Quality Assessment and Features of Microdrilled Holes in Aluminum Alloy Using Ultrafast Laser

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Abstract

In this work, we present the use of an ultrafast laser system for the high aspect ratio micro-drilling of aluminum alloy thin foils. Hole sizes in between 20 and 40 µm were fabricated in arrays with sub-micron level precision in terms of diameter and hole location. The Design of Experiment approach was employed to analyze the influences of the laser process parameters like laser power, frequency, and exposure time on the resulting quality of the produced micro-holes. The outputs measured were hole size, location and the variability in these measures. The metallurgical and geometrical features were examined using a scanning electron microscope and optical microscope. Processing throughput is also important in industrial laser processes. The parametric effect on circularity and taper has been observed to understand the features of the hole. The features of holes help in fabrication in a plethora of industries to produce applications such as fins, filters, microgrid circuits, and biomedical devices.

Keywords

Aluminium alloy • Femtosecond laser • Circularity • Taper • Micro drilling

Introduction

In laser drilling, a high-intensity infrared laser beam is focused on a spot of the workpiece (generally between 0.1 and 2.0 mm in spot diameter) to remove materials to produce a hole. This laser drilling operation takes place in three phases (I) melting of material (II) vaporization and (III) chemical degradation throughout the depth of the material [1]. Laser drilling is gradually becoming a popular machining technique for micro-drilling on various engineering materials and components of intricate shapes. Researchers and scientists are working diligently to develop a new technology to attain the recent demand in the scientific field. There is the widespread application of micro-machined products in heat exchangers for micro-electronic products, micro-nozzle systems, micro-electromechanical systems (MEMS), micro-molds and micro-fluidic systems etc. [2–4]. Literature suggests that the present trend of research is directed toward the micro-machining of a wide variety of work materials ranging from easy-to-cut to hard-to-cut materials for aerospace applications [5–7].

Micro-machining on engineering materials such as aluminum alloys, stainless steels, titanium alloys, nickel alloys and ceramics is quite popular among practitioners because of their widespread applications in aviation, automobile, aerospace, medical and electronic industry as they possess favorable properties like low thermal conductivity, resistance to high temperature, high corrosion resistance and high strength to weight ratio [8–12].

Laser drilling of aluminum alloy is not as effective as it could be because aluminum alloy has a poor absorption rate of laser beam energy and is easily oxidized in the air,

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necessitating the use of protective gas during drilling. As a result, a few investigations have been done on the laser drilling technology for aluminum alloy [13–15]. In order to increase the rate of material removal and lessen the taper of the hole, Mishra et al. [4, 16] primarily constructed a numerical model for aluminum alloy laser drilling and predicted and set the best drilling process parameters (pulse width, pulse repetition frequency, pulse peak power, etc.) through the numerical model. The processing of materials using different pulsed lasers was studied by Fujita et al. [17] to determine the dependence of wavelength and pulse width. The research revealed that processing efficiency and thermal damage might be improved using shorter wavelengths and pulse widths. Higher cutting efficiency and a smaller heat-affected zone (HAZ) phenomenon resulted from shorter wavelength and pulse width.

However, micro-machining of aluminum alloy using conventional machining techniques is difficult due to continuous chip production and built-up edges near the drilled holes. As far as micro-drilling is concerned, laser drilling is a preferred drilling technique because a high-intensity laser beam can be focused on a precise location for a small-time interval to achieve the desired hole avoiding thermal degradation of the material. In the present study, laser drilling of aluminum alloy has been performed using a femtosecond millisecond laser in ambient air. The influence of machining parameters such as laser power, repetition rate, and exposure time on the quality characteristics of laser drilled samples is examined. Quality characteristics considered for the study are circularity at entry, circularity at the exit, and taper. The study has adopted the design of experiment (DOE) approach to design the experimental layout so that maximum process-related information can be gathered from fewer experimental trails.

Materials and Methods

Materials

The material considered in the present study is made up of commercially available Aluminum alloy Al 1145 (UNS A91145) in the form of thin foils having 0.03 mm thickness. The chemical composition and mechanical properties of Al 1145 are as mentioned in Tables 1 and 2.

Table 1 Chemical constituents of Al 1145 [18]

Constituents	% Content
Titanium, Ti	0.03
Zinc, Zn	0.05
Magnesium, Mg	0.05
Manganese, Mn	0.05
Copper, Cu	0.05
Aluminum, Al	99.45
Silicon, Si + Iron, Fe	Remaining

Table 2 Physical properties of Al 1145 [18]

Properties	
Density	2.6–2.8 g/cm^3
Elastic modulus	70–80 GPa
Poisson's ratio	0.33
Thermal conductivity	227 W/mK

Experimental Procedure

Laser drilling on Al 1145 foil (a thin foil of 0.03 mm) has been carried out to study the effect of process parameters on performance measures. In this study, we used an ultrafast femtosecond laser (NKT One Five Origami 10XP) that generates 400 fs pulses with 1030 nm central wavelength at a maximum pulse repetition rate of 1 MHz. The beam diameter of the laser at the focused position was 45 µm. Figure 1 shows the schematic layout for the laser drilling operation. The workpiece is mounted suitably on the vice and the laser beam is focused on the workpiece. Here, a stand-off distance of 221 mm has been considered. The laser processing parameters considered for the drilling operation are laser power, repetition rate, and exposure time. Table 3 shows the parametric setting and their levels. The study has adopted the design of experiment (DOE) approach to design the experimental layout to gather maximum process-related information from fewer experimental trails.

Characterization of Quality Features

Laser drilling of micro holes on aluminum alloy has been performed using the experimental plan as per Box-Behnken designs. Seventeen experimental runs have been performed and each experiment has been repeated more than 20 times. The laser-drilled holes are shown in Fig. 2. The average value of each quality characteristic is calculated and noted for the analysis of aluminum alloy. The quality of the hole can be assessed in terms of circularity (both at entry and exit) and taper. Image of the laser-drilled holes is acquired using a scanning electron microscope to measure the performance measures viz. circularity at entry, circularity at the exit, and taper using image processing software ImageJ. Figure 2 indicates the quality characteristics of the workpiece after the laser drilling process. The circularity of the hole is expressed as the ratio of minimum diameter to maximum diameter

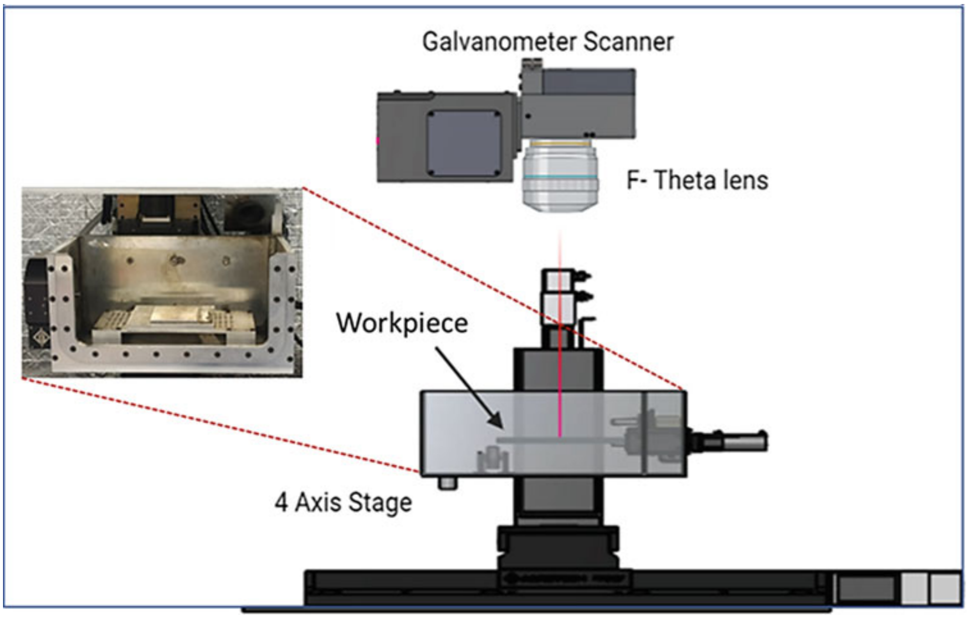

Fig. 1 Schematic of laser drilling setup

Table 3 Laser drilling setup and the parametric levels

Parameters	Level		
	1	0	−1
Laser power (W)	2	2.5	3
Repetition rate (kHz)	100	200	300
Exposure time (μs)	30	40	50

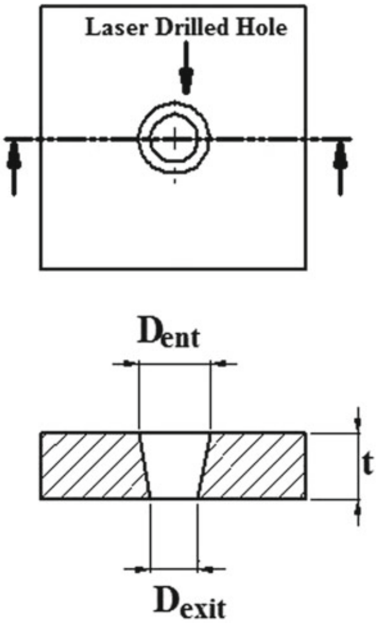

Fig. 2 Schematic diagram of taper [20]

Ferret's diameter of the hole [19, 20]. The taper of the laser-drilled hole is calculated by Eq. (1) as shown below [19, 20].

$$\text{Taper} = \frac{D_{ent} - D_{exit}}{2 \times (\text{thickness of workpiece})} \tag{1}$$

where D_{ent} and D_{exit} represent the diameter of the hole at entry and exit, and t is the thickness of the hole.

Results and Discussion

The measured quality characteristics for laser drilled holes on aluminum alloy Al 1145 has been discussed in the following section. To know the significance of process parameters, analysis of variance (ANOVA) has been performed for each performance measure for laser drilled holes on Al 1145. Co-efficient of determination (R^2) for circularity at entry, circularity at exit, and taper are 0.845, 0.8087 and 0.772, respectively, indicating statistical validity of the analysis. The surface plot for the performance measures shown in Figs. 3, 4 and 5 helps to understand the parametric effect on quality features of laser drilled holes. The main effect surface plot in Fig. 3 shows that circularity (at entry and exit) increases with increase in laser power, repletion rate and exposure time. The surface plot shows that circularity varies linearly with repetition rate and pulse width. Circularity increases with increases in repetition rate and laser power. As the pulse repetition rate increases, pulse off-time gets reduced, materials get melted and solidified with lower agitation and disorder and maximum circularity is attained. Similarly, an increase in exposure time leads to increased heat input, resulting in higher circularity. Similar type of observation has been observed for circularity at exit (Fig. 5).

The surface plot (Fig. 5) discusses the influence of control parameters on taper formation. Figure 5 indicates the combined effect of laser power and repetition rate on the taper of drilled holes. The graph shows that taper of holes

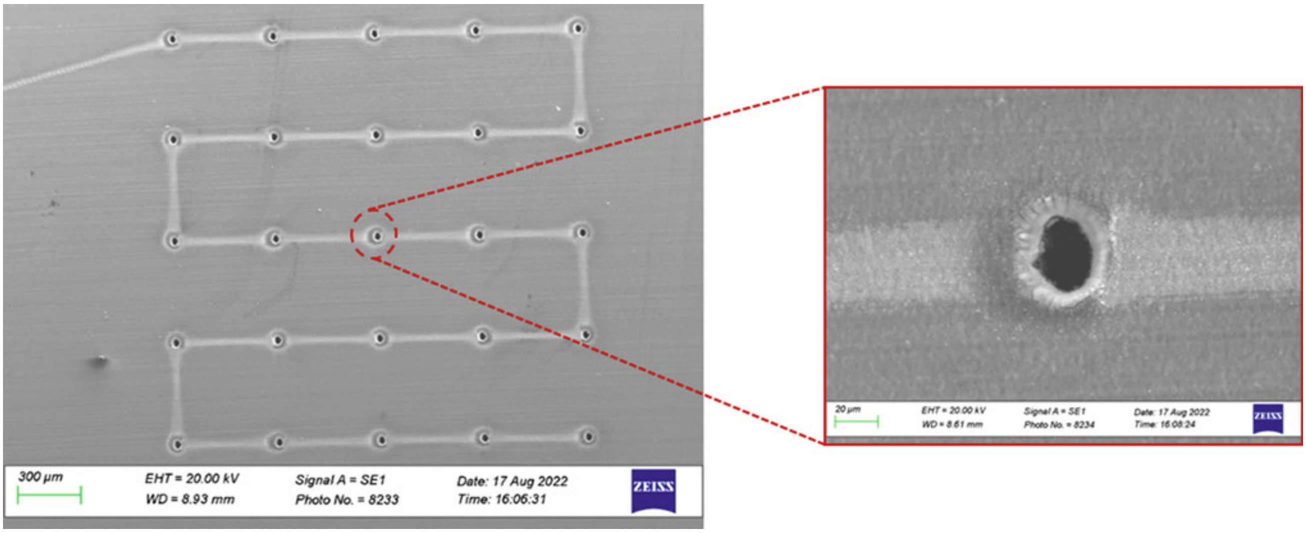

Fig. 3 SEM image showing the array of laser drilled holes at identical experimental setting for experiment number 6 (at top side)

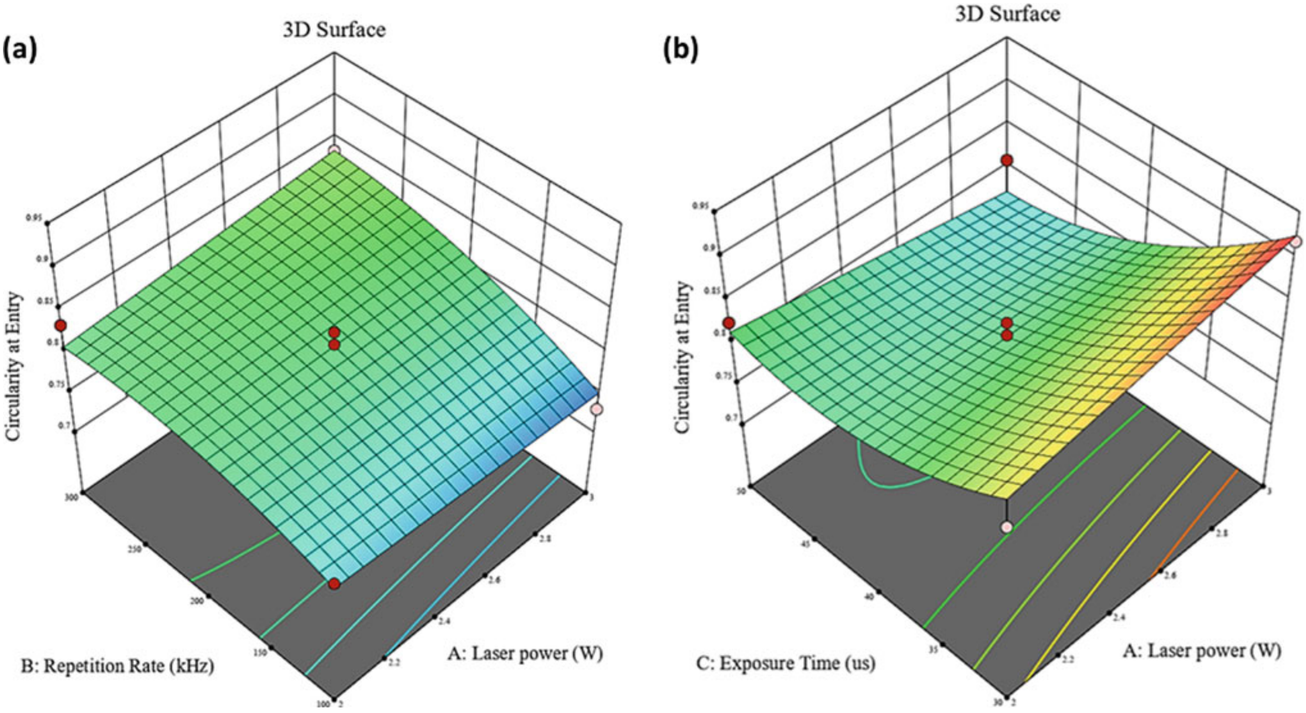

Fig. 4 Response surface plot for circularity at entry with respect to **a** repetition rate and laser power, **b** exposure time and laser power

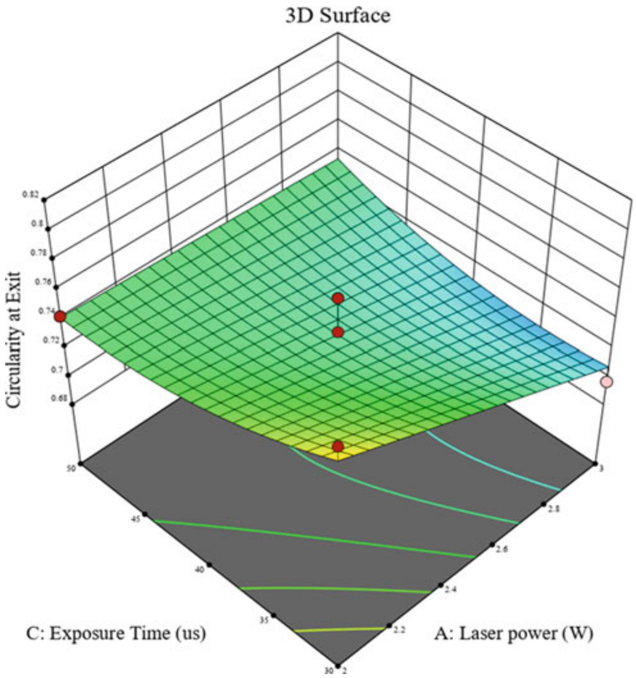

Fig. 5 Response surface plot for circularity at exit with respect to exposure time and laser power

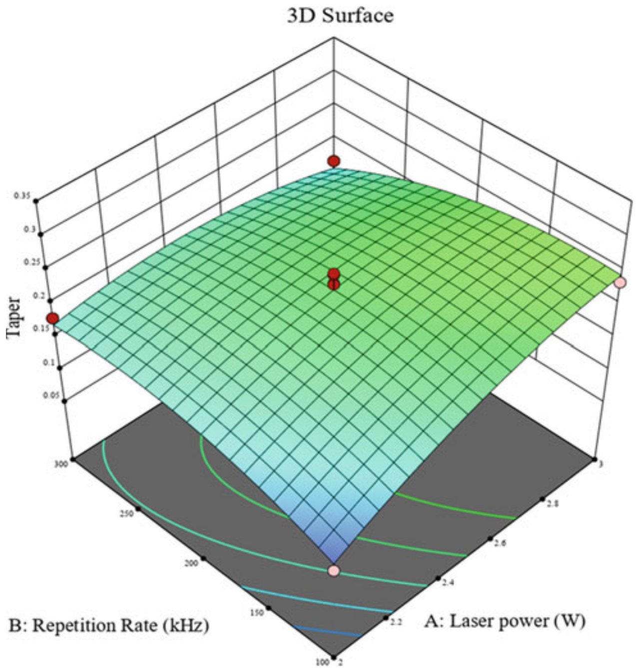

Fig. 6 Response surface plot for taper with respect to repetition rate and laser power

increases simultaneously with the increase in repetition rate and laser power. As the control parameter, viz. laser power current is directly proportional to laser energy [9, 21]; as a result, at a higher value of laser input current thermal energy will also be high. This indicates that at high laser energy, the material's surface gets melted and vaporized instantly; as a result, a huge volume of material is removed from the top surface as compared to the remaining thickness of the material. This may lead to the formation of taper of drilled holes. At the same time the graph also suggests that taper increases with an increase in repetition rate. A similar observation has been reported by Biswas et al. [22].

To analyze the microstructural features of the drilled holes, the drilled holes were observed under a scanning electron microscope. Figure 6 shows the presence of spatter deposition near laser drilled holes for experiment number 6. The microstructural analysis for all the holes were performed at 5000X magnification in SEM. The study suggests that spatter deposition increases on increasing the laser power and exposure time. It may be due to the vapour pressure developed inside the laser-drilled hole which leads to the generation of molten material ejection [23, 24] (Fig. 7).

Conclusion and Future Studies

This paper provides an experimental study of ultrafast pulse laser micro-drilling of commercially available grade aluminum alloy (Al1145). Al1145 surfaces were drilled with a femtosecond laser source using a galvo scanner at different laser power, repetition rates, and exposure times. The study was carried out using the design of experiment approach to determine the influence of laser control parameters on performance characteristics such as the circularity of the hole, and taper. The study shows the significant effect of laser power and exposure on all the performance measures. The microstructural study reveals the impact of process parameters on spatter deposition. It was observed that spatter deposition increases with increasing the laser power and exposure time. Further study will be extended to optimize and select the best laser parametric settings for the desired conditions. The work will be further extended to the use of scanning optics and spatial light modulation (SLM) to contribute toward developing a rapid and scalable ultrafast laser process. The timeframe for conventional galvanometer

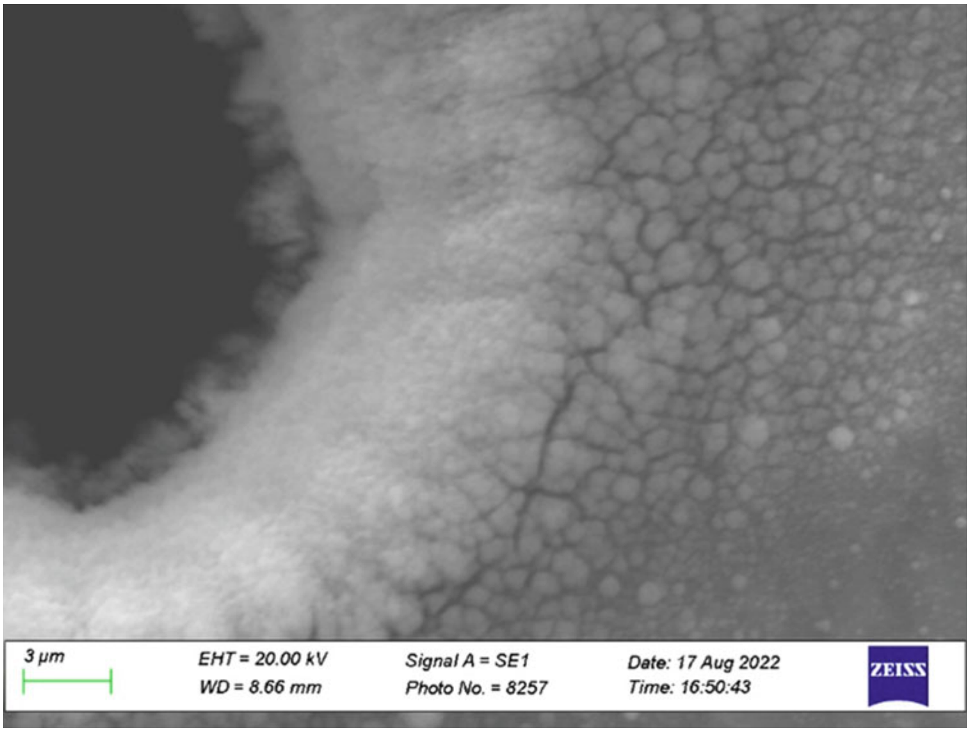

Fig. 7 SEM image shows the spatter deposition near laser drilled holes for experiment number 6 at 5000X

processing versus SLM processing will be compared for different geometric array patterns (number and geometric arrangement of holes) production.

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