

Effect of Laser Micro-drilling Parameters on Hole Geometry and Hole Formation of Thin Sheet SS304



M. S. Haneef, G. H. Lau, M. H. Aiman, M. M. Quazi, and M. Ishak

Abstract The recent advances in manufacturing technology have led to the development of miniature products in the field of automobiles, aerospace, and robotics. Laser micro-drilling has developed as a potential substitute over conventional machining due to the advantages of operational precision, reduced operational costs, and a high-speed production rate. This process involves high power intensity from the laser to break down the bond between molecules of the workpiece and hence form a hole on the workpiece. This project aims to study the effect of laser power on the drilled hole geometry and to analyse the mechanism of the hole formation during laser micro-drilling. The material used in this project is SS304 sheet metal. The holes' geometry and hole formation will be analysed by using an optical microscope. The size of the hole diameter for each power is almost the same in the range of 101.669–102.978 μm for the frontside. Meanwhile, the diameter of the backside hole increases from 64.343 μm to 88.852 μm at 15 W to 21 W of laser power respectively. For hole formation, the more material is ablated as the ablation process advances. As a result, the removal area from the micro-drilled hole grows from 3577.852 to 6516.237 m^2 . The shape of the hole is irregular due to the uneven power distribution of the laser towards the SS304 sheet metal when it undergoes an ablation process.

Keywords Micro-drilling · Laser drilling · Laser power · Hole geometry · Hole formation

1 Introduction

In recent years, the micro-machining process for producing miniature parts has become increasingly important for several sectors such as electronics, aerospace and biomedical [1]. Micro-machining is a machining method that involves removing small bits of material in order to obtain great geometrical accuracy. Micro-drilling

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is an ideal process among the micromachining processes to generate the micro-holes, generating deeper holes with better roundness, better smoother surface, and straightness. Micro-drilling is a process of drilling micro-sized holes in the range of 1–999 μm [2]. Micro-holes are currently created using a variety of production techniques, including micro-electrical discharge machining (micro-EDM), micro-mechanical drilling and laser micro-drilling. The type of material, its size and thickness, and the cost of the process is all the factors to consider when choosing the right micromachining technology [3]. Laser micro-drilling has an advantage towards those factors for overcoming the limitation in the micro-drilling process.

Laser micro-drilling is a non-contact, precise, and repeatable process for forming small diameter ($\sim 100 \mu\text{m}$) and high-aspect-ratio holes in a wide range of materials first paragraphs that follows a table, figure, equation etc. does not have an indent, either [4]. Besides, the method that uses a laser as an energy source possesses a fast process because only the selected part should be heated, and the amount of heat input is small [5, 6]. In laser micro-drilling, a stationary, high-intensity laser beam is directed onto the surface at power densities sufficient to remove the solid phase material [7]. To ablate the material, the erosion of the drilled hole propagates in the direction of the line source. Figure 1 shows the physical processes that occur during laser micro-drilling. There are three stages to the process. The beam is initially focused onto the material's surface, and the layer that is being targeted absorbs the energy of the beam before being irradiated [8]. Material ablation occurs when the pressure gradient on the surface of the layer is large enough to overcome the surface tensile force and subsequently remove the material from the hole [9]. This mechanism will be continuously repeated until the one fine through-hole is successfully drilled.

In general, there are three techniques to laser micro-drilling, namely as single pulse, trepanning, and percussion drilling. For this research, trepanning laser drilling will be applied. This procedure at first works similarly to single-shot or percussion laser drilling by piercing an opening in the material that it is being utilized on [10].

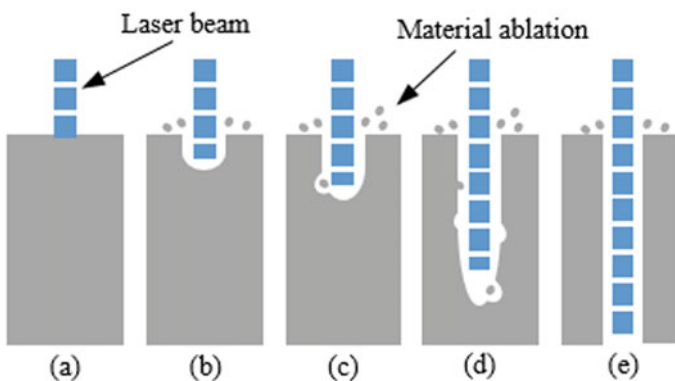


Fig. 1 Physical processes during laser drilling. **a** initial laser radiation **b–d** material ablation **e** through-hole fine drilled

After piercing the material, the laser beam moves in a spiral pattern utilizing a motion mechanism to carve a hole. The beam begins at the center of the diameter and spirals outwards in an increasing spiral diameter until the correct hole size is achieved.

However, it has also some shortcomings which can affect the hole geometry. In laser processing, an understanding of the fundamental laser energy absorption mechanisms plays a significant role in determining the optimum parameters [11]. Therefore, it is necessary to find out the best parameter for enhancing the geometry of the micro-drilled hole. The laser power will give a big impact in laser micro-drilling. The hole geometry and appearance are depending on the laser power due to different ablation rate towards the material. Besides, it is necessary to look at the basic fundamentals of material removal and hole formation throughout the laser micro-drilling process. Towards the number of drilling loops. This study focuses on the effect of laser power on the micro-hole geometry and the mechanism of hole formation during laser drilling. Knowing how laser power and drilling loop affects micro-hole geometry, major development can be made to produce a better micro-drilled hole that meets satisfaction.

2 Experimental Setup

2.1 Material Preparation

The material used for laser micro-drilling was stainless steel SS304 with a sheet thickness of 0.1 mm. The selection of this material has met the requirements of the wide range of uses in the industry sector, i.e., excellent corrosion resistance and ability to withstand corrosion from most oxidizing acids [12]. Tables 1 and 2 shows the material properties and chemical composition of the stainless steel used.

Table 1 Thermophysical properties of SS304

SS304	Parameters
Density	8.0 kg/m ³
Melting point	1723.15 K
Thermal conductivity	16.2 W m ⁻¹ K
Tensile strength	540–750 MPa

Table 2 Chemical composition of SS304

Fe	Ni	Cr	Mn	Si	C	P
Bal	8.0–10.5	17.5–19.5	0.0–0.2	0.0–0.1	0.0–0.07	0.0–0.05

2.2 Experimental Procedure

Before starting the laser micro-drilling process, the hole's array must be designed first as shown in Fig. 2. This design should consider the effect of the laser process mechanism, i.e., the heating area and its spatter deposition, to avoid overlapping between each drilled hole [13]. The hole diameter size is set to 100 μm and the gap between each hole is 300 μm . In addition, the samples will be immersed in the acetone solution to remove any residual contaminant.

The source used is a pulsed wave fibre laser from a laser marking machine with a maximum output power of 30 W and a maximum repetition rate of 20 kHz. Besides, the maximum pulse that can achieve is up to 1.0 mJ. Laser micro-drilling parameters applied in this study were listed in Table 3. This experiment was divided into 2 parts which are the effect of laser power on the hole geometry and the mark loop number towards the mechanism of the hole formation during laser micro-drilling. In the first part, the laser power was set at 15, 18 and 21 W while the number of the mark loops was kept constant at 40. For the next part, the laser power is kept constant at 15 W, but the mark loop was altered. The laser mark loop was set to 5, 7, 10, and 15.

Fig. 2 Drilling shape design layout

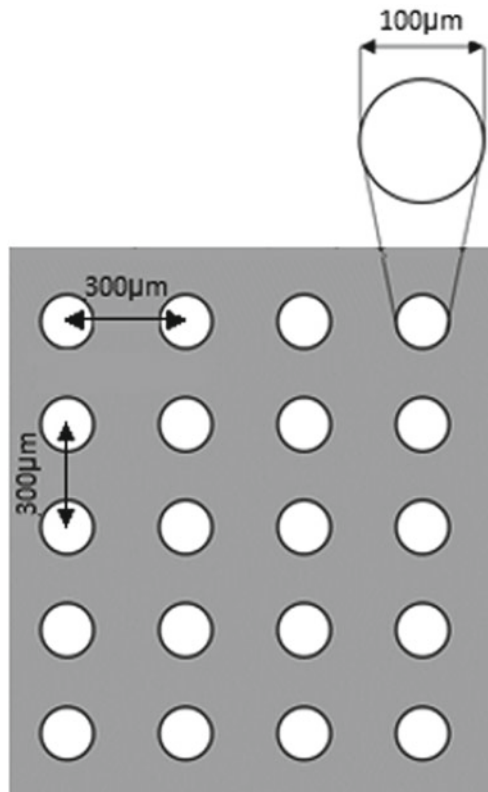
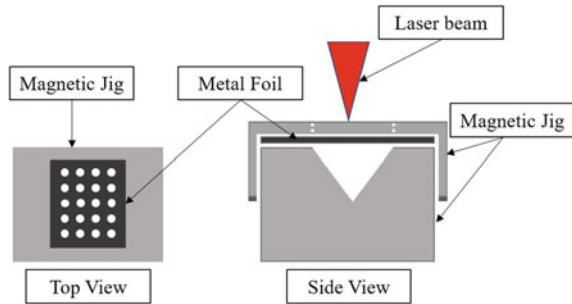


Table 3 Laser micro-drilling process parameters

Laser specification	Parameter
Number of loops	5, 7, 10, 15, 40
Focal length (mm)	19.2
Laser power (W)	15, 18, 21
Pulsed frequency (kHz)	20

Fig. 3 Schematic of laser micro-drilling process and set-up



The schematic diagram for the laser micro-drilling experimental setup was shown in Fig. 3. The laser source emits pulses with a fixed repetition rate and scanning speed over the workpiece. In addition, the trepanning drilling technique will be used in this process considering that this process is the best compared to a single pulse and percussion drilling [14]. Besides, the sample will be placed on a magnetic jig to avoid any movement considering formability during the process.

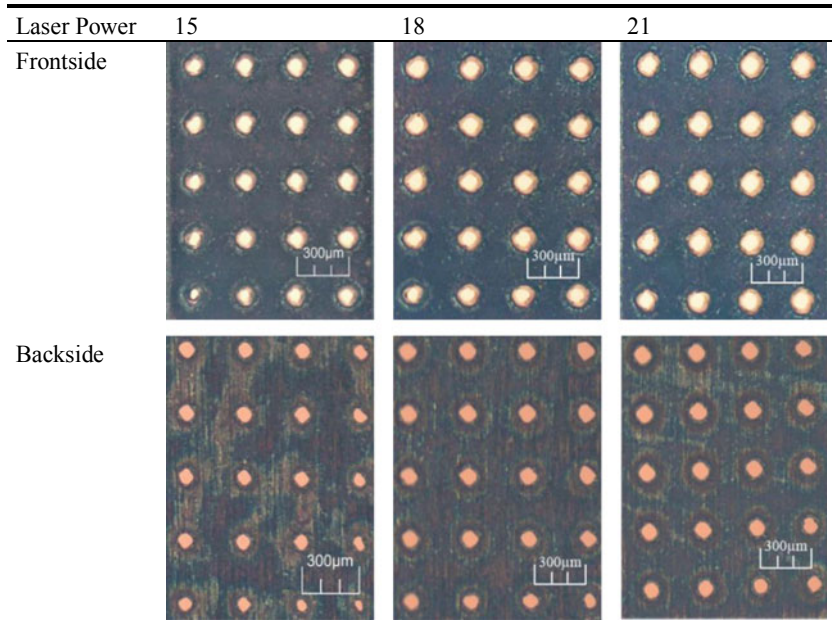
The drilled hole was analyzed according to the diameter and area of the hole. The hole geometry will be measured by using an optical microscope with 20X magnification. The hole geometry extracted are horizontal diameter ($D - x$), vertical diameter ($D - y$) and hole area. After that, the specimen will be mounted for cross-section analysis. The hole depth was analysed by using an optical microscope with 50X magnification.

3 Results and Discussion

3.1 Effect of Laser Power on Hole Geometry

After completing laser micro-drilling, the array of holes with a diameter of $100 \mu\text{m}$ were successfully drilled thoroughly as shown in Table 4. From the appearance, the size of the hole visually increases as the laser power increase for both sides. The frontside of the hole appeared to be larger than the backside, and all the micro-drilled holes seemed to be consistent in geometry. Besides, the surface's colour between both

Table 4 Frontside and backside hole 100 μm, 40-mark loop for 15, 18 and 21 W



sides is slightly different due to the laser beam interaction that directly focuses on the front side of the hole.

Furthermore, 20 micro-drilled holes for every set of parameters have been measured by using an Image J software. Tables 5 and 6 show the frontside and the

Table 5 Frontside hole of average diameter and average area

Power (W)	Average diameter (μm)		Average area (μm ²)
	Horizontal	Vertical	Value
15	101.846 ± 1.610	102.123 ± 1.232	9127.799 ± 1.980
18	102.118 ± 1.160	101.669 ± 1.108	8941.035 ± 2.708
21	102.978 ± 1.481	102.179 ± 1.391	9026.257 ± 3.313

Table 6 Backside hole of average diameter and average area

Power (W)	Average diameter (μm)		Average area (μm ²)
	Horizontal	Vertical	Value
15	64.343 ± 2.959	67.049 ± 2.475	4558.682 ± 3.440
18	77.547 ± 2.157	78.933 ± 3.648	5820.406 ± 2.983
21	88.253 ± 2.376	88.852 ± 1.115	6945.261 ± 2.330

backside hole of average diameter and average area respectively. For the frontside, the size of the hole diameter for each power is almost the same in the range of 101.669–102.978 μm . This shows that the increasing power of laser micro-drilling does not affect the material ablation at the entrance hole. Meanwhile for the backside hole diameter, when the power output increases, the value of the hole diameter also increases as well. The diameter of the backside hole increases from 64.343 μm to 88.852 μm at 15 W to 21 W of laser power respectively. This shows that the relationship between laser power and the average diameter of the exit hole is directly proportional.

In addition, the area of the frontside hole for each power is nearly the same, ranging from 8941.035 to 9127.799 m^2 . Between these two values, there is no substantial difference. This indicates that raising the power of laser micro-drilling has no effect on the area of the entrance hole as well as the hole diameter itself. For the exit hole area, when the power output increases, the hole area also increases. This is because the effect of laser power at the exit hole is different according to the material that has been ablated. The area of the exit hole increases from 4558.682 μm^2 at 15 W power to 6945.261 μm^2 at 21 W power, respectively. The area difference is 2386.579 m^2 . This proves that the laser power affects the exit hole’s average area. In addition, the standard deviation was observed to be less than 5, which means that the process was consistently met.

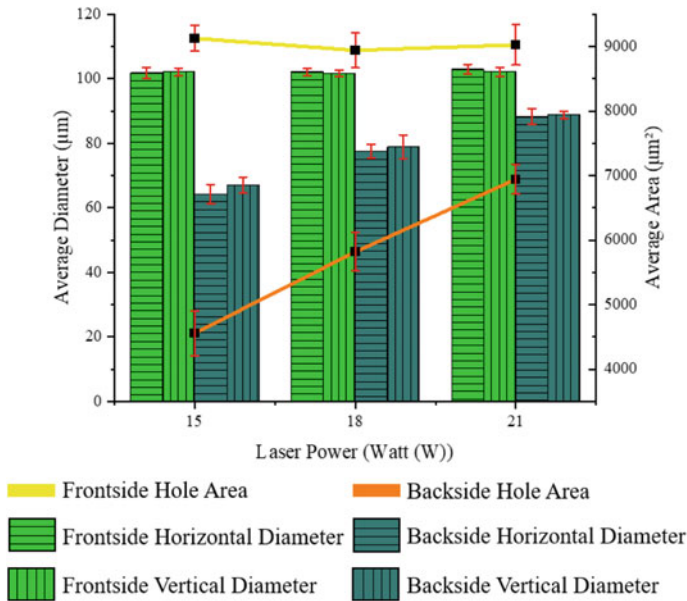


Fig. 4 Laser power versus average hole diameter and average hole area for frontside and backside (Bar shows average diameter. Line shows average area)

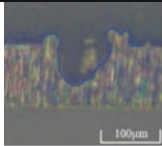
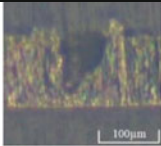
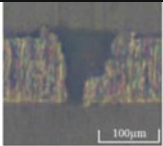
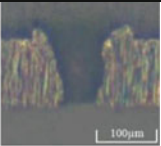
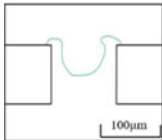
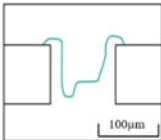
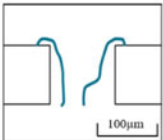
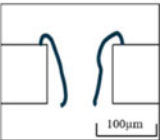
Figure 4 presents the line plot and bar graphs constructed in order to show the values of hole area and hole diameter obtained towards laser power, respectively. The graph pattern illustrates that there is not much significant difference between diameter for the frontside hole. The area also shows no significant difference when the laser power increase. Meanwhile, the hole diameter and hole area for the backside are clearly trending upward.

Through comparison based on the graph pattern, the effect of the laser power towards the entrance diameter is minor. As reported by Witte, they noticed similar trends and the amount of solid molten material around the entrance was said to have been increased due to the increase heat load [15]. Moreover, high laser power is not needed to accomplish a front side hole because it will immediately achieve the same value as the preset at the beginning. However, when it goes through into the sample to reach the backside, the laser power will play an important role. This is because when the laser power increases, the ablation speed will increase, and the hole geometry will get bigger. Therefore, it is assumed that if more loops are added, the preset value can also be achieved at the backside of the hole geometry.

3.2 Effect of Laser Power on Hole Geometry

In this section, the hole formation for a different number of laser mark loops can be found out. The laser power remains constant at 15 W. However, the number of laser mark loops were varied from 5-mark loops until 15-mark loops. The depth of the micro-drilled hole and its tracing line is shown in Table 7. 15 W of laser power with 5-laser mark loop numbers is unable to make a through-hole on the 0.1 mm thickness SS304 sheet. The laser mark loop barely ablated half of the SS304 sheet, and the entrance hole diameter is not fully ablated to reach 100 μm. For the 7-laser mark loop number, the laser power drills deeper into the SS304 sheet but is still unable to make a through-hole.

Table 7 Hole depth and tracing line of laser mark loop

Number of Mark Loop	5	7	10	15
Micro-drilled Hole				
Tracing Line				

Meanwhile, for the 10-mark loops, the laser power starts to penetrate through the SS304 sheet and make a through-hole. Although the exit hole is tiny, it is considered a through-hole. The entrance hole diameter starts to have the standard hole diameter as preset, which is around 100 μm . For the fifteenth laser mark loop number, the hole shows a complete through-hole that has passed more than 60% from the entrance hole size. The size of the exit hole is also more significant compared to the previous 10-mark loops.

The data of the hole is collected with the assistance of ImageJ software. Table 8 shows the number of laser mark loops against the average depth of the hole and the area of removal. This table indicates that the area removal and the average depth from the SS304 sheet increase with the laser mark loop number. This is because the duration of the fibre laser performing ablation on the workpiece will surge correspondingly as the number of laser mark loops increases. The further the ablation process progresses; the more material is ablated. Hence, the area of the removal from the micro-drilled hole is increasing from 3577.852 to 6516.237 μm^2 .

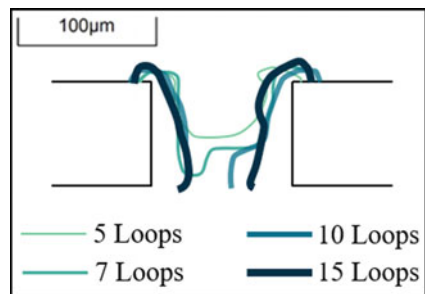
In short, the number of the mark loop will affect the removal area and hole depth of the SS304 sheet during laser drilling. Furthermore, only minor changes in the top side diameter of the holes are observable, ranging between 98.673 and 101.732 μm . It has been proven that only ablation occurs throughout the process.

Figure 5 visually presents the hole formation mechanism from 5-mark loops until 15-mark loops in laser micro-drilling of 0.1 mm thickness of SS304 sheet metal. It is observed that the laser power was not sufficient enough to penetrate with the

Table 8 Number of mark loops against an average depth of hole and area of removal

Number of mark loop	Top side Diameter (μm)	Bottom side Diameter (μm)	Average depth (μm)	Area removal (μm^2)
5	98.673	–	66.206	3577.852
7	99.295	–	80.680	4503.195
10	101.582	31.877	100 (Through Hole)	5564.026
15	101.732	73.051	100 (Through Hole)	6516.237

Fig. 5 Mechanism of hole formation



5-mark loops to 7-mark loops. Besides, the laser started to penetrate at the 10-mark loops which gets more prominent for 15-mark loops. With further improvement in parameters, a better laser micro-drilled hole could be achieved.

4 Conclusions

In order to get a better result and optimum properties of the laser micro-drilled holes, laser parameters such as laser power and laser mark loop number should be explored more because the current experiments had just shown a uniformly rising trend. The graph should reach an optimum point to acquire the optimum value for the laser parameter.

- (a) High laser power creates a larger exit hole; for example, a 21 W laser power produces a hole area of 6945.261 m^2 . The pulse energy increases as the laser power increases, causing the hole wall to ablate more material. The diameter of the entrance hole showed not significantly change in value, which was the range between 101.6691 and 102.9778 μm . This shows that high laser power is not needed to accomplish a front-side hole because it will immediately achieve the same value as the preset. However, the laser power will play an important role when it goes through into the sample to reach the backside.
- (b) For the hole formation, laser mark loop from the number of 5–7, the depth of the hole increases from 66.206 to 80.6802 μm . The micro-drilled area becomes a through-hole at the tenth laser mark loop. The size of the through-hole grows as the loop number increases.

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