Characterization of Hole Morphology in Deep Hole Micro Drilling using QCW Laser

WCMNM 2021

Bhargavi Ankamreddy, Sachin Alya, Ramesh Singh

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai, India

Abstract

Lasers find applications in various fields of science and engineering. One such application is micro-scale drilling of high aspect ratio holes. Laser-based drilling is a viable option for micro-scale hole manufacturing. In this paper, laser micro-drilling of three different materials of different optical and thermal properties, namely stainless steel, copper and aluminium, are studied. The drilling operation is performed by firing a single pulse with a quasi-continuous wave (QCW) fiber laser. Various characteristics of the holes, such as the diameters at the entry and exit of the hole, the taper angle, the circularity, and the spatter on the entry surface of the hole have been studied. In the range of parameters investigated, the hole diameters of stainless steel at the entry and exit are found to be larger than copper and aluminium. The holes are more circular in the case of stainless steel, and aluminium has relatively clean holes with minimal spatter.

Keywords: Laser drilling, micro-drilling, long pulse drilling, hole diameter, circularity, spatter

1. Introduction

The emerging shift towards miniaturization continuously challenges the existing manufacturing technologies. One of the most important operations is mechanical drilling, which becomes extremely challenging at the micro-scale, especially for high aspect ratio micro-holes. On the other hand, deep hole drilling using laser has proven to be a sustainable solution for micro-scale drilling. This process uses a laser beam, which melts and ablates the material locally. The process can accommodate a wide range of materials and is advantageous in micro-scale drilling, and a pulsed fibre laser is ideal for drilling micro-scale high aspect ratios holes.

Gautam and Pandey [1] reviewed the laser drilling using pulsed Nd:YAG laser. They emphasized that the geometry and quality of the drilled holes depend on the laser power, pulse width, pulse frequency, specimen thickness, the focus position of the laser beam, and material properties. The laser drilling can be performed using a single pulse or multiple pulses. The single pulse drilling is useful for micro-drilling where a taper of the hole across the thickness of the specimen is allowed. Meszlenyi and Bitay [2] studied the single pulse drilling of highly reflective materials and the role of focus position. They used a quasi-continuous wave (QCW) laser for drilling copper and silver and found that the focal position of the laser beam is the main factor affecting hole morphology. Marimuthu et al. [3] determined the micro-drilling characteristics in nickel super alloy drilled by using QCW laser. The authors determined that micro holes of a 20:1 aspect ratio can be drilled using a QCW laser.

In drilling using lasers, material removal happens by vaporization and ejection of the molten material. The ejected melt forms a spatter near the entry surface of the hole. Low et al. [4] characterized the formation of spatter during laser drilling and observed that the spatter areas are smaller for high pulse frequency, low peak power and short pulse width. Pocorni et al. [5] investigated the piercing of stainless steel using a fibre laser. The authors concluded that the short laser off times in pulsing mode could help the melt ejection. Ahn et al. [6] studied the effect of process parameters on drilling of Aluminum 1050 sheet. They determined that the drilled hole geometry is highly dependent on pulse width and frequency. They further added that the drilled hole has a taper angle of 6 degrees under optimal drilling conditions. Solana et al. [7] discussed the liquid ejection process and ablation in single-pulse drilling of aluminium and titanium. Tunna et al. [8] studied the micromachining of copper using Nd: YAG laser radiation and concluded that at 1064 nm, the copper highly reflective nature decreases the processing rate. From the literature, it can be seen that very limited work has been reported on single-pulse laser drilling.

The present work includes the study of the single pulse laser micro-drilling of stainless steel 304 (SS), and highly reflective commercially pure copper (Cu) and aluminium (Al) using long pulse by QCW Ytterbium laser system. The entry and exit holes diameter, the taper angle of holes, circularity of entry and exit holes, and spatter after drilling is determined. This study shows the micro-drilling aspects of three different materials with varying optical and thermal properties.

2. Experimental details

The laser drilling experiments were conducted using a QCW Ytterbium laser system (YLS - 600/6000- QCW- AC) in the Machine Tool Laboratory (MTL) at IIT Bombay. The system can deliver a peak power of 6000 W in pulse mode. The operational ranges of pulse frequency and pulse width of the system are 1-500 Hz and 0.1-10 ms, respectively. The laser delivery end is connected to the drilling head, which contains optics for focusing the laser beam. The laser drilling head is shown in Fig.1. The micro-drilling is done using a single pulse with parameters as shown in Table 1. Three levels of peak power and pulse width are selected in such a way that through-hole is achieved in all three materials considered in this study. The materials selected for the study are stainless steel, copper, and aluminium. Based on their optical and thermal properties, like absorptivity for a wavelength of 1070 nm, copper and aluminium are considered to be highly reflective materials due to their poor absorptivity. The thickness of each specimen was 1.5 mm. The laser beam spot size is 125 microns at a standoff distance of 10 mm from the drilling head.

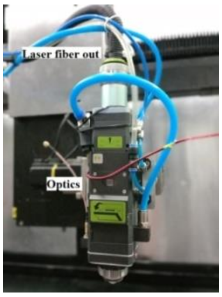

Fig.1. QCW Laser system drilling head

The 600/6000 W QCW laser is a multi-mode and flat-top distribution. The compressed air is used as a process gas at 8 bars for melt expulsion and protection of optical components in the drilling head from the vapours formed.

Table 1 Parameters

S.No	Peak power (W)	Pulse width (ms)	Fluence (J/cm^2)
1	5000	2.5	2.547e4
2	5000	3	3.057e4
3	5000	3.5	3.566e4
4	5500	2.5	2.802e4
5	5500	3	3.363e4
6	5500	3.5	3.923e4
7	6000	2.5	3.057e4
8	6000	3	3.668e4
9	6000	3.5	4.280e4

For each studied material, 9 experiments are conducted with three repetitions. After the micro-hole drilling, the geometry (hole diameter at entry and exit), circularity and spatter of the holes are characterized using Alicona, 3D optical profilometer. The full taper angle (θ) of the drilled hole is determined by using the entry and exit diameters of the hole, as shown in Eq. (1). The circularity (C) of the hole at entry and exit is given by Eq. (2). The spatter after drilling the holes is determined by the distance of the longest point of the spatter from the wall of the entry hole. Fig. 2 shows the full taper angle and spatter of the drilled hole.

$$\theta = 2tan^{-1}\left(\frac{(D-d)}{2t}\right) \quad (1)$$

where D is the entry diameter of the hole, d is the exit hole diameter, t is the thickness of the specimen.

$$C = \begin{cases} \frac{D_{min}}{D_{max}} \ (at\ entry) \\ \frac{d_{min}}{d_{max}} (at\ exit) \end{cases} \quad (2)$$

where D_{min}, D_{max}, d_{min} and d_{max} are the minimum and maximum entry and exit hole diameters, respectively.

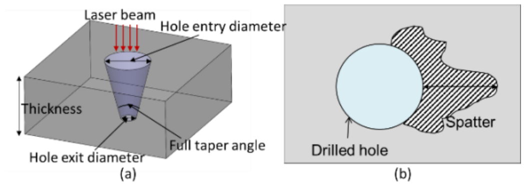

Fig.2. (a) Full taper angle of a hole (b) Spatter of the hole

3. Results and discussion

3.1 Geometry of hole – diameter and taper

The laser drilling process is a thermally driven process where the material is removed by vaporization and expulsion of the melt. This process is highly dependent on the process parameters and the properties of the material. Therefore, the optical and thermal properties of the selected materials play an important role besides the process parameters like pulse width, pulse energy and pulse frequency. In the current study, the pulse frequency is not a process parameter as only a single pulse is fired for removing the material.

In this work, the micro-drilling is performed by a long single pulse (millisecond pulse) for varying peak power and pulse width. In drilling, the hole diameter at entry and exit are of utmost importance. The geometry of the holes is highly dependent on the process parameters like peak power and pulse width in single-pulse drilling. The absorptivity of the material also plays an important role in the determination of the hole diameter. The entry and exit diameters of the holes with varying peak power of 5000 W, 5500W and 6000 W at 2.5 ms pulse width for SS, Cu and Al are shown in Fig.3. This shows that the hole diameters increases if the peak laser power is increased.

The hole diameters at entry and exit in stainless steel are larger than copper and aluminium for similar process conditions. It can be attributed to the high absorptivity of stainless steel compared to copper and aluminium. As the absorptivity of SS is nearly seven times that of Cu and Al for 1070 nm wavelength, the absorbed power is much higher in the case of SS. Fig. 4 shows the entry and exit diameters of the hole at 6000 W peak power and varying pulse widths of 2.5 ms, 3 ms and 3.5 ms. It can be noted that at higher pulse widths, the exit diameter of the aluminium is larger than the copper. The exit diameter of the hole depends upon the absorptivity, thermal diffusivity and thermal conductivity of the material. Copper has higher thermal conductivity than aluminium. Due to this, the heat dissipated in the lateral direction is higher in copper. As a result of this, the exit hole diameter of the copper is smaller than that of aluminium.

The diameters at entry and exit of the hole are generally not equal in laser drilling, causing the hole to be taper instead of cylindrical. The taper angle of the hole is determined by using Eq.1. The taper angle depends on the entry and exit hole diameter and the thickness of the specimen. Though the taper angle is not desirable in many applications, it is of importance in applications like spinneret in the textile industry. The full taper angle of SS, Cu and Al at 3 ms pulse width and 5500 W peak power is shown in Fig. 5. As seen in Fig. 5, the full taper angle of the aluminium is less than copper due to the smaller exit holes in copper at higher pulse widths.

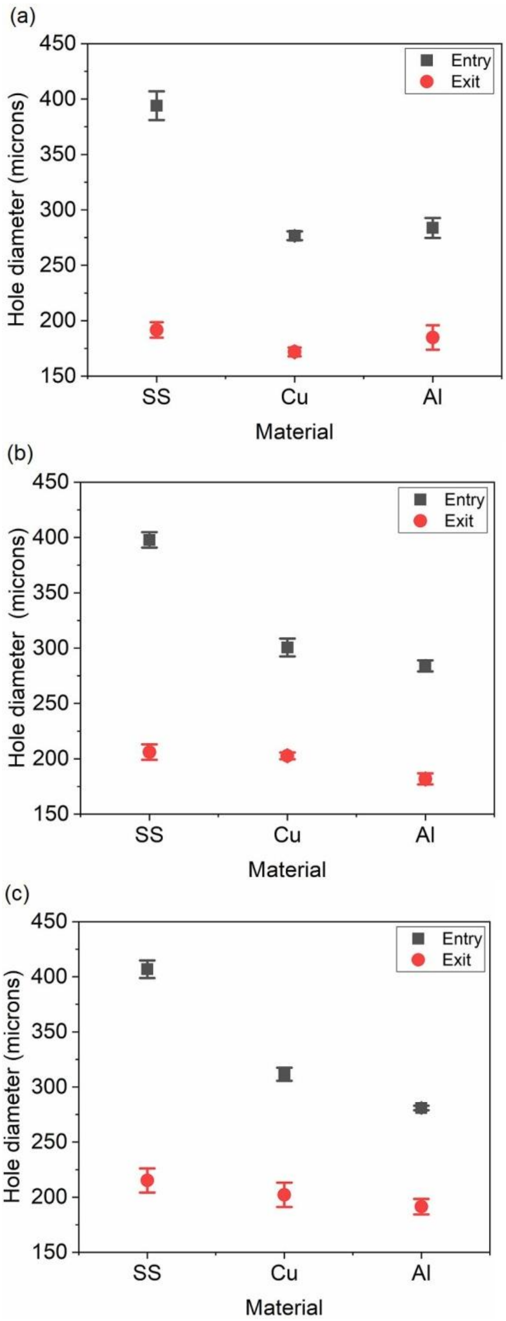

Fig. 3 Entry and exit hole diameter at peak power and pulse width of (a) 5000 W and 2.5 ms (b) 5500 W and 2.5 ms (c) 6000 W and 2.5 ms

3.2 Circularity and spatter

The quality of the drilled hole depends upon the circularity of the hole. For a quality hole, in addition to the desired hole diameter at entry and exit, the circularity of the hole is also important. The circularity of the hole depends upon the distribution of the laser. For most of the applications, the hole should be circular. The circularity of all the entry and exit holes is calculated by using Eq. (2). Figure 6 shows the average circularity of the holes at the entry and exit for SS, Cu and Al. From Fig. 6, it can be seen that the SS has more circular holes than Cu and Al.

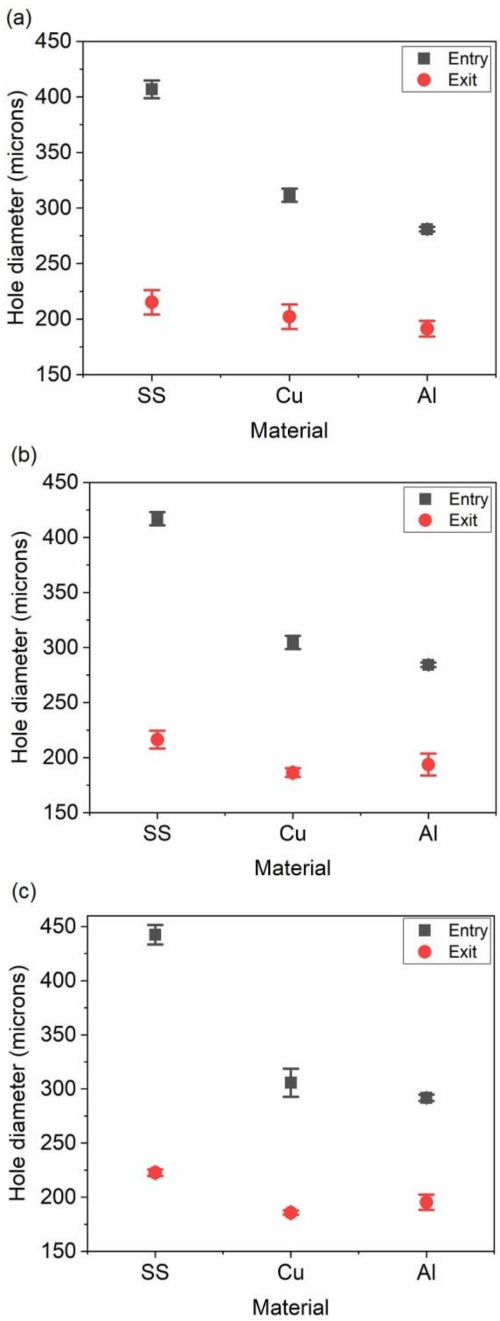

Fig. 4. Entry and exit hole diameter at peak power and pulse width of (a) 6000 W and 2.5 ms (b) 6000 W and 3 ms (c) 6000 W and 3.5 ms

The average circularity of holes at the entry and exit in SS is 0.94 and 0.90 respectively. Copper has a circularity of 0.88 at entry and 0.84 at the exit of the hole. The circularity of the holes drilled in copper is less compared to the other two materials. The exit hole circularity is less than their respective entry holes in all the three materials drilled. While the drilling process using the laser, the material removal happens by vaporization and melt ejection. The melt formed during drilling is expulsed through the entry surface of the hole. Once the melt solidifies, it attaches to the entry surface as a spatter. The spatter on the surface should be removed by finishing operations to get a quality hole.

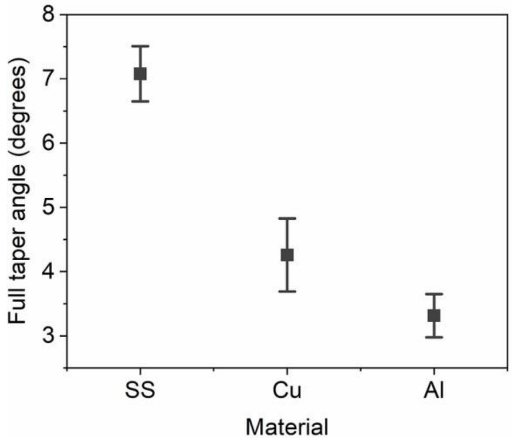

Fig. 5 Full taper angle of holes at 5500 W peak power and 3 ms pulse width

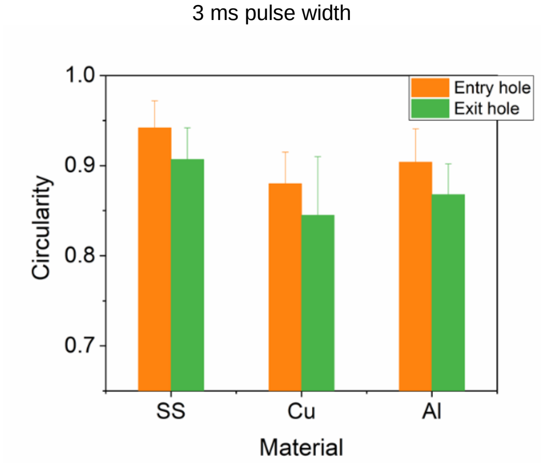

Fig. 6 Average circularity of holes

The amount of spatter on the surface depends upon the process parameters and the properties of the material used. In this study, the spatter analysis is done by taking the distance between the longest point of the spatter and the wall of the entry hole. The average spatter of SS, Cu and Al are shown in Fig. 7. The figure shows that copper has more average spatter when compared to SS and aluminium.

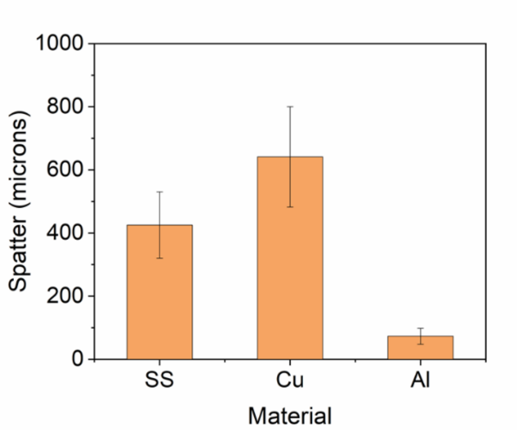

Fig. 7 Average spatter of holes

The spatter in the holes can be seen in the micrographs, as shown in Fig. 8. The aluminium has very minimal spatter when compared to the other two materials used. The spatter has to be removed before the use of the drilled hole. It can be done by finishing operations like polishing the surface of the drilled hole. Due to the minimal spatter, the aluminium offers fewer efforts in finishing mechanisms.

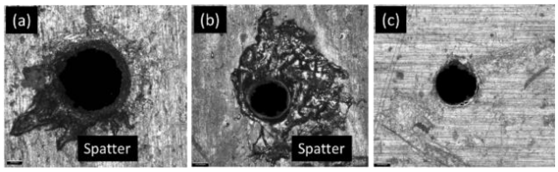

Fig. 8. Micrographs showing spatter of holes in (a) SS (b) Cu (c) Al

4. Conclusions

This work focuses on micro drilling using QCW laser by single long pulse on stainless steel, copper and aluminium specimen. The following conclusions can be drawn from this work:

- In the studied parametric range, the entry and exit hole diameter of stainless steel is higher than that of copper and aluminium.
- At higher pulse widths, the hole exit diameter of copper is smaller than that of aluminium.
- The stainless steel has a higher average circularity of holes at both exit and entry compared to copper and aluminium with 0.94 and 0.90 at entry and exit of the hole. The copper's hole average circularity is the least in comparison with 0.88 and 0.84 at entry and exit respectively.
- The average spatter observed in copper is significantly higher than the average spatter observed in stainless steel and aluminium.
- Aluminium has very minimal spatter and requires less effort in finishing operations.

Acknowledgement

The authors wish to gratefully acknowledge that this research was funded by the DST-Swarnajayanti Fellowship award [DST/SJF/ETA-02/2014-2015] and the Technology Systems Development Program [DST/TSG/AMT/2015/226/G], Government of India.

References

[1] G.D. Gautam et al., "Pulsed Nd:YAG laser beam drilling: A review," Opt. Las. Tech., 2018; 100: 183-215.

[2] G. Meszlenyi et al., "The Role of Focus Position in Single Pulse Laser Drilling of Highly Reflecting Materials," Act. Mat. Trans., 2019; 2/1: 61-68.

[3] S. Marimuthu et al., "Characteristics of micro-hole formation during fibre laser drilling of aerospace superalloy," Pre. Eng.,2019;55:339-348.

[4] D.K.Y. Low et al., "Characteristics of spatter formation under the effects of different laser parameters during laser drilling,"J. Mat.Pro.Tech.,2001;118:179-186.

[5] J. Pocorni et al., "Investigation of the piercing process in laser cutting of stainless steel,"J. Las.App.,2017;29:022201.

[6] D.G. Ahn et al., "Influence of process parameters on drilling characteristics of Al 1050 sheet with thickness of 0.2 mm using pulsed Nd:YAGlaser,"Trans. Nonferr.Met.Soc.Chi.,2009;

157-163.
[7] P Solana et al., “Time dependent ablation and liquid ejection processes during the laser drilling of metals,”Opt. Comm.,2001;97-112.
[8] L. Tunna et al., “Micromachining of copper using Nd:YAG laser radiation at 1064, 532, and 355 nm wavelengths’, Opt. & Laser Tech.,2001:135-143