Experimental study on deep hole drilling of GH4169 alloy

Liu ZhanFeng¹, Li ZhanHui¹,a, Han XiaoLan¹, WangYu¹
¹School of Mechanical Engineering, Xi'an Shiyou University, Xi'An, China
a1808612891@qq.com

Abstract: GH4169 alloy material has good corrosion resistance, radiation resistance and other excellent properties, and has been widely used in aerospace and other manufacturing fields. At the same time, due to its severe machining hardening phenomenon and high cutting force during machining, it is also one of the typical difficult-to-machine materials, and the deep hole drilling of GH4169 alloy has been rarely studied. In this paper, the deep hole drilling test of GH4169 is studied, and BTA system is adopted in the test, the wear and failure modes of the cutting tool, and the change of chip morphology were analyzed. Results showed that the middle cutter tooth wear focused on central blade, the wear of the center tooth occurs mainly at the tip of the cutter tooth, the wear of edge tooth mainly occurs at the arc of the tool tip where the main cutting edge is connected with the secondary cutting edge: the chips produced by the central cutter tooth are mostly short and small c-shaped chips, the chip produced by the middle tooth is not easy to break the chip, most of which are elongated spiral chip, the cuttings produced by the edge tooth are not easy to discharge, and most of them are hard spiral coils.

1. Introduction
GH4169 alloy is a nickel-based high-temperature alloy with good fatigue resistance, radiation resistance and other excellent properties [1]. Therefore, it is widely used in aviation, aerospace, shipping, power and petrochemical industries, and is one of the key materials for aviation jet engines and rocket engines [2]. But at the same time, because of its high cutting temperature, high cutting force, and severe work hardening during processing, it is one of the typical hard-to-process materials [3-4].

Due to the particularity of deep hole machining, the cutting tool is in a harsh environment during the machining process, and the machining process cannot be directly observed, deep hole machining is a difficult machining method. The GH4169 alloy itself is difficult to cut, so deep hole drilling of GH4169 alloy is even more difficult. The factors that affect the quality of GH4169 deep hole drilling mainly include tool wear, chip shape. At present, the research of domestic scholars mainly focuses on the spark erosion machining, milling and high-speed turning processing of GH4169 alloy, etc, and the research on deep hole drilling of GH4169 alloy is less. Therefore, this paper conducts an experimental study on BTA deep hole drilling of GH4169 alloy, and analyzes the wear and tool failure forms of BTA tools under fixed cutting parameters, as well as the deflection of the hole axis and the change in chip shape.

2. Material properties of GH4169 Alloy
The density of GH4169 alloy is $\rho = 8.24\text{g/cm}^3$. GH4169 alloy has high strength at high temperature of 650–1000°C, such as high fatigue resistance and tensile strength at 700°C. At room temperature, its tensile strength $\sigma$ can reach 1450MPa [3]. The chemical composition of GH4169 alloy are shown in Table 1, and its mechanical properties are shown in Table...
Table 1 Chemical composition of GH4169 alloy (wt%)

| Element | Ni  | Cr  | Mn  | Si  | Co  | Al  |
|---------|-----|-----|-----|-----|-----|-----|
| Content | 52.25 | 19.0 | 0.35 | 0.35 | 1.0 | 0.5 |

| Element | Ti  | Mo  | Nb  | Cu  | S   | Fe  |
|---------|-----|-----|-----|-----|-----|-----|
| Content | 0.9 | 3   | 5.1 | 0.3 | 0.015 | 18  |

Table 2 Mechanical properties of GH4169 alloy

| Workpiece material | Tensile strength $\sigma_b$ (MPa) | Yield strength $\sigma_s$ (MPa) |
|--------------------|----------------------------------|-------------------------------|
| GH4169             | 1430                             | 1260                          |

| Workpiece material | Elongation $\delta$ (%) | Shrinkage $\Psi$ (%) |
|--------------------|-------------------------|----------------------|
| GH4169             | 24                      | 40                   |

3. Deep Hole Drilling Experiment

3.1. Drilling test plan

For the GH4169 workpiece with a diameter of Φ125mm, a length of 1590mm, and a drilling diameter of Φ60mm, a drilling test study was carried out based on a 630X8000 turning deep hole drilling machine. The drilling system was a BTA deep hole drilling system, and the machining methods were tool feed and workpiece rotate, the bit is a machine clamp type indexable BTA bit, as shown in Figure 1. The cutter base material is cemented carbide and the coating material is CBN. According to the previous experience of processing GH4169, the spindle speed is set to 145r/min and the feed rate is 0.04mm/r during processing. Observe the tool wear after machining; collect 12 groups of chips in stages, and measure under the microscope chip width and thickness, analysis of chip shape changes.

3.2. Analysis of test results

For the BTA deep hole drilling test of GH4169 alloy, the tool wear, and the chip shape changes were analyzed.

3.2.1 Tool wear analysis

The tool wear analysis includes the wear of the rake face, the wear of the flank face, the damage of the cutter teeth and the wear of the guide block.
3.2.1.1 Rake face wear
As shown in Figure 2, the CBN coating on the flank of the three teeth of the center tooth, middle tooth and edge tooth has been peeled to varying degrees. This is because when the GH4169 alloy is drilled by the BTA deep hole drill, a large amount of cutting heat is generated in the cutting area, and the poor thermal conductivity of the GH4169 alloy causes the cutting heat generated in the cutting area to be difficult to dissipate, forming a high temperature and high pressure environment, and the adhesion between the cutter teeth and the chips is carried away by the chips, resulting in bond wear. From Figure 2(b), it can be seen that the coating material also flakes over a large area where the intermediate tooth rake face is far away from the cutting edge. This is mainly due to the friction between the chips and the rake face when flowing out along the rake face. From Figure 2(c), it can be seen that the cutting edge arc where the main cutting edge and the auxiliary cutting edge of the edge tooth are connected is the most severely worn, this is because the larger the cutting radius, the larger the cutting linear velocity and torque, and the most severe tool wear.

![Knife tooth rake face wear](image)

3.2.1.2 Flank wear
As shown in Fig. 3(b), the wear of the middle teeth mainly occurs in the middle of the cutter teeth. This is due to the repeated cutting phenomenon of the tip of the three teeth, that is, the three teeth have a certain amount of overlap with each other on the cross section of the tool, and because the cutting sequence is center tooth cutting first, edge tooth cutting second, and middle tooth cutting last, the cutting edge of the middle tooth basically does not participate in cutting. It can be seen from Fig. 3(a) that the wear of the center tooth mainly occurs at the tip of the cutting edge that first enters the workpiece for cutting. It can be seen from Fig. 3(c) that the flank wear of the edge teeth is more uniform. Stripe-shaped wear bands on the flank of the teeth, this is because the flank of the tooth mainly squeezes and rubs against the bottom of the hole, causing the temperature in the cutting area to rise, and the hardness of the tool is reduced, and more hard points in the GH4169 alloy continuously
scratch the flank of the tooth, resulting in serious abrasive wear on the flank of the tooth, forming a white wear ribbed zone with a back angle close to zero. It can be seen that black adhesives appear near the wear bands of the front and rear cutter faces, which is caused by the chemical reaction between the cutting fluid and the cutter teeth and the workpiece surface under high temperature and high pressure environment.

![Figure 3 Wear of flank of cutter teeth](image)

### 3.2.1.3 Tool damage

As shown in Figure 4, damage to the central teeth has not completely peeled off. The damage of the cutter teeth is an abnormal wear and a sudden brittle fracture [6]. Due to the characteristics of high cutting temperature and large cutting force, the mechanical impact and thermal shock of the tool are relatively large, resulting in the tool being prone to breakage. In batch processing of GH4169 alloy workpieces, it was found that the side of the center tooth close to the center line of the tool is prone to damage, and the excessive wear of the tool does not occur in the place where the damage occurs. The reason for this is that the linear velocity of the tool decreases with the decrease of the radius. The closer to the centerline of the tool, the lower the linear velocity of the cutting, the greater the cutting resistance, which leads to the damage of the cutter teeth.

![Figure 4. Tool damage](image)
3.2.2 Chip shape analysis
The shape of the chip directly affects the smoothness of the chip discharge, thus affecting the tool life. Fig. 5 shows the chip shape corresponding to the three teeth of the machine-clamped indexable BTA bit.

Figure 5. The chip shape of the three teeth

Figure 6. Change trend of average chip width
1-Central tooth  2-Middle tooth  3-Marginal tooth

Figure 7. The trend of average chip thickness conversion
1-Central tooth  2-Middle tooth  3-Marginal tooth
The lateral dislocation of the three teeth of the staggered BTA drill bit has a good chip separation effect. There is a chip separation table on the front face of each tooth to increase the chip bending deformation and assist chip breakage. The cutting linear velocity of the three teeth of the staggered BTA drill bit gradually decreases along the radius from the center to the edge teeth, resulting in different cutting environments where the three teeth are located. The cutting speed of the center tooth is the smallest, and the width of the generated chips is between the width of the middle and edge teeth. However, the thickness of the chip is the thickest and the degree of bending is the largest, mostly short and small C-shaped chips, and the material removal rate is the smallest. The cutting speed of the middle tooth is between the center tooth and the middle tooth. The thickness of the chip produced is less than the center tooth and close to the edge tooth, but the chip width is the smallest. Most of them are long spiral chips and are not easy to break. The cutting speed of the edge teeth is the largest, and the minimum thickness and width of the generated chips are the largest. Most of them are hard-belt spiral-shaped chips, which are not easy to discharge and have the largest material removal rate. During processing, it was found that the chips generated by the middle teeth and the chips generated by the edge teeth are easily entangled, causing chip jamming.

As far as the chip width is concerned, the change trend of the chip width of the three cutter teeth as a whole tends to be stable, with little change. As far as the chip thickness is concerned, the chip thickness variation of the center tooth fluctuates greatly. On the one hand, the analysis is due to the vibration of the machine tool during processing, and on the other hand, it may be due to an error in the measurement. The chip thickness of the middle tooth and the center tooth fluctuated in the early stage of processing, which was basically stable at about 0.13mm, and the chip thickness in the later stage of the drill bit was increased. The reason for the analysis is that with the progress of the machining process, the wear of the cutters has increased, resulting in an increasing trend in the chip thickness of the three cutter teeth in the later stage of the drill bit.

4. Conclusion

During the deep hole drilling GH4169 alloy test, the wear of the center tooth mainly occurs at the tip of the cutting edge that first enters the workpiece. The wear of the middle tooth mainly occurs in the middle of the tooth. The wear of edge tooth mainly occurs at the arc of the tool tip where the main cutting edge is connected with the secondary cutting edge. The rake face of the cutter teeth mainly suffered from adhesive wear, and the flank face mainly suffered from abrasive wear.

Due to the different cutting radii of the three teeth, the chip shape produced by the three teeth is also different. The chips produced by the center teeth are mostly short and small C-shaped chips, which are easy to be discharged, which is the ideal chip shape. The chips produced by the middle teeth are mostly long spiral chips which are not easy to break. The chips produced by the edge teeth are mostly hard-belt spiral-shaped chips that are not easy to be discharged, which is easy to cause chip blocking.

The change trend of the chip width produced by the three cutter teeth as a whole tends to be stable. The change in the chip thickness of the center tooth fluctuates greatly. The thickness of the chip produced by the middle tooth and the edge tooth is similar. In the later stage of drilling, the thickness of the chips produced by the three teeth of the cutters tends to increase due to tool wear. The removal rate of material is edge tooth > middle tooth > center tooth. The chips generated by the middle teeth and the edge teeth are easily entangled, causing chip clogging.

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