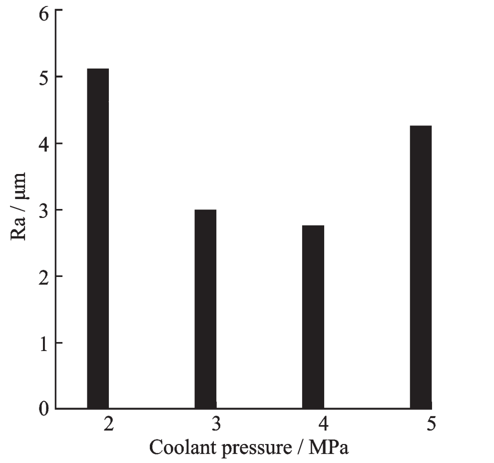
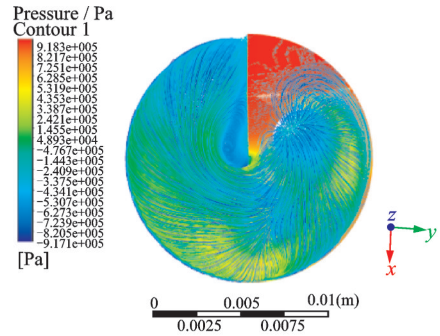
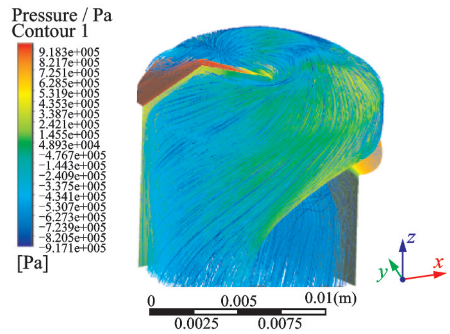


Fig.15 Relationship between coolant pressure and roughness



(a) Simulation diagram of vortex near the cutting edge



(b) Diagram of the coolant pressure at the cutting edges

Fig.16 Flow field simulation of coolant

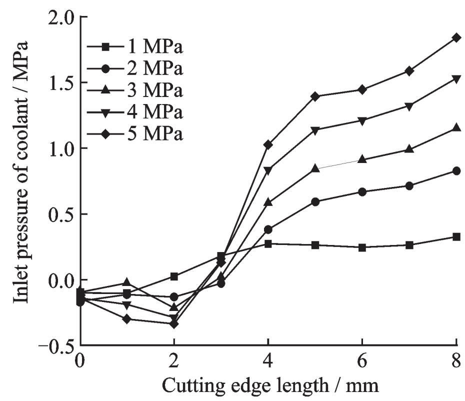


Fig.17 Coolant pressure near the cutting edge

of the rake face, the change of coolant pressure is shown in Fig.17. It is found that the coolant pressure at the inner and the outer edges have different changing trends, and the negative pressure state appears in the inner edge area, and its value increases gradually with the increase of inlet pressure[15-17]. On the rake face, the pressure in the inner edge area increases gradually from the center of rotation to the drill tip, and the critical point of positive and negative pressures is the rotary center. The oil pressure on the edge increases gradually from the drill point to the maximum edge of the outer edge, which explains that the chip always starts to crack from the edge area of the outer edge. Meanwhile, when the coolant pressure difference on the inner and outer edges increases, chips tear on both sides and the cracks occur at the drill tip, which leads to chip separation between the inner and outer edges. When the inlet coolant pressure is reduced, the pressure acting on the chips becomes smaller, and the turbulence makes the chip blocked. Therefore, the distribution diagram of coolant pressure on the rake face can explain the reasons for the change of chip morphology under different inlet pressures.

The turbulent energy chart of the fluid near the cutting edge on the rake face is illustrated in Fig.18. Combined with Fig.16, vortex appears near the rake face, and the turbulent kinetic energy gradually increases with the increase of inlet pressure. The increase of inlet pressure makes the chip length shorter and the chip removal speed faster, which reduces the number of secondary scratches and roughness. However, the turbulent kinetic energy of coolant will also generate additional dynamic load on gun drill shaft. When the coolant pressure is too heavy, the stability of the drill pipe declines, the additional kinetic energy of coolant to chips increases, and the chip deformation is more obvious, the kinetic energy of impact wall increases and the roughness increases. This is why the roughness increases when the inlet pressure reaches 5 MPa, although the chip size is smaller.

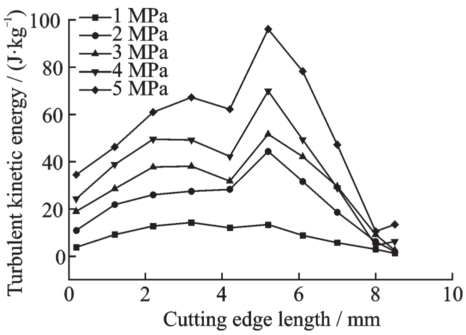


Fig.18 Turbulent kinetic energy near the edge of rake face

4 Conclusions

(1) The forming process of spiral chip and the influencing factors of fracture in gun drilling are analyzed theoretically. The fracture mechanism of the chip in the deep hole gun drilling of Ti6Al4V titanium alloy is studied, which belongs to the quasi-cleavage fracture. The chip morphology relates to the drilling parameters.

(2) With the increase of the cutting speed of gun drill, the cutting heat increases, the chip presents spiral curl shape, the chip thickness becomes smaller and the chip length becomes longer gradually. As the increase of feed rate, the chip becomes short cone-shaped, and the curling radius increases. With the increase of cutting speed, the chip compressibility decreases obviously at low speed and gently at high speed. In addition, with the increase of feed rate, the chip compressibility appears a downward trend. The decrease of chip compressibility reflects the decrease of plastic deformation, the fracture mode gradually changes from adiabatic shear to ductile fracture, the processing condition deteriorates and the roughness increases.

(3) Coolant pressure is one of the main factors affecting chip fracture in deep-hole gun drilling. Too small inlet pressure leads to the excessive length of chips, obvious wrinkles of chips extrusion, chips blockage and poor processing quality. Too large oil pressure leads to shorter chips, but the drilling stability becomes worse and the roughness increases.

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Ti6Al4V钛合金深孔枪钻加工切屑成形机理

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摘要:深孔枪钻加工过程中,切屑形貌是影响其加工质量的一个重要因素,并且切屑的成形机理与工艺参数之间的关系也一直是深孔加工研究的难点。本文以Ti6Al4V钛合金为研究对象,一方面,通过理论分析了枪钻加工螺旋形切屑成形的4个过程和影响因素;另一方面,借助于扫描电镜检测研究了Ti6Al4V钛合金枪钻加工切屑的断裂机理;最后,通过加工试验和流场仿真,分析了切削速度、进给量和冷却液油压变化对切屑形貌的影响,结合切屑厚度测量得出了切屑压缩比与表面粗糙度的关系。研究结论对Ti6Al4V钛合金深孔枪钻加工工艺参数的优化提供了指导 。

关键词:切屑成形; 枪钻; Ti6Al4V钛合金; 表面粗糙度