Effect of Laser Beam Focusing Adjustment on the Processing Quality of Aluminum Nitride Ceramic Micro-Holes

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Abstract. The Gaussian laser beam was used to drill micro-holes with a diameter of 500μm on a 0.15mm thick aluminum nitride (AlN) ceramic. The geometry, processing quality, and surface fusion of the micro-holes were studied. The fusion recast layer at the edge of the hole is thick, the inner wall of the hole has a lot of slag, and the side wall of the laser entrance area is seriously inclined. Through spatial reshaping and focusing of Gaussian light, Bessel light with higher energy density, greater depth of focus, and smaller beam spot was achieved and used to perforate AlN ceramics. The fusion recast layer at the periphery and inner wall of the hole are both very thin, and the taper of the hole is very small. These results show that the focusing adjustment of the laser beam has a significant impact on the processing quality of AlN ceramic micro-holes.

1. Introduction

Compared with traditional mechanical drilling, laser drilling has the characteristics of fast speed, low cost, high efficiency, small deformation, wide applicability, and no direct contact with the samples. It is especially suitable for processing hard and brittle materials which is not suitable for mechanical processing [1-4]. At present, laser drilling technology has developed into an advanced processing method in the fields of aviation, aerospace, optoelectronics and many other industries [5-8].

In recent years, researches on laser precision micro-hole processing have been very active. Hsiao et. al. studied the effects of current scanning speed and milling time on the surface morphology, cone angle and melting residue height of Al₂O₃ ceramic materials by laser milling method [9]. Adelmann et al. studied the drilling process of Al₂O₃ and AlN ceramic substrates with a fast single-mode fiber laser [10]. Tsai et. al. used an improved electronic dynamics theory to study the ablation rate of nano-sized Al₂O₃ ceramics processed by femtosecond lasers, and discussed the influence of material thermal properties on the ablation characteristics of ceramics [11]. Wang et al. studied the effects of key laser experimental parameters on the quality and physical mechanism of drilled ceramics, and showed that heating and liquid-assisted laser processing are effective methods to improve the processing quality [12]. The above researches mainly focus on the effect of laser processing parameters on micro-holes, however, there are few researches on the influence of spatial adjustment of the laser beam.

This work investigates the results of micro-hole processing with Gaussian light and the spatial reshaped Bessel light beam. Firstly, Gaussian light was used to drill micro-holes with 500μm diameter
on a 0.15mm thick AlN ceramic substrate, in order to study the surface morphology, inner wall morphology and geometric characteristics of the hole. Then the Gaussian light beam was spatially reshaped to obtain Bessel light beam with stronger focusing ability. The Bessel light is similarly used to drill micro-holes with 500μm diameter on a 0.15mm thick AlN ceramic to study the surface and inner morphology of the hole. The differences between the two types of laser beams are discussed to reveal the mechanism of laser beam shape on ceramic processing quality.

2. Experimental methods

2.1. Gaussian beam processing

In the experiment, the Gaussian beam was firstly used to process micro-holes on hard and brittle AlN materials. The laser was operated in the fundamental transverse mode (TEM00), and the beam cross section had a Gaussian intensity distribution, as shown in Fig. 1(a). The Gaussian beam was collimated, converged and finally irradiated to the surface of the sample as shown in Fig. 1(b). The M2 factor of the fundamental mode of the Gaussian beam is close to 1. The beam has a uniform and uninterrupted intensity distribution, small divergence angle, and focused spot size. At the same time, the near-axis spatial propagation of Gaussian light is actually based on the Fourier transform diffraction process. Therefore, in an optical system composed of simple lens, the Gaussian beam can always maintain a Gaussian lateral intensity distribution in the propagation path. These characteristics ensure that the Gaussian beam can obtain a reliable resolution close to the diffraction limit during material processing.

![Image](image1.png)

Figure 1. Radial energy distribution and drilling principle of Gaussian beam.

2.2. Space reshaping and focusing of the beam

Figure 2 is the schematic diagram of a system for generating tightly focused Bessel beam composed of an axicon and a 4f beam reduction system. As shown in Fig. 2(a), when Gaussian light with beam spot radius \( W_1 \) is incident on an axis prism with base angle \( \alpha \), the transmitted beam has a small convergence angle \( q_1 \) and is determined by \( \alpha \). The interference of the convergent beam produces the first Bessel region (filled area in the figure). Using the midpoint of the first Bessel area as the reference position (the position indicated by the arrow), the front focal plane of the first lens of the 4f system coincides with it, and the light beam will converge again after passing through the 4f system of beam reduction to form the second Bessel region. The 4f system connects the first and the second Bessel region in the form of relay imaging, which functions to enlarge the half-cone angle and reduce the beam width. The focused 0-level Bessel light is shown in Fig. 2(b).

The axicon used in the research is a high-precision version produced by Altechna. It generates a wavelength of 1064nm by an Nd: YAG laser (BX-2-G, Edgewave). After laser spatial reshaping and focusing, the frequency doubling generates green light at 532nm. When the nanosecond pulse is 10ns, \( \alpha=2.5^\circ \), \( f_1=150\text{mm} \), the focusing mirror of the galvanometer is equivalent to the second lens \( f_2=100\text{mm} \). In the experiment, Gaussian light was first used to process 500μm through holes in a 0.15mm thick
AlN ceramic substrate, and then the Bessel light obtained by beam spatial reshaping and focusing was used to drill micro-holes. The influence of the two beams on the wall taper, hole morphology, and recast layer were studied.

Figure 2. Beam spatial reshaping and focusing: (a) axicon+4f system; (b) focused 0-level Bessel light.

3. Results and discussion

3.1. Impact of Gaussian light on the hole processing quality

3.1.1. Surface morphology. Figure 3 is the surface morphology and composition of 500μm diameter micro-hole drilled in a 0.15mm thick AlN ceramic substrate by Gaussian light. It can be seen from Fig. 3(a) that there is obvious fusion recast layer around the hole. Figures 3(b) and (c) indicate that the recast layer at the edge of the hole is thick and completely cover the surface of the substrate. The recast layer exhibit in the form of small particles. In the area away from the hole edge, the recast layer is thinner and only part of the substrate is covered. Figure 3(d) is the surface composition obtained by EDS analysis for the micro-holes. The recast layer contains a large amount of oxygen element, because AlN may react with oxygen and form alumina under high temperature during laser processing.

Figure 3. Surface morphology and composition of 500μm diameter micro-hole prepared by Gaussian light: (a) surface of the hole; (b) recast layer near the hole; (c) morphology near the hole edge; (d) Surface composition.
3.1.2. *Inner morphology.* Figure 4 is the morphology and composition of the inner wall of the hole. It can be seen that the inner wall of the hole also has a significant fusion recast layer as the surface has. The recast layer at the laser inlet is more significant than that of the outlet. It is known from Fig. 4(b) and (c) that uneven dross occurs on the side wall of the hole. Before the substrate is completely penetrated, the lower surface generally does not form obvious slag. At this time, the melted layer is unstable and the airflow will recoil out of the upper surface. The resulted particles have poor sphericity and small size. When the substrate is completely penetrated, part of the material can be sprayed out through the uneven cutting holes that just appeared on the lower surface. But due to the poor airflow passing effect, the blowing material is too little, causing the dross height to increase rapidly. When the lower surface is completely penetrated and reaches a stable state, the increase in the average diameter of the particles means that the amount of material participating in the removal increases, the material dragging on the lower surface becomes more obvious, and the increase in the slag height tends to be linear. Figure 4(d) is the composition of the inner wall, there is large amount of oxygen elements which indicating the oxidization of the recast layer.

![Figure 4](image)

**Figure 4.** Morphology and composition of the inner wall of 500μm diameter micro-hole prepared by Gaussian light: (a) overall of the inner wall, (b) (c) local enlarged morphology of the hole, (d) composition of the inner wall.

3.1.3. *Geometry of the hole.* Figure 5 shows the geometry of the micro-holes observed by a confocal laser scanning microscope (CLSM). It can be seen that the inner wall of the hole has a certain tilt, especially in the laser entrance area, the tilt of the side wall is particularly serious.

![Figure 5](image)

**Figure 5.** Geometry of 500μm diameter micro-holes prepared by Gaussian light.
3.2. Impact of Bessel light on hole processing quality

3.2.1. Surface morphology. Figure 6 is the surface morphology and composition of AlN micro-holes prepared by Bessel light. It can be seen that when Bessel light is perforated, a fused recast layer is also formed on the edge of the micro-hole, but its area is smaller than Gaussian light do and is only limited to the edge of the hole. The fusion recast layer has a coarse particle structure, and there is almost no fused recast layer in the area away from the hole’s edge. Figure 6(c) shows the surface composition of AlN micro-holes prepared by Bessel light. The recast layer at the edge of the hole has been completely oxidized and contains almost no N element. While in the area leaving the edge, it is partially oxidized and there is still a considerable amount of N, indicating that the fused recast layer is very thin.

![Figure 6](image)

**Figure 6.** Surface morphology and composition of 500μm diameter micro-hole drilled by Bessel light: (a) overall of the micro-hole; (b) morphology near the hole’s edge; (c) surface composition.

3.2.2. Inner morphology. Figure 7 is the inner wall morphology and composition of AlN micro-holes prepared by Bessel light. As can be seen from Fig. 7(b) and (c), the inner wall of the hole is covered by loose and porous recast layers and particles. Figure 7(c) is the inner wall composition of the AlN micro-holes prepared by Bessel light, the main composition is alumina. This is because that the energy is absorbed by the substrate during laser processing and the temperature rises rapidly. Then the AlN is vaporized and oxidized to produce alumina. The vaporized alumina quickly solidifies and is adsorbed on the side wall of the hole to form a loose, particulate-like porous layer.
Figure 7. Morphology and composition of the inner wall of the 500μm diameter micro-hole prepared by Bessel light: (a) overall of the inner wall, (b) (c) local enlarged morphology of the hole, (d) composition of the inner wall.

3.2.3. Geometry of the hole. Figure 8 shows the geometry of AlN micro-holes prepared by Bessel light. The inner wall of the hole is very steep, and there is no tilt as the hole processed by Gaussian light. Through spatial reshaping of the laser beam, the fusion recast layer of the Bessel light processed micro-holes is weakened, and the steepness of the side wall is improved. Because the energy distribution of the 0-level Bessel light is more concentrated, the focus depth is larger, and the peak power density is extremely high, the material removal during the drilling process is easier and thorough. At the same time, after further converging the laser pulses with a lens, the concentrated distribution of energy is more conducive to processing microstructures with small tapers.

Figure 8. Geometry of 500μm diameter micro-hole prepared by Bessel light.

4. Conclusions
Spatial reshaping and focusing of Gaussian light were used to generate Bessel light. The surface fused recast layer of the AlN micro-holes prepared by Gaussian light is obvious, the fused recast layer at the edge of the hole is thick, the side wall of the laser entrance area is seriously inclined, and the inner wall recast layer is oxidized. While the periphery and inner wall of the micro-holes drilled by Bessel light has less recast layer, and the fused recast layer at the edge of the hole has been completely oxidized. Furthermore, the taper of the hole is very small. It can be concluded that focusing adjustment of the laser beam has a significant impact on the processing quality of AlN micro-holes.
5. References

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