Experimental Study on the Axis Line Deflection of Ti6A14V Titanium Alloy in Gun-Drilling Process

Liang Li¹,², Hu Xue¹,³ and Peng Wu¹
¹Yancheng Institute of Technology, Yancheng,China.
²The first author
³The corresponding author
Email: jzlliang@163.com

Abstract. Titanium alloy is widely used in aerospace industry, but it is also a typical difficult-to-cut material. During Deep hole drilling of the shaft parts of a certain large aircraft, there are problems of bad surface roughness, chip control and axis deviation, so experiments on gun-drilling of Ti6A14V titanium alloy were carried out to measure the axis line deflection, diameter error and surface integrity, and the reasons of these errors were analyzed. Then, the optimized process parameter was obtained during gun-drilling of Ti6A14V titanium alloy with deep hole diameter of 17mm. Finally, we finished the deep hole drilling of 860mm while the comprehensive error is smaller than 0.2mm and the surface roughness is less than 1.6μm.

1. Introduction
Titanium alloy is a typical difficult-to-cut material widely used in the fields of aerospace, shipbuilding and petrochemical industry due to its excellent mechanical properties, such as high specific strength, good corrosion resistance [1]. In the field of machining, hole machining accounts for about 1/4 of workload, of which deep hole processing occupies a large proportion, and with the widespread use of titanium alloys, the demand for deep hole machining of titanium alloys is increasing. But the research on the cutting methods of titanium alloy is mainly focused on turning and milling. Therefore, the deep processing of titanium alloy is of great significance.

Gun drill is the most common deep hole machining tools in modern deep hole machining. A large number of scholars have done a great deal of research on the borehole quality of gun-drilling and found that the main factors that affect the axis deviation of gun-drilling are the misalignment of drill shaft [2], the angle of inside and outside edge of drill head and the location of guide stripes [3, 4]. The main factors affecting the quality of the surface of the borehole are the geometric parameters of the drill head [3], the drill shaft material and the tool coating material [5, 6]. But there are few research on the gun-drilling used to process titanium alloy. There are many problems in the process of gun-drilling of titanium alloy, such as the titanium alloy has small elastic modulus, poor thermal conductivity and high thermal strength, which not only accelerates tool wear, but also increases the difficulty of machining titanium alloy with gun drilling [7].

Based on the requirements of high precision and high surface quality of ultra-long deep hole for a large aircraft shaft, the straightness error of gun-drilling and its causes were analyzed through the gun drill experiment of Ti6A14V titanium alloy. Finally, the best parameters of machining φ17mm deep hole were obtained with the drilling surface roughness, chips and processing sound as the experimental indexes on the Titanium alloy workpiece, and the gun drilling of 860mm deep hole was completed.
2. Experimental Conditions

Machine: The experimental machine adopts NCS1600 CNC Deep Hole Drilling Machine from Dongguan Nice Machinery Co., Ltd. The maximum drilling depth is 1600mm, the drilling diameter range is 3-30mm, the fastest spindle speed is 6000rpm and the fastest feed speed is 5000mm/min, as shown in Figure 1.

Tool: The tool used in the experiment is a cemented carbide continuous guide single-blade gun-drilling with drill diameter of 17mm, inside angle of 20° and outside angle of 30°.

Workpiece material: Ti6Al4V titanium alloy, which is a typical α-β titanium alloy.

Processing methods: workpiece fixed, tool rotation.

3. Gun Drill Straightness and Aperture Error Test

3.1. Experiment Scheme

Using annealed titanium alloy bar as the work piece material, the size is φ32 × 350mm. Firstly the bar is processed into four mutually perpendicular planes as a measurement reference. The drilling depth is 320mm. The process parameters are \( V_c = 40m/min, \ f_n = 0.03mm/r \), cutting fluid pressure maximum, but the cutting fluid pressure is about 3Mpa after the drill fully into the aperture.

After drilling the bar will be cut into 7 sections, each length 50mm. Then we measure each aperture error and the distance between the inner hole to the wall twice in the same drilling depth and calculate average value of the two measurement. Finally, we got the distribution of hole diameter error and center of circle relative to the center of bar, as shown in Figure 2.

3.2. Axis Deviation Analysis

As can be seen from the Figure 3, that show the axial deviation of the deep hole gun-drilling in Ti6Al4V titanium alloy, the coordinate of the center of the circle is inclined to the same direction, and with the increase of the drilling depth, the axial deflection increases and the slope increases.
In gun-drilling, so the general drill shaft are slender and poor stiffness for reaching the standard of larger depth-to-diameter-ratios, so it is prone to bend under the influence of feeding force, which results in the deviation of the axis of the machined hole. The main reasons for the axis deviation are: (1) clamping error (2) spindle skew (3) tool bore deflection. The axis deviations can be considered as a superposition of two errors in the test results, as shown in Figure 4.

Linear deviation 1 is mainly caused by the clamping error and spindle deviation, which could be reduced by adjusting the machine or tooling. The nonlinear deviation 2 is mainly caused by the deviation of the tool during drilling. Here we mainly discuss the nonlinear deviation 2.

The main reasons for the axis deviation caused by the tool are as follows: the gap between the tool head and the pilot bushing, the axis misalign of intermediate support and the weight of the drill shaft.

The effect of the gap: To ensure the drilling accuracy, gun-drilling needs to process the guide hole at the drilling entrance or use the pilot bushing. The gun drill tip is an asymmetric structure, which results in unbalanced forces in the gun drill when it is cut into the material. This in turn causes the drill head to deflection toward the pilot bushing side, so drilling axis deflection caused by the gap of the pilot bushing is unavoidable, but we can reduce borehole deviations by increasing the stability of the drilling entry phase [8], such as layouting the guide position reasonably and reducing the axial distance from the outside edge to the guide strips as shown in Figure 5.
a. the pilot bushing gap; b. weight of the drill shaft c. the deviation of support.

**Figure 5.** Bore-hole axis deflection caused by

The effect of misaligned axes of intermediate support: in gun-drilling, usually, 2-3 supports are added to the drill shaft to improve its rigidity and the stability of gun-drilling reasonably, but it is difficult to ensure that the intermediate support and machine tool spindle is completely coaxial. Deviation of the intermediate support will add a directional load to the drill shaft, which will also result in axial deviation of the machined deep hole [9].

Other factors: except the above, there are many random factors that can affect the axis deviation. Such as uneven hardness of the workpiece material, hard point, and chip evacuation situation.

Conclusion: By analyzing the experiment we can see that the axis of the bore-hole is more skewed relative to the axis of the bar, which is mainly due to the deviation of the the machine tool spindle .

This error can be reduced by adjusting the spindle. Regardless of the linear deviation of the axis, the error of the axis of the bore- hole is about 0.025mm, which is within the acceptable range.

### 3.3. Aperture Error Analysis

The experimental results show that the diameter of the hole is larger than the diameter of the drill head, and as the depth of the hole increases, the diameter of the hole increases, as shown in Figure 6.7.

**Figure 6.** Changes of drill hole diameter with drilling depth.

**Figure 7.** The process of drilling into material
The process of gun drill cutting into workpiece can be divided into two phase: the outer edge cutting into the workpiece completely and the guide strip penetrating into the material.

In the process of cutting edge cutting into the workpiece, there is a gap between the drill head and the pilot bushing, and the cutting speed of the outer edge is greater than that of the inner edge, resulting in the force of the outer edge being greater than that of the inner edge so that the cutting force working together toward the axis, making the guide strip close to the inner side of the pilot bushing and the hole diameter being less than the ideal hole diameter. In the second stage, Due to the entry of the guide strip, the diameter of the drilled hole is forced to be enlarged, and the drilling hole is extruded and rubbed by the guide strip and the side edge, which eventually leads to the enlargement of the bore-hole diameter. With the increase of the clearance of the pilot bushing, the influence of the change of the aperture size is greater. Bore-hole diameter error is mainly related to the material of the drill shaft, the cutting speed and feed speed [10], the number of guide strip [8] and the tool coating.

4. Gun-Drilling test of Ti6Al4V Titanium Alloy

In order to know the influence of processing parameters of drilling Ti6Al4V titanium alloy on drilling process and drilling quality, we conducted process parameters experiment of drilling φ17mm deep hole on Ti6Al4V titanium alloy, the experimental parameters and test results are shown in Table 1:

| Cutting speed Vc(m/min) | feed fn(mm/r) | Cutting fluid pressure(Mpa) | Roughness Ra(μm) | Chip condition | Sound |
|-------------------------|--------------|----------------------------|-----------------|----------------|-------|
| 20                      | 0.02         | 3                          | 2.2             | Chip breaking well | smooth |
| 30                      | 0.03         | 3                          | 2.2             | Chip breaking well | smooth |
| 40                      | 0.03         | 3                          | 1.8             | Chip breaking well | smooth |
| 50                      | 0.04         | 3                          | 2.25            | Chip breaking well | harsh |
| 50                      | 0.06         | 3                          | 3.25            | Chip breaking well | harsh |

It can be concluded from Figure 8 that the chip breaking condition is good during the process of drilling Ti6Al4V titanium alloy. However, when we chose the process parameters Vc= 50m/min, fn= 0.04mm/r and Vc= 50m/min and fn= 0.06mm/r, the processing sound is harsh and the chips become large, in addition the roughness of machined surface becomes larger. When the process parameters were Vc=20m/min, fn= 0.02mm/r and Vc=30m/min, fn= 0.03mm/r, the chip breaking conditions and the drilling surface roughness are better, but the processing efficiency is lower. Considering the processing efficiency and processing effect, when we drill φ17mm deep hole on Ti6Al4V titanium alloy by carbide drill, the best processing parameters are Vc= 40m/min and fn= 0.03mm/r.

![Figure 8. φ17mm deep hole drilling cuttings on Ti6Al4V titanium alloy](image_url)
Although the surface roughness has achieved good results, but the machined titanium alloy surface can be seen obvious scratches. As can be seen from the micro-surface topographies of the machined Ti6Al4V titanium alloy in Figure 9, the maximum distance of peak and trough is about 13μm on the machined surface, which is unmeasured by the roughness tester.

Variation cycle of scratch on the machined surface is much larger than the feed rate of gun-drill, 0.03mm / r. At the same time the scratch is not regular, so the main reason for the above scratches was cuttings. Because of the larger drilling diameter, insufficient supply pressure of the cutting fluid, and the pressure loss in the cutting fluid transmission inside the drill shaft, the actual pressure for ejecting chips is less than the theoretical value, which can not provide enough cutting fluid to quickly drain the cuttings out of the deep hole. Therefore, when the tool rotates, the cuttings also rotate in the deep hole, so that the machined surface is scratched.

Conclusion: The optimum technological parameters of drilling φ17 deep-hole on Ti6Al4V titanium alloy by gun-drill are $V_c = 40m / \text{min}$, $f_n = 0.03mm / r$, and the surface roughness Ra about 1.8μm. However, there are cuttings scratches on the surface of φ17mm machined deep hole. In order to improve the surface quality of Ti6Al4V titanium alloy drilling, it is recommended to use a larger flow pump or to use the gun reamers to further improve the surface quality of the drilling.

5. Conclusion
In this paper, the characteristics of gun-drilling of Ti6Al4V titanium alloy were preliminarily studied through the deep hole drilling experiment of Ti6Al4V titanium alloy, and the main causes of axis deviation and aperture error in deep hole machining by gun drill were analyzed. By adjusting the machine tool and tooling, the axial deviation of the drill hole is reduced. Through the process parameters experiment, we optimized the technological parameters of gun-drilling φ17mm deep hole of Ti6Al4V titanium alloy. The smaller drilling surface roughness is obtained by the experiment of drilling technological parameters, but the cutting fluid pressure is not enough, resulting in serious scratches on the machined surface. In the end, the surface quality of the drilled hole was further improved by the combination of the gun drill and the gun ream. Finally, the deep hole machining of the Ti6Al4V titanium alloy with a depth of 860 mm was completed, so that the integrated error of the drilling was less than 0.2 mm and the roughness Ra was less than 1.6 μm.

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7. References
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