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Pulsed Nd: YAG laser drilling of aerospace materials (Ti-6Al-4V)

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Abstract. This paper studies the influence of Nd:YAG (neodymium-doped yttrium aluminium garnet) laser process parameters on laser drilled hole quality. Ti-6Al-4V of 1 mm and 3 mm thickness were used as the workpiece substrate. The principal findings are mainly based on minimising the taper angle in laser drilled holes, reducing the heat affected zone and reducing the production of spatter. Identification of key process variables associated with laser drilling process is accomplished by trial experimentation. Using the identified key process variables, further experiments were then performed with the assistance of statistical design of experiment (DOE) to find the interaction and individual effects of various laser process parameters on laser drilled hole quality. The lowest taper angle of 1.8 degrees was achieved with use of nitrogen as the assist gas. Furthermore, from the laser process observations, it was found that laser power significantly affects the quality of the laser drilled hole. Increase in laser power would increase the hole size and result in more spatter on the entry hole surfaces. The nozzle focus position substantially influenced the laser drilled hole size. The amount of spatter deposits increased with decrease in the nozzle offset. Increase in laser frequency significantly increased the exit diameter, which resulted in smaller taper angle. Number of pulse required to drill through a workpiece depends on the material properties and physical properties of the material. For 1mm Ti-6Al-4V, a minimum of two pulses was required to successfully removed the material during drilling and a minimum of 4 pulses was required to drill through the same material with 3mm thickness.

1. Introduction

The use of titanium alloy Ti-6Al-4V has been prominent in aerospace industry due to its outstanding material properties compared to other materials. The main aero components with Ti-6Al-4V are in the gas turbine engines where a large number of small holes (diameter < 1mm) [1] is required to provide cooling to the engine components. In order to produce the holes, Nd: YAG (neodymium-doped yttrium aluminium garnet) laser drilling system has been employed due to its ability to drill a large number of holes within a shorter time (approximately 340,000 holes/min for diameter less than 0.025mm). Nd: YAG laser drilling has been widely established and adopted in the aerospace industry mainly in the production line [2] to produce the cooling holes [3] due to its ability to drilled a large number of fine holes on aerospace components such as turbine engine, nozzle guide vanes, airfoils and combustion chamber [4].

The pulsed Nd:YAG laser system uses an average power of 500W with the capability to deliver enhanced peak powers and superb beam quality, resulting in an excellent quality of material removal during drilling application [2]. Millisecond pulse laser drilling of metals and alloys is used extensively in high value manufacturing to produce holes of size ranging from 0.25 mm to 1 mm and it is a well-established technology for manufacturing various components in aero-engines due to its capability to drill difficult materials at acute angles. The key trend in turbine design is to use increased numbers of complex shaped holes to maximise cooling and subsequently fuel efficiency. In the afterburner of a gas turbine, there are around 40,000 holes with a diameter of 0.5 mm. The increase in the numbers of cooling holes highlights the need for high speed-high quality laser drilling process. There were several types of laser drilling such as single pulse [5], helical [6], percussion [7] and trepanning [8]. Most industrial laser drilling is performed using a percussion or trepan laser drilling process [9], in which a millisecond laser pulse with power density of 106–109 W/cm^2 is being used to produce holes by combination of melting and vaporisation techniques. Percussion drilling process is most often used in high value manufacturing industries due to its ability to produce holes of better quality at high speed. In general, millisecond laser drilling process is also associated with a number of undesirable defects including hole taper, recast layer, heat affected zone, oxide layer and spatter. Taper and heat affected zone formation are considered very critical for rotating components like the turbine blades as it can lead to initiation of fatigue cracks and ultimately, the failure of the laser drilled components.

Prior work on percussion laser drilling has been done on Ti-6Al-4V with thickness of 4 mm and 8 mm by Bandyopadhyay *et al.* [10]. The study revealed that laser drilling defects including geometrical characteristics (hole size, taper angle and aspect ratio) and metallurgical characteristics (heat affected zone, recast layer and micro-cracking) can be minimised by optimising the laser parameters such as average power, pulse energy, pulse duration, pulse frequency and focal positions. Low *et al.* [11] also reported that the amount of spatter depositions can be reduced by having the right combination of laser parameters, i.e. shorter pulse width, low peak power and high pulse frequency. Yilbas [12] reported that the mean diameter depends significantly on the material thickness and focus position. This was agreed by Bandyopadhyay *et al.* [10] and they reported that the hole size decreased with the increase of substrate thickness. Further parameter studies done by Yilbas [12] discovered that the amount of re-solidified material was mainly contributed by inappropriate pulse length and the interaction with the focal position setting. Bandoyadhyay *et al.* [10] used nitrogen as assist gas for drilling of Ti-6Al-4V. The use of assist gas during the drilling process is to prevent the laser optic from being contaminated by the debris ejection. It also helps to remove the material and speed up the breakthrough [13]. Thus choosing the proper assist gas may also result in better drilling and improvement of the hole quality. There are several types of assist gas used in laser drilling process. The typical types of gas jet used are oxygen (O_2), nitrogen (N_2), argon (Ar) and compressed air. The oxygen gas is mainly used for reactive fusion while nitrogen is for high speed and thin sheets, and also to prevent oxidation scales on steel. Argon is mainly used in aerospace application. Compressed air is a low cost gas jet compared to other gas jet used in drilling. The disadvantage of the compressed air is that it increases oxidation and dross. Attentive reminder has also been given on the utilisation of oxygen on metals like titanium as it gets burnt easily [13]. Other laser parameters such as beam focal position contributes to the effect of the final shape and the finishing of the hole [14].

Chien *et al.* [15] investigated the recast layer formation during Nd:YAG laser drilling of Inconel 718 and showed that gas pressure, peak power and focal position had significant influence on the recast layer thickness. They also showed that increasing the pulse energy and reducing the speed can result in reduced recast layer. Wang *et al.* [16] used electrochemical polarisation tests to assess the corrosion performance of the recast layer produced during laser drilling of stainless steel. The result showed that the use of nitrogen as the assist gas provides better corrosion resistance performance, followed by argon and oxygen. Noddin *et al.* [17] proposed a new drilling method to achieve good quality with two different lasers and trepanned motions, in which the second trepanned motion will smooth the edges of first trepanned motion. Lozier *et al.* [18] suggested a new laser drilling technique to achieve high quality, in which second trepanning orbit will be performed in opposite direction to the first one. Yilbas *et al.* [12] reported that the mean diameter can be controlled by material thickness and the position of focus point. Jacobs *et al.* [19] studied the effect of number of trepanning orbit and reported that the increase in the number of orbits can result in increased hole quality.

This paper investigates the effect of laser drilling process parameters on laser drilled hole quality. Experiments were performed on the aerospace material Ti-6Al-4V with thickness of 1 mm and 3 mm. The study took into consideration the main laser parameters including average power, pulse energy, pulse frequency, pulse width, focal position, gas pressure, number of pulse and type of assist gas used. Based on the considered range of parameters input, the angle of taper was calculated. Initial selection was performed based on the lowest tapered angle.

2. Experimental

2.1. Laser drilling experiments

The laser drilling experiments were performed using Nd: YAG solid state laser (class 4) with 550 Watts maximum output power and 1.064µm wavelength. The pulse length was within 0.5 – 20 ms and the maximum repetition rate was up to 500 Hz. The raw beam size was 10 mm focused beam, which resulted in an approximate beam size of 0.5 mm. Figure 1 shows the general construction of an Nd: YAG solid-state laser and the experimental set-up used for this investigation.

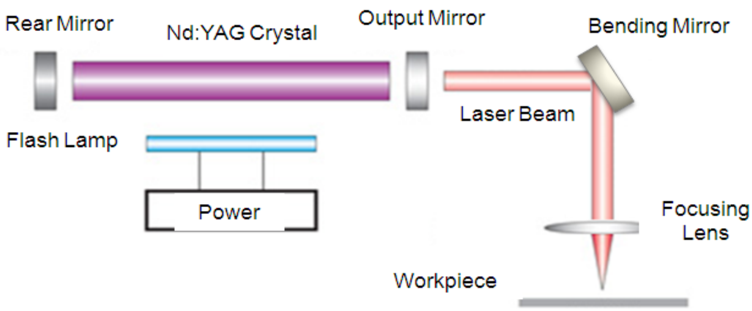


Figure 1. General construction of Nd: YAG solid-state laser used for laser drilling

The drilling process has been done in percussion drilling mode at three different focal positions: focused on the surface, and defocused in and out of the work piece with distance from the nozzle tips to the work piece of 2.829 mm, 2.329 mm and 3.329 mm, respectively. This drilling process was a photo thermal process that can result in thermal defects such as heat affected zone (HAZ), recast layer and taper angle. Ti-6Al-4V was used for the experiments due to its wide use in aerospace applications. Initial experiments were carried out prior to full experiments, which involved seven laser parameters (pulse width, pulse frequency, pulse energy/power, type of assist gas, gas pressure, focal position and number of pulse). This was done to ensure that only appropriate range of parameters was used and simultaneously reduced the time and energy consumption due to arbitrary parameter setting. The initial experiments mainly involved pulse frequency, pulse width and power. The parameters were initially set from low to high to identify the lowest range for the Ti-6Al-4V to be drilled through. The process has been iterated with the pulse width and power. Appropriate laser power had to be identified in order to achieve the desired material removal rate [20]. After the initial laser parameters ranges had been identified, combination of all laser parameters was then structured using statistical tools. Combination of seven parameters resulting 150 runs of experiments. In the 150 runs of experiments, four types of assist gas were evaluated including nitrogen (N_2), oxygen (O_2), argon (Ar) and compressed air. The laser drilling was set at peak power within 3 kW to 7.33 kW. The effect to the hole size on the entry and exit was evaluated and simultaneously, the taper angle of the holes were calculated. In order to have a deep understanding on the effect of number of pulse in the laser drilling process, two different thicknesses of same material (Ti-6Al-4V) had been examined during the experiments to obtain number of pulses required to enable the substrate to be drilled through. Different range of gas pressure from 2 bars to 6 bars was used during the experiment to study the effect to the material removal. Pulse width and pulse frequency were also varied during the experiments. Optimum laser parameter for Ti-6Al-4V of 1 mm thickness was mainly selected based on the hole taper angle. The combination of best laser parameters was obtained through the Design of Experiment (DOE).

Further analysis on hole characterization including heat affected zone and recast layer was executed by studying the significant difference in terms of hole size, spatter pattern and taper angle. The sample preparation was carried out by sectioning the sample and cutting through the middle of the hole. The sample was then mounted for its surface to be grinded and it was finished by finely polished 200μm diamond paste. After that, the sample was etched with Kellar etching agent to reveal the heat affected zone and recast layer microstructure when viewed under the microscope. The observation of the heat affected zone and the recast layer was performed using the microscope up to 100x Nikon lens and also Scanning Electron Microscope (SEM). It is known that laser drilling process will contribute to the range of severity effects such as holes tapering, spatter, recast layer, micro cracking and dross with different used of laser parameter. Taper angle is calculated by using Equation 1 [21]. This is vital as the optimum laser parameters are mainly selected by the corresponding lowest taper angle obtained. The range of taper mainly depends on the entry and exit diameters. Small difference between the entry and exit hole size leads to a lower taper angle, and vice versa.

$$Taper\ (\theta) = Tan^{-1}\left[\frac{d_{entry}-d_{exit}}{2t}\right] \tag{1}$$

where (θ) is the taper angle, d is the hole diameter and t is the material thickness. The other vital parameter in hole quality is the circularity of the hole, which can be computed by using Equation 2. This is performed by taking the ratio of the maximum and the minimum diameters of the same hole either the entry or the exit.

$$C_1 = \frac{D_{min}}{D_{max}} \tag{2}$$

where C_1 is the hole circularity and D is the hole diameter.

2.2. Laser parameters and ranges

The experiment was carried out with respect to the laser parameters within the stated range shown in Table 1. The range of laser parameters given was selected based on the initial experiments. The initial experiments were performed to ensure that only appropriate range of laser parameters was used for the laser drilling studies. Identified laser parameters were then simplified by DoE through combination of all laser parameters, which resulted with 150 numbers of runs. In the 150 runs, it consisted of different combinations of laser parameters within their identified range.

Table 1. Range of laser parameters used for the experiments

Laser parameters	Range
Pulse energy (J)	6.0 – 11.0
Number of pulse	2.0 – 4.0
Pulse width (ms)	1.5 – 2.0
Pulse frequency (Hz)	4.0 – 6.0
Gas pressure (bar)	2.0 – 5.0
Focal position	- 0.5 – 0.5
Type of assist gas*	2.0 – 4.0

*1.0 – 5.0 represents no gas, nitrogen, argon, oxygen and compressed gas, respectively.

3. Results and discussions

3.1. Effect of number of pulse (NOP)

The number of pulse used for drilling imposed significant effect on the drilling quality. Figure 2 shows the effect of the number of pulse to the drilling depth. 1 mm and 3 mm thickness of Ti-6Al-4V were drilled with similar other laser parameters except for number of pulse, resulting in a minimum of two pulses required to drill through 1 mm thickness of Ti-6Al-4V and a minimum of four pulses to drill through 3 mm thickness of the same material.

3.2. Effect of pulse width and pulse frequency

Range of pulse width from 1.5 ms to 2.0 ms was used during the experiments. It was observed that there were significant effects on the entry and exit size of the hole. Initially, when pulse width utilised was too low, the laser drilling process unsuccessfully removed the material. The diameters for both entry and exit started to stabilise approximately at pulse length of 1.5 ms. Han [20] reported that the presence of the laser supported absorption (LSA) wave could occur from the exceeding long pulse width. This phenomenon caused the hole to be unsuccessfully drilled through. Pulse width is always kept as low as possible in order to produce high peak power. Increase in pulse frequency significantly increased the exit diameters of the laser drilling holes, which simultaneously improved the taper angle as shown in Figure 3**.** Han [20] reported that higher frequency will result in straighter sidewall profile because of less melted material re-solidified and more molten material is pushed in the laser beam direction. However, the effect of pulse frequency may not be significant to all workpiece thickness, Ghoreishi *et al.* [22] reported hole entrance diameter of stainless steel was found significantly affected by the pulse energy while not in drilling the mild steel.

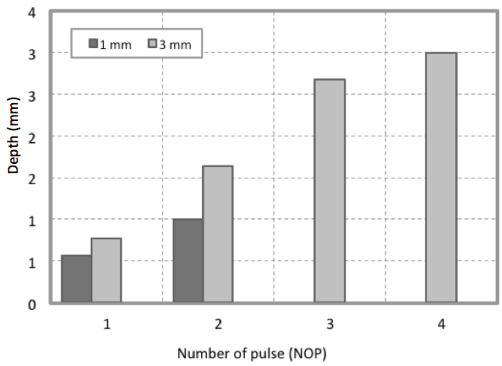


Figure 2. Number of pulses required to drill 1mm and 3 mm of Ti-6Al-4V, f = 4 Hz, fpp =-0.5, peak power = 4 kW, gas pressure = 3 bars, assist gas = nitrogen

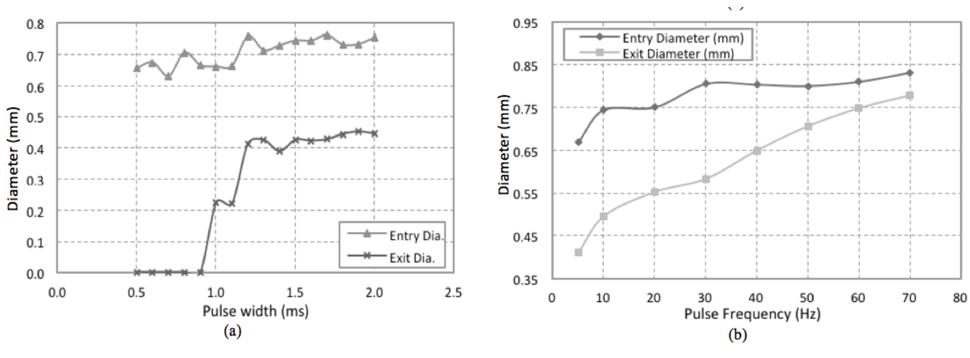


Figure 3. Entry and exit diameter affected by (a) various pulse width: f = 5 Hz, fpp = 0, gas pressure = 6 bars, assist gas = argon and (b) various pulse frequencies: pulse width = 1ms, fpp = 0, gas pressure = 6 bars, assist gas = argon

3.3. Effect of assist gas

Four types of assist gas including nitrogen (N_2), argon (Ar), oxygen (O_2) and compressed air were used in the experiments with remaining similar laser parameters. The taper angle was determined by using Equation 1. Figure 4 illustrates that compressed air produced the lowest taper angle with 8.11 degrees, followed by the nitrogen with 9.79 degrees. Argon and oxygen produced an even higher taper angle, within 10 to 11 degrees, respectively. The entry hole sizes were obtained within 700μm to 800μm for all assist gases used except for the oxygen, which reached up to 2.5 mm. The material removed was observed to be not in circular shape. Figure 5 illustrates the shape of the Ti-6Al-4V, which was drilled using oxygen. The substrate was severely destroyed due to the over burnt during the drilling process. Dahotre *et al.* [13] study showed that use of oxygen as assist gas in laser machining produced the best quality holes in iron, nickel and their alloys as it assists burning the metal away. However, attentive reminder has been given when dealing with metals like titanium because it can burn easily. Nitrogen is the second assist gas, which produced the second lowest taper angle after compressed air. Further investigation and study was carried by changing the laser parameters in order to minimise the taper angle currently produced.

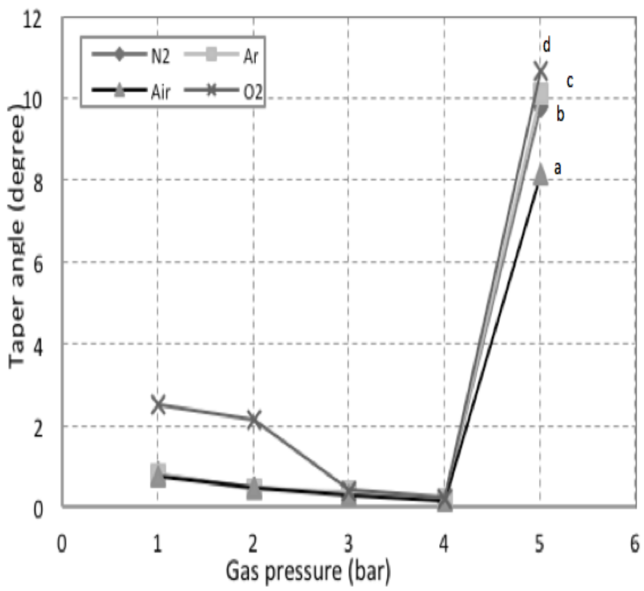


Figure 4. Taper angle at different gas pressures: (a) compressed air, (b) nitrogen, (c) argon and (d) oxygen, with f = 4 Hz, fpp = -0.5, peak power = 4kW, gas pressure = 3 bars

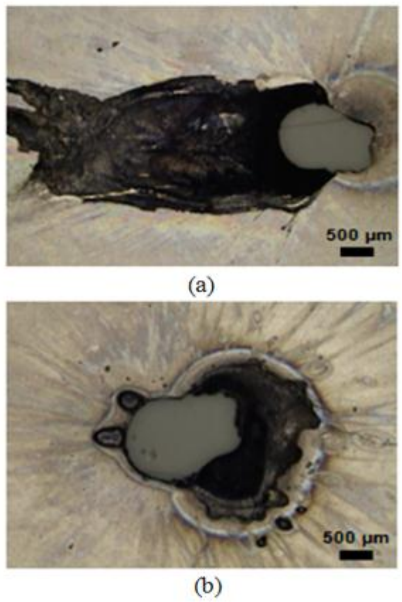


Figure 5. The hole drilled by the oxygen assist gas: (a) entry diameter and (b) exit diameter

3.4. Effect of gas pressure

The effect of gas pressure was evaluated from a minimum of 2 bars to the maximum of 6 bars. The investigation showed that setting appropriate gas pressure helped to achieve a better hole quality. As noticed from Figure 6, insufficient gas pressure led to the failure in removing the material. However, excessive gas pressure can also result in increased hole diameters, mainly at the entrance and hence increasing the taper. Higher assist gas also reduced the recast layer but can also result in increased material distortion [22].

3.5. Effect of the focal positions

Experiments were performed at three different focal positions (at the surface, above the surface and also below the surface). This was performed by adjusting the vertical distance between the nozzle and the work piece. The defocused positions were mainly focusing in the middle of the substrate and far above the substrate. The distance from the tips of the nozzle to the work piece was as stipulated below:

- The zero focal position was the condition where the laser was focussed on the surface of the workpiece and the distance of the nozzle tip to workpiece was 2.829 mm with the uncertainty of ± 0.002 mm
- 0.5 focal position was the condition where the laser beam was zoomed out from the focussed surface position and the distance of the nozzle tip to workpiece was increased to 3.329 mm with the uncertainty of ± 0.003 mm
- -0.5 focal position was the condition where the laser beam was focused at the middle of the workpiece and the distance of the nozzle tip to workpiece was 2.329 mm with the uncertainty of ± 0.013 mm

As shown in Figure 7, focal position maintained on the surface produced the smallest entrance and exit hole size, and also produced lower taper angle compared to the other beam positions. Increase in the nozzle offset resulted in high taper angle. However, the amount of spatter deposition was observed to be in opposite trend. The amount of spatter deposition on the workpiece was found to increase with the offset distance.

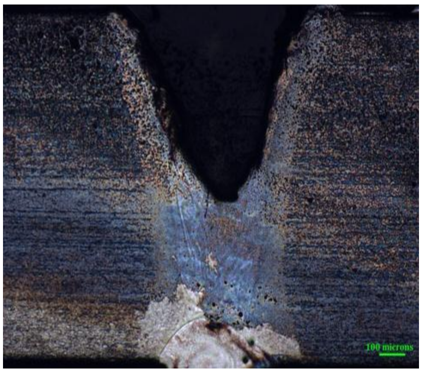


Figure 6. Ti-6Al-4V 1 mm thickness drilled with 2 bars gas pressure, f = 4 Hz, fpp = -0.5, gas pressure = 3 bars, assist gas = nitrogen, nop = 2, peak power = 4kW

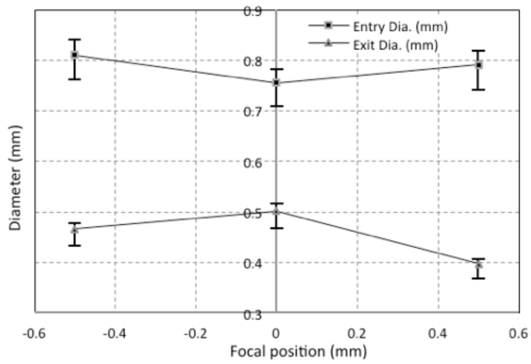


Figure 7. Entry and exit diameters at different focal positions, f = 4 Hz, gas pressure = 3 bars, assist gas = nitrogen, nop = 2, peak power = 4kW

3.6. Effect of average power

Three different average power settings, ranging from 24 W, 44 W and 66 W, were investigated. Both entry and exit hole size showed significant effect when the power was increased from 24 W to 66 W. The entry hole diameter was about 790µm at 24 W power and increased to approximately 910µm at 66 W. Similarly, the exit hole was increased from 400µm at 24 W to roughly 750µm at 66 W. However, the difference between the entry and exit hole diameters was smaller at the highest power level and hence resulting in lower taper angle. The other defects including spatter deposition on the surface were increased with laser power. The patterns of deposition were observed to be distinctly different from each other. Figure 8 shows the hole drilled at 24 W, 44 W and 66 W. Deposition of spatter has been analysed and observed to be increasing with laser power. At higher power, the spatter was observed to be accumulated around the entry hole. In severe cases, depending on the substrate properties, removal of overlapped spatter from drilling with inert gas would have to compromise with undesired substrate surface and hole geometry modification [11]. Ng *et al.* [23] found less spatter when holes were drilled with low laser energy and high power. Similar phenomenal was also observed in Figure 8, where the hole drilled with 24 W of power shows less spatter deposition and vice versa.

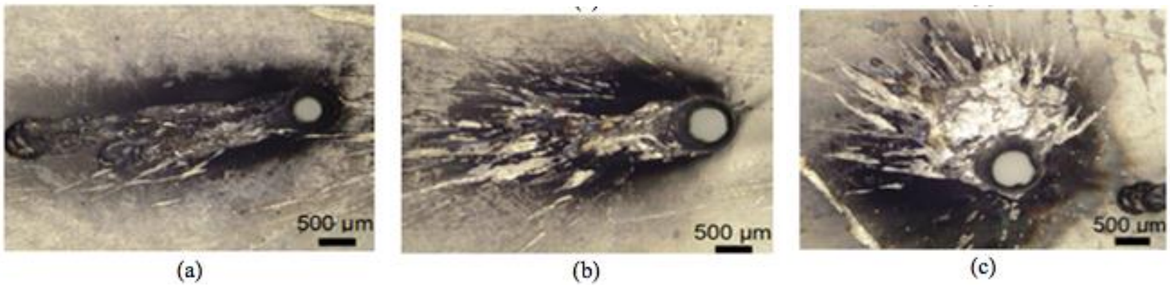


Figure 8. The deposition of spatter at different ranges of power: (a) 24 Watts, (b) 44 Watts and (c) 66 Watts, f = 4 Hz for 24 W and 44 W and f = 6 Hz for 66 W, fpp = 0.5, gas pressure = 3 bars, assist gas = nitrogen, nop = 2 for 24 W and 66 W and nop = 4 for 66 W

In all experiments, the diameter of hole was larger at the entrance than at the exit. As can be seen from Figure 9(i) for 66 Watts laser power, the top and bottom diameters were 850µm and 460µm, respectively. The entrance diameter for 24 Watts and 44 Watts indicated by (a) and (b), respectively, in Figure 9(i) were obtained at approximately 763µm. HAZ along the hole depth showed an increasing trend with increased power. The HAZ observed with 24 Watts, 44 Watts and 66 Watts is illustrated in Figure 9(ii). HAZ were found to be smaller in 24 Watts power and increased with laser power. The diameter ranges only started to vary when it passed 200µm in depth with approximately 100µm apart. Distinctive shape of hole also was observed for 66 Watts power where the hole diameter diverged back from approximately at 600µm depth to approximately 37µm. This is because, in Figure 9(i)(c), higher frequency was used compared to (a) and (b), thus increased the exit diameter. This improved the taper angle due to the effect of pulse frequency. Han *et al.* [20] reported the increased laser peak power had less effect on the entrance hole size than the exit diameter.

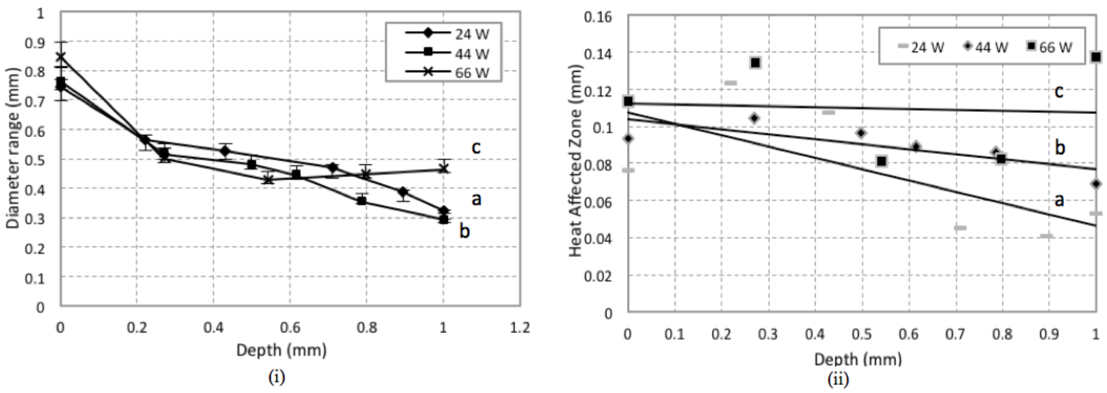
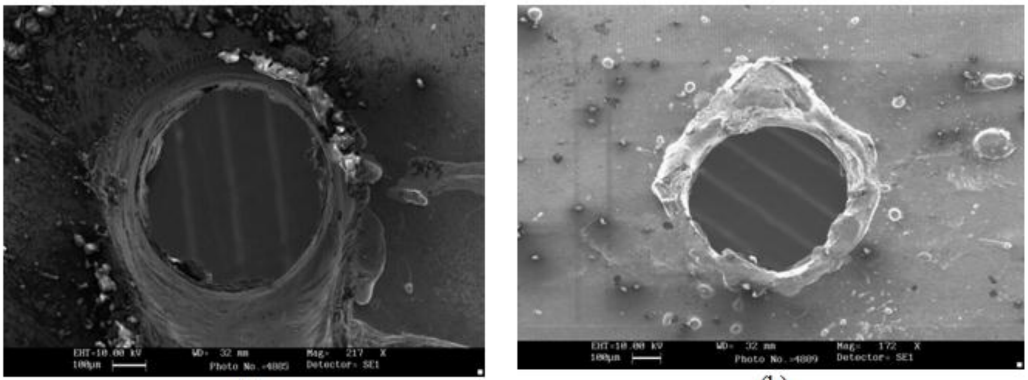


Figure 9. The effect of power to the diameter range and HAZ: (i) depth of the material (Ti-6Al-4V, 1mm thickness) vs. diameters and (ii) depth of the same material with the HAZ, f = 4 Hz for 24 W and 44 W and f = 6 Hz for 66 W, fpp = 0.5, gas pressure = 3 bars, assist gas = nitrogen, nop = 2 for 24 W and 66 W and nop = 4 for 66 W

3.7. Optimum laser drilling parameters

Figure 10 illustrates the hole drilled with the optimum laser parameters. The entry and exit hole size of 752µm and 689µm resulted in the lowest taper angle of 1.8 degrees. The hole was drilled with nitrogen gas with pressure set to 3 bars. Laser power was set to 66 W with respectively 11 Joule of pulse energy and 6 Hz repetition rate. Additional two pulses from the actual requirement in number of pulse for the substrate to be drilled through, making the total of four pulses utilised during the laser drilling process.



(a) (b)

Figure 10. Ti-6Al-4V, 1mm thickness holes obtained by the optimum laser parameters taken by SEM: (a) entry hole and (b) exit hole, with f = 4 Hz, fpp = -0.5, gas pressure = 3 bars, peak power = 5.5kW, nop = 4, assist gas = nitrogen

4. Conclusions

At the optimal parameters setting, laser drilling of 1mm thickness Ti-6Al-4V produced a taper angle of 1.8 degrees. Higher power led to larger hole size but the difference between entry and exit diameters were reduced, thus decreased the taper angle compared to that obtained from lower power. The amount of spatter deposition increased with increased of power. Heat affected zone (HAZ) was also found to increase with increased power. Percussion drilling with low pulse width resulted in better drill quality but high pulse frequency resulting straighter hole geometry and subsequently lower taper angle. The use of nitrogen and compressed air as assist gas produced low taper angle whereas oxygen was not the best assist gas to be used for drilling Titanium Ti-6Al-4V 1mm thickness. Furthermore, it was found that the amount of spatter deposition increased with increase in nozzle offset. Sufficient gas pressure was vital in the laser drilling process to ensure that the vaporised material was successfully removed. However, excessive gas pressure might lead to larger hole size.

Acknowledgement

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