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Micro drilling with Copper Vapor Laser

G. S. Mendhe
Department of Physics
Adarsha Science, J. B. Arts and Birla Commerce Mahavidyalaya
Dhamangaon (Rly), Dist: Amravati, Maharashtra (India)
Email Id: girish24mendhe@gmail.com

Abstract - In this paper the application of 8 W copper bromide laser for micro machining has been demonstrated. Micro machining experiments involved micro drilling of metals such as copper, aluminum, and stainless steel. It has been found that micro machining was greatly influenced by the optical and thermal properties of the materials. The fine holes are drilled in aluminum as compared to copper because of its lower absorption and lower thermal conductivity. The repeatability of laser drilled holes in stainless steel of thickness 0.15 mm has been examined by statistical data analysis. The percentage standard deviation in hole diameter of entrance and exit side and in circularity has been found out.

Keywords - Laser micro drilling, micro machining, copper vapor laser

I. INTRODUCTION

Laser micro machining is an increasingly important production method used in the automotive, aerospace electronics, telecommunications & medical device industries [1]. A variety of laser types are used in laser micro machining. The laser types that are most commonly used are fiber lasers, copper vapor lasers, excimer lasers, Nd-YAG, solid-state lasers [2]. The laser type must be matched to the application & that no single laser type will be optimum for all applications. It is generally accepted that short pulses (<100 ns) generate considerably less recast and thinner heat affected zones (HAZ) than long pulse lasers [5].

The copper vapor lasers (CVL), including CuBr lasers have been used for some niche applications in the area of laser micro machining technology for some years [4]. Principal applications of these lasers are in micro hole drilling & precision drilling. In number of applications it has been demonstrated that the copper vapor laser is the most viable tool because of the excellent results achieved with its combination of high power, short pulses, visible radiation, diffraction limited beam quality, high reliability & low cost of ownership [3]. One of the key advantages of the copper vapor laser is its ability to generate high beam quality at very high average power [4].

II. EXPERIMENTAL ARRANGEMENT

The experimental set up for the study of micro machining consists of an 8 W sealed off copper bromide laser, a beam delivery system including a 45° inclined plane mirror and a 25 mm focal length focusing lens and a 2 – axis CNC work station. The ray diagram for experimental set up is shown in *fig. 1*. The experiment is performed on metals namely copper, aluminum, and stainless steel. The beam divergence is about 0.65 mrad for unstable configuration of the resonator. Experimental parameters include laser pulse width of 40 ns and pulse repetition rate of 19 kHz.

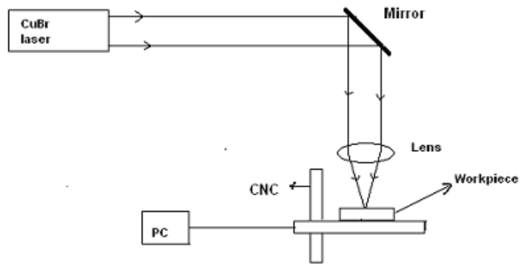


Fig 1: A schematic layout for the experimental set up

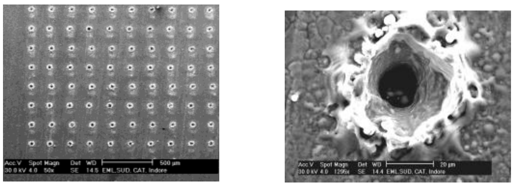
III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. *Micro drilling*

High rate laser drillings are commonly accomplished by percussion drilling because of its fast material penetration. The experimental results of micro-drilling performed on copper, aluminum and stainless steel are summarized in *Table 1*. The diameters of entrance side are in the range between 10 to 60 μm. The drilled holes are tapered. As compared to copper, finer laser-drilled holes were produced in aluminum foil of same thickness. The drilling time for aluminum is also less as compared to that of copper. This is because of higher thermal conductivity of copper. The diameter of the drilled hole increases with thickness of the foil. In copper the drilled holes are more tapered as compared to stainless steel and titanium due to its higher thermal conductivity. The cross section of laser drilled hole in copper of thickness 0.25 mm is shown in *fig. 3(c)*. The taperness of the drilled hole increases with thickness of the foil because as the thickness increases the greater laser beam defocusing takes place that results in reduction of resultant recoil pressure which leads to inefficient melt ejection. The laser drilling in thicker foils (0.25 mm) of copper is relatively easier than in aluminum because of the greater laser absorption [1]. These holes show no measurable heat-affected zone and the hole quality is distinctively superior to those drilled with CO_2 and Nd: YAG laser [7,8]. Assist gas was found to be not essential in CVL micro drilling, but there is evidence that oxygen increases drilling speed because of exothermic reaction during drilling [5].The SEM picture of the laser drilled hole matrix in copper foil of thickness 100 μm is shown in *fig. 2 (a)* and its magnified view of single laser drilled hole is shown in *fig 2. (b)*. The SEM picture of the laser drilled holes in copper foil of thickness 250 μm is shown in the *fig. 3*. The *fig. 4 (a)* shows the SEM picture of the entrance side of laser drilled hole in stainless steel while *fig. 4 (b)* shows its exit side. The SEM picture of the laser drilled holes in aluminum foil of thickness 50 μm and 100 μm are shown in the *fig. 5* and *fig. 6* respectively.

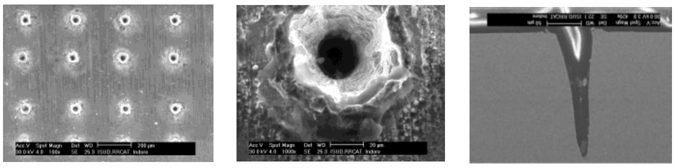
TABLE 1

S. N.	Material	Thickness (μm)	Drilling time (Approximately) (Seconds)	Hole diameter (Entrance side) (μm)	Hole diameter (Exit side) (μm)
1.	Copper	100	1	40	12
		250	5	60	--
2.	Aluminum	50	0.4	12	8
		100	0.6	15	8
3.	Stainless steel	150	1	40	20



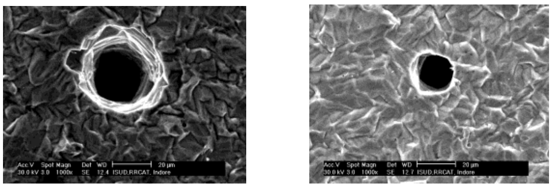
(a) 100 holes in 4mm^2 ***(b) Magnified view***

Fig 2: Laser drilled holes in copper foil of thickness 100 μm



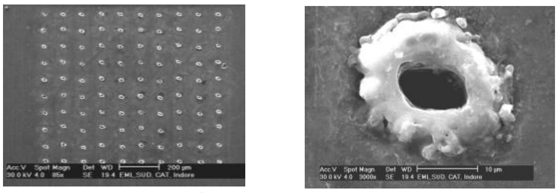
(a) Holes grid ***(b) Magnified view*** ***(c) Cross section view***

Fig 3: Laser drilled holes in copper foil of thickness 250 μm



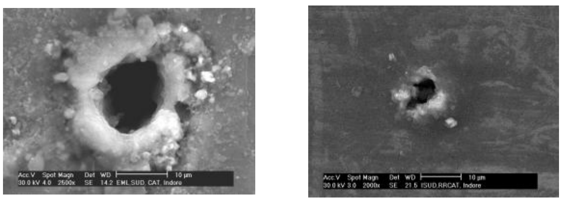
(a) Entrance side ***(b) Exit side***

Fig 4: Laser drilled hole in stainless steel foil of thickness 150 μm



(a) 100 holes in 1mm^2 ***(b) Magnified view***

Fig 5: Laser drilled holes in aluminum foil of thickness 50 μm



(a) Entrance side ***(b) Exit side***

Fig 6: Laser drilled hole in aluminum foil of thickness 100 μm

B. Repeatability of Laser Drilled Holes

In drilling process the work-piece is subjected to a series of laser pulses at the same location that results cyclic melt ejection from the laser interaction zone and consequently forming a hole. However, the determination of optimum process parameters to drill holes of particular diameter is often based on a method of trial and error. It is often difficult to produce repeatable holes with laser percussion drilling. This makes the process of fabricating holes with desired hole geometry to the industrial tolerances difficult to achieve. *Fig. 7* and *fig 8* illustrates a set of three holes drilled with the same laser parameters and yet the hole geometry is different from one hole to another for both entrance and exit side respectively. Incapability of drilling accurate holes with respect to repeatedly, limits the applications of laser percussion drilling in the industry. In view of this, it becomes necessary to understand the characteristics of repeatability of these laser drilled holes.

There are many factors that could affect the hole geometry when repeatability is concerned and these include:

- Changes in alignment of the beam,
- Changes in air temperature, pressure and humidity,
- Changes in material properties,
- Fluctuations of operating parameters, and
- Contamination of the optics.

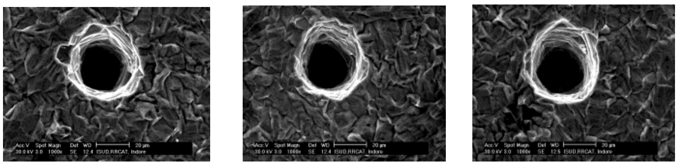


Fig 7: Variation of geometry for holes drilled in stainless steel under the same conditions (Entrance side)

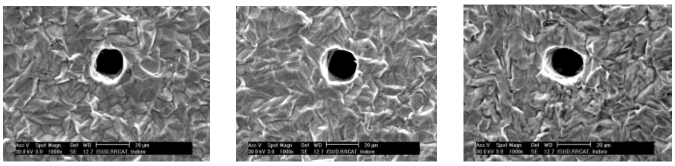


Fig 8: Variation of geometry for holes drilled in stainless steel under the same conditions (Exit side)

C. Statistical Data Analysis

For repeatability analysis, it was necessary to devise a method to measure the geometrical variation of one hole from another. The standard deviation is a suitable tool for this purpose. It is obvious that a larger hole will give a larger value of standard deviation. This would defeat the purpose of the comparative analysis and hence it was more appropriate to take the percentage standard deviation (PSD) of the hole geometry as an indication of the repeatability. The larger the value of PSD of hole diameter, the less repeatable the drilling process would be. The PSD for each set of holes was calculated by the following equation:

$$PSD = \frac{\sqrt{\frac{1}{n-1}[(d_1-\bar{d})^2+---+(d_n-\bar{d})^2]}}{\bar{d}} \times 100 \quad \text{-------- (1)}$$

where d_1 and d_n are the equivalent diameters of the individual holes and $\bar{d}$ the mean diameter of the total number of holes under the same set of operating parameters (μm), 'n', the total number of holes, PSD the percentage standard deviation of the hole diameter (%).

To characterize repeatability of hole geometry, the circularity of holes was also examined and correlated with processing conditions. This was calculated by the following equation:

$$C_i = \frac{d_{min}}{d_{max}} \quad \text{-------- (2)}$$

where, C_i is the average circularity of the individual hole, d_{min} the minimum diameter of the hole (μm) and d_{max} the maximum diameter of the hole (μm).

The average circularity, C_{ave} of the hole for each parameter set is

$$C_{ave} = \frac{1}{n}\sum_{i=1}^{n} C_i \quad \text{-------- (3)}$$

where, n is the total number of holes.

Therefore, a C_{ave} value of 1 represents perfect circularity. Non-circular holes will have $C_{ave} < 1$.

Results

In order to determine a suitable number of holes required for the analysis of repeatability, 50 holes were drilled in stainless steel of thickness 0.15 mm under the same laser parameters and the standard deviation were calculated for the increasing number of holes. It has been found that the percentage standard deviation in entrance side of the hole is about 5% while that for exit side is about 8%. The average circularity of the holes in entrance side is about 0.94 and that in exit side is about 0.93. The PSD in circularity of entrance and exit side is about 5%. *Fig 9* shows the accumulated standard deviation of entrance hole diameters and exit hole diameters with increasing number of holes and *fig. 10* shows accumulated standard deviation of circularity of Entrance side and exit side with increasing number of holes. From *fig 9 (a)* we find that stability of standard deviation was reached at around 33 holes and the deviation is less than 2% from that onwards for the diameters of entrance side while *fig. 9 (b)* shows that stability of standard deviation was reached at around 35 holes and the deviation is less than 3% from that onwards for the diameters of exit side. From *fig. 10* we find that stability of standard deviation was reached at around 37 holes and the deviation is less than 2% from that onward for the circularity of both entrance and exit side.

Discussions

Laser hole drilling is a material removal process involving complex laser interaction, heat transfer, fluid flow and phase change. There are two forms of material removal; vaporization and liquid expulsion. When the surface of a work-piece is heated beyond its boiling point, vaporization occurs and a recoil pressure is generated. This pressure ejects the melt from the interaction zone, and a cavity is formed as a result. Wei and Chiau showed that the evaporation rate was only 1/200 of that of melting [6]. Therefore, the hole formation takes place largely in the form of liquid melt ejection rather than evaporation. Due to incomplete expulsion of the ejected material from the drilling zone, spatter is formed which adheres to the work piece surface around the periphery of the hole entrance. Because melt ejection is the dominant material removal process in laser percussion drilling, spatter formation is an influential factor of hole formation and hence the hole geometry. Thus for better repeatability in hole diameters and geometry of holes the material must removed by vaporization.

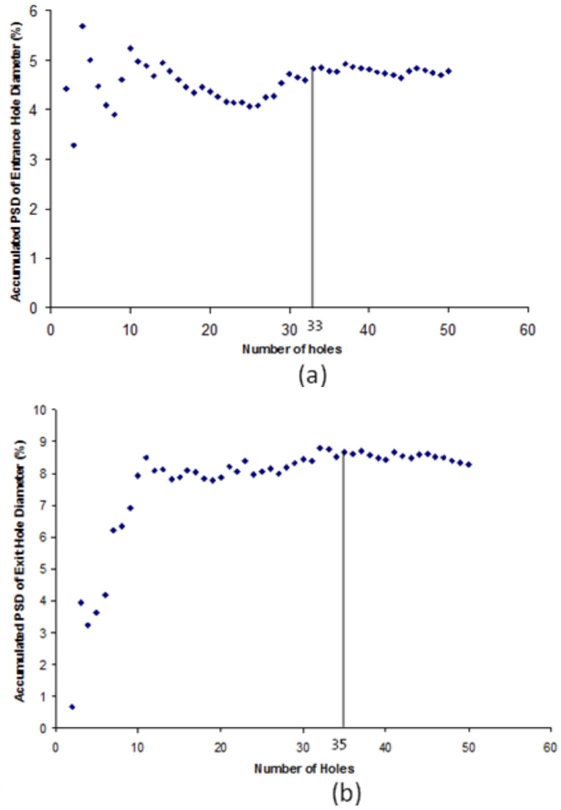


Fig 9: Accumulated standard deviation of (a) entrance hole diameters and (b) exit hole diameters with increasing number of holes.

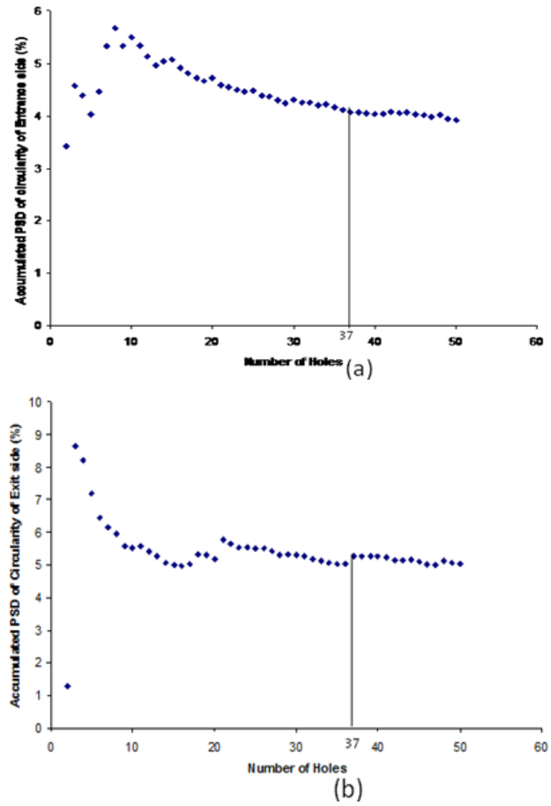


Fig 10: Accumulated standard deviation of circularity of (a) Entrance side and (b) Exit side with increasing number of holes.

IV. CONCLUSIONS

The laser micro drilling on various metals such as copper, aluminum and stainless steel has been demonstrated with 8 W copper bromide laser. The drilled holes found negligible HAZ. The micro- machining applications are greatly influenced by the optical and thermal properties of the materials. In aluminum the fine holes are drilled because of its lower thermal conductivity as compared to copper. In copper, drilling in thicker sample is possible as compared to aluminum because of its high absorption of the laser beam in the visible range of the spectrum. The laser drilled holes are tapered. In copper the holes are more tapered as compared to stainless steel and aluminum due to its higher thermal conductivity. With increasing the thickness of the foil the taperness of the holes increases.

Using statistical data analysis, the repeatability of laser drilled holes in stainless steel of thickness 0.15 mm has been examined. It has been found that the percentage standard deviation in entrance side of the hole is about 5 % while that for exit side is about 8 %. The average circularity of the holes in the entrance side is about 0.94 and that in exit side is about 0.93. The percentage standard deviation in circularity of entrance and exit side is about 5 %.

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