Effect of defocused plane on entrance and exit hole geometry of high grade steel 18CrNi8 during percussion drilling by Nd:YAG millisecond laser system

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Abstract
Modern manufacturing industries prefer laser drilling processes owing to the adequate controlled drilling in comparison with existing alternatives. The presented experimental study mainly accounts defocusing impact along with other technical parameters and optimization of Nd:YAG millisecond pulsed laser drilling; and finally their influence on the entrance and exit holes profile. The key technical parameters such as pulse frequency, pulse width and assisting gas pressure with respect to different defocused focal plane are explored experimentally for the percussion laser drilling of high grade steel 18CrNi8. Experiment results revealed that increase in defocusing distance has caused an increment in hole entrance diameter; however, with different defocusing distance, the entrance diameter increasing rate keep changing. Different trends of increasing and decreasing diameter at entrance and exit are recorded and investigated with respect to work-piece defocusing positions. The defocusing variation of laser beam has been investigated with the hole profile, changing from straight hole to tapered blind hole. Which leads to conclusive and optimized results for obtaining optimal hole profile (at entrance and exit). The optimum parametric combinations for attaining lower heat treatment effects are also discussed for superior hole quality.

1. Introduction
The laser drilling is a controlled drilling process as compared to available alternatives, such as wire EDM, CNC, broaching, conventional drilling, other destructive hole techniques, etc [1]. The laser drilling demand has been extended owing to its rapid machining capability in emerging industries of automotive, electronics, heavy machinery and aerospace [2–5]. This zero-contact machining has advantages of enhanced accuracy, reproducibility, superior hole profile, etc and equally employed to variety of metals or alloys for micro orifices, fuel injection nozzles, holes in air turbine blades, and many other auto and aerospace equipment manufacturing [6, 7].

Quality of hole in laser drilling is largely dependent upon the operating parameters, such as laser beam wavelength, pulse repetition rate, intensity, pulse duration and operational current, etc and their combinations thereof. In general, the cracks, debris, major tapering effect, HAZ, shapes defects, are the main concerns [8–11]. Therefore, laser drilling has extensively studied theoretically and experimentally. Liang W et al studies declared that the hole depth is directly proportional to laser energy and observations are far from the theoretical calculations [12]. Machining is a challenge in some alloys, especially titanium and steel, due to its absorptivity for laser beam energy and low conductivity. Mei WQ et al established a characterization method of hole...
manufactured by millisecond pulsed laser drilling [13]. Yu et al studied heating, melting, beam energy absorption, vaporization and resolidification influence on the machining performance of semiconductor different materials [14]. Micro-hole ablation using Nd:YAG millisecond pulsed laser and its impact on the depth of hole was less discussed [9, 10]. Controlling the morphology and quality of the holes is considered as an important factor in fulfilling the requirements of laser drilling applications [15, 16]. Low et al investigated the melt ejection process in laser drilling of dielectrics and various metals [17, 18]. Biswas and Yilbas investigated the different parameters in the pulsed Nd:YAG laser drilling of ceramic composites for hole circularity. Yilbas and Bishwas carried out work on laser drilling of Nickel, Stainless Steel, and Titanium, etc [19, 20]. Ghoreishi et al developed a statistical model for analyzing and comparing hole entrance and taper circularity of steel alloys [21]. Not many researchers have addressed the defocusing impact on drilling hole quality in depth [22–27]. Saad and Chao have also investigated the taper angle during millisecond laser drilling of 18CrNi8 steel under multiple parameters and defocused plane but investigation of recast layers at entrance and exits as well as molten pool splashes was not studied yet [28–30].

This presented research has mainly addressed defocused laser percussion drilling by with respect to different positive and negative defocused positions. The operating parameters with different ranges are deeply analyzed with respect to various defocused positions resulting blind holes on either sides. Defocusing effect is also investigated for steel alloy in combination with different parameters and their different ranges. Work piece is moved above and below the focal point and experimental results containing entrance and exit radius, and longitudinal profile are recorded. While defocusing each time there is an increment of 0.5 mm on either positive or negative defocusing. The optimum laser drilling conditions of operating parameters and their combinations are also proposed for blind hole to taper hole and tapered to straight hole.

2. Material and methods

Steel DIN18CrNi8 alloy (containing carbon 0.13%–0.21%), made by company Bosch (BOSCH) was chosen as work piece (thickness 1 mm and length 20 mm) for current investigation, due to its large variety of applications such as fuel injection nozzles, heat exchangers, turbine blades and nano-manufacturing. This material is favorable in high temperature applications because it maintains its hardness at elevated temperatures because of its high hardness and yielding strength. The work piece has yield strength (154 MPa), high hardness (180–240 HB), tensile strength (231 MPa), elasticity (491 GPa), low density (221 kg cm$^{-3}$), thermal expansion ($\sim$11.8 e$^{-6}$/K), melting temperature ($\sim$1650°C), good creep and oxidation resistance. Owing to extreme brittleness and low fracture toughness at room temperature it’s machining is always challengeable.

Current experimentation used Nd:YAG laser system of CHUTIAN LASER EQUIPMENT GROUP (wave length 1064 nm, average power 120 W, pulsed 0.1–20 ms, current 0–500 Amp and assisting gas flow 0.4–0.8 bar). For measuring optical emissions such as laser beam energy and average power, a thermal sensor (7Z02786) of OPHIR LASER MEASUREMENT GROUP has been used. This optical measuring instrument can measure power range 30 mJ–150 W and beam energy range is 30 mJ–300 J. The operating parameters used for sensitivity analysis are pulse width (1.0–4.0 ms), current (180–300 Amp), number of pulses (1–3), frequency (1–20 Hz) and assisting gas flow rate (0.5–0.8 bar). Defocusing plane systematics has been analyzed ±2.5 mm (see figure 1). A large volume of the material removed by melt ejection is related to laser beam power and the material type. In general, the peak power decreases with the increase in pulse width and power density. In some cases, material removed in vapor form falls back and more energy is needed to remelt. Ultimately bigger burrs will have formed and resolidification at the exit boundary will occur.

3. Result and discussions

Millisecond laser system (emitting Gaussian beam) is employed to drill holes in the steel work piece of defined thickness. Percussion drilling process is repeated for different defocused positions with range of operating parameters as disclosed in previous section. Detailed experimental sensitivity is conducted to analyze the operational parameters and their combinational impacts on the topology of the hole; in particularly evaluating the changes occurred while moving away from focal point. In each case, the hole entrances and exit diameters, increasing or decreasing trends of debris, burr deposition and resolidification are critically monitored.

3.1. Hole shape and geometry

In all the experiments, hole entrance diameter increases while moving away from focal point until have a blind hole on both ends of negative and positive defocusing. However, the said increase in diameter seems slow in case of moving below the focal point. This is because of increase in beam energy dissipating to atmosphere which resulted in decrease in beam power. For assisting gas, the entrance hole diameter increases as moving away from
defocusing below the focal point. However, the increasing diameter trend remains the same for 0.5, 0.6, 0.7, 
0.8 bar pressure, but the entrance diameter increases at each defocused position, as pressure increases (see 
figure 3). Assisting gas played a vital role in cleanness of entrance of the hole and it also facilitates the ablation 
rate. All test cases have the similar number of holes, till blind hole, while 0.7 bar pressure seems the most 
favorable for the said work piece drilling, as number of holes drilled in this case counted as 6 (see figure 3). 
Entrance diameter first slightly increase with increase in defocusing plane but after 1 mm defocusing, drastic 
increase in diameter was observed because of large spatial size of laser beam.

While on defocusing above the focal plane, 0.5 bar have more holes than other cases. But the trend of 
increasing diameter seems to be disturbed as at −1.0 mm position the diameter size surprisingly lower than 
−0.5 mm position. The reasonable justification of said phenomena could be the lower pressure of gas which 
disturbed by external atmosphere. It was observed during investigation that if plane is defocused beyond 1.0 mm 
on each side will leave blind holes instead of through hole with same parameters (see figure 2). The basic reason 
behind these behind holes is increase in spatial size, which ultimately disturb beam intensity and pulse energy. 
Due to this phenomena entrance diameter will increase as spatial size increase, however depth of drilling will 
decrease. Hole exit for assisting gas seems having different trends similar to the hole entrance.

In exit diameter case sensitivity, the first diameter decreases as the defocusing increases till 1 mm but after 
that it is suddenly increases sharply and then decreases in the end before blind hole. This trend can be explained 
by observing sudden increase in entrance diameter of hole after 1 mm defocusing which forced to increase exit 
diameter too, while overall entrance to exit diameter ratio remains almost the same (see figures 4, 5). It is further 
noticed that on gas pressure 0.7 bar exit diameter increases even at +0.5 mm defocusing which is clear deviation 
from general trend mentioned. So the above said trend seems accurate while negative defocusing trend seems a little disturbed in some cases. The entrance radius to exit hole radius ranges between 1.3–3.1 while at 0.7 bar there is a significant deviation before blind hole where ratio 
recorded was 5.7.

For assisting gas, the entrance hole diameter is increased while defocusing below the focal point (see 
figure 5). However, the said trend of increasing diameter trend remained the same for 0.5, 0.6, 0.7, 0.8 bar 
pressure, but the entrance diameter is increased for each defocused position, as pressure increases. Assisting gas 
has played a vital role in cleanness of entrance of the hole as it facilitates the ablation rate. All test cases have the 
similar number of holes, until blind hole, while 0.7 bar pressure seems the most favorable for the said workpiece 
drilling: a number of holes drilled in this case count as 6. While on defocusing above the focal plane, 0.5 bar has 
more holes than other cases. But the trend of increasing diameter is seemed to be disturbed as at −1.0 mm 
position the diameter size surprisingly lower than −0.5 mm position. The reasonable justification of said 
phenomena could be the lower pressure of the gas, which disturbed by the external atmosphere and restricted it 
to the drilling center. It has been observed that the radius increase from 185 μm to 283 μm at the rate of 30 μm
Figure 3. Entrance, exit and longitudinal profile of the hole for 0.5, 0.6, 0.7, 0.8 bar.

Figure 4. Exit and entrance Radius for 0.7 bar.

Figure 5. Defocused position impact on hole Entrance (a) and exit (b) radius at various pressures.
per 0.5 mm for 0.5 bar while moving below the focal point. While moving above the focal point the said increase in radius is recorded as 35 μm, which ended at 323 μm. Here it is investigated and confirmed that the radius of the blind hole on negative defocusing is more than the blind hole on positive defocusing. The change of radius does not have constant increasing trends in each case. Increase in diameter is less around the focal point and it became dominant while moving further away. The entrance radius of the hole was tabulated in Table 4.2, which ranges from 185 μm to 323 μm for 0.5 bar, 153 μm to 349 μm for 0.6 bar, 201 μm to 371 μm for 0.7 bar and 165 μm to 367 μm for 0.8 bar.

Hole exits for assisting gas seemed to have different trends similar to the hole entrances. In exit diameter case, first diameter is decreased as the defocusing increases until 1 mm but after that, it has a sharp sudden increase and then decreased.

For 0.5 bar, exit radius while moving below the focal point ranges from 124 μm to 79 μm before the formation of the blind hole. On the other hand, for negative defocusing, the radius ranges between 124 μm to 93 μm. For 0.6 bar, while moving below the focal point exit radius ranges from 116 μm to 137 μm before blind hole. On the other hand, for negative defocusing, the radius ranges between 116 μm to 90 μm. For 0.7 bar exits radius while moving below the focal point ranges from 122 μm to 133 μm before approaching to blind hole. On the other hand, for negative defocusing, the radius ranges between 122 μm to 64 μm. For 0.8 bar, exit radius while moving below the focal point ranges from 175 μm to 142 μm before approaching to blind hole. On the other hand, for negative defocusing, the radius ranges between 175 μm to 143 μm.

Graphs of individual or combined pulse width demonstrated that it’s one of the important factors that can influence shape of the hole dominantly. Increase in pulse width causes increase in pulse energy which ultimately increases diameter of hole and vice versa in case of decreasing. The basic reason behind this is decreasing concentration of laser beam energy and increase in dissipated energy to surroundings in the form of heat. For this study four pulse widths 1.0 ms, 2.0 ms, and 3.0 ms 4.0 ms are used with defocused plan in order to investigate its combine influence on shape of the hole. It was observed that entrance radius of hole increases for each pulse width as pulse width increases. For all pulse widths the trend of increasing diameter with respect to change in defocusing plane was same however the ratio or amount of change in diameter was different. Unlike other parameters tendency of increasing radius with increase in defocusing length is same for both negative and positive defocusing. Till 1 mm increase on either sides gradual increase in radius was recorded 40 μm–50 μm except 2 ms pulse width where change was observed more than 90 μm on negative side. While after 1 mm defocusing the change in radius suddenly increased more than 70–80 μm for each 0.5 mm, because at low pulse width, high resolute laser beam energy leads high rapid rate of penetration to high pulse width; as result, bigger entrance diameter is created.

Hole exit radius for pulse width exhibited different trend at different defocusing points because of mixed tendency of increasing and decreasing radius. It is observed that for increase in defocusing length resulted in decrease in hole exit diameter till 1 mm, while defocusing below the focal point. But after 1 mm defocusing exit diameters started increasing till the end. However, on the other side while moving above the focal point the tendency of increasing exit diameter was discovered till the blind hole was obtained. For different pulse widths and defocusing positions, ratio of entrance radius to exit hole radius lied between 1.1–2.0 till 1 mm defocusing distance. While after that ratio increases up to 3.0 before blind hole.

No of pulses defined the total pulse energy for the process, more number of pulses will have resulted in higher total beam energy. Consequently, more energy would cause increase in depth of the hole as well as the increase in hole exit. In this experimental study it was observed that number of holes drilled for 3 pulses are greater than drilling with single and double pulse due to higher total pulse energy. There would be more difference if the frequency would high, because most part of energy needed to deal with remelting. For single, double and triple pulses after defocusing above, radius of the hole first decreases then started increasing while on defocusing below the focal point it starts increasing straight. In case of exit radius, diameter started decreasing while defocusing above the focal point but after 1 mm it starts increasing with same proportion to entrance diameter. On the other hand, while defocusing below the focal point will be increase in exit diameter except single pulse, it is because of remelting of solidified material at the bottom of the hole because of more pulses.

Frequency of the pulses does not have prominent effects on the drilled hole and its shape because change in frequency won’t affect the total energy. Entrance diameter increases as the defocusing away from the focal point on either side. The rate of increasing radius is slightly increases in case of increase in frequency, because of more pulses in short time which may cause decrease in solidification of melted material. Hole exit radius gradually decreases with increase or decrease in defocusing in each case because of unchanged total energy (see figure 6). Hole entrance to hole exit ratio remains near 1.2 till the blind hole but near blind hole it increases immensely till 4.5. This trend depicts that total energy for each frequency 1, 10, 20 HZ remains same.

Operational Current is a machining parameter which has direct influence on the beam power ultimately has influence on shape of the hole. For this experimental study three 180, 240, 300 Amp currents are used ranging from low to high. As a general trend defocusing will have increase in diameter for all currents, but number of
straight holes will be increased if there is an increase in current. Radius measured for each current at different
defocused levels are also increased for increasing current which can be seen at 0.5 mm defocusing the entrance
radius recorded as 242, 250, 269 μm for 180, 240, 300 Amp respectively (see figure 7). And entrance exit the same
trend was observed at 0.5 mm defocusing while exhibits exit radius as 127, 139, 142 μm.

3.2. Material deposition, recast layer and debris
During the experiments many unwanted factors affected the processes in the form of recast laser which resulted
in loss of beam energy, debris and material deposition on walls and entrance surface. The trend of increasing and
decreasing of these all factors at different defocusing levels are discussed in order to propose the best parameters
for well-shaped clean.

Material deposition around entrance of the hole increases gradually in for each 0.5, 0.6, 0.7, 0.8 bar as the
defocusing increases above the focal point hole (see figure 8). This is because of increase in diameter which
causes decentering of assisting gas and molten material start depositing on entrance. But trend seemed disturbed
because of unwanted circumstances at −1.0 mm defocusing where increase in deposition immensely increased.
It was discovered that increase in gas flow rate will resulted in increase of material deposition at entrance. This
may be because of high flow rate speed up the melting as well as molten material removal in which chances of
material deposition suddenly increased. While for hole exit the material deposition first increases till 1 mm
defocusing but after that started decreasing and proposed a clean hole. While increasing gas flow rate material
deposition decreases because of high flow rate further assisted the drilling process which ultimately resulted in
fine clean hole exits, as shown in figures 8 and 9.
Uniform molten pool splashes trend has been observed for all assisting gas pressures. However at 0.7 bar and 0.8 bar, considerable hike in molten pool splashes up to 500 um radius has been investigated (figure 10).

For all pulse widths (1 ms, 2 ms, 3 ms, 4 ms) molten material deposition increased in direct proportion defocusing distance are discussed. But while increasing pulse width, it is observed that hole entrance became more clean till 1 mm defocusing. This is because of high intensity and high power of laser beam. But after 1 mm trend seemed different because of higher defocusing distance which facilitate the beam energy dissipation to atmosphere as well as increase in spatial size. On the other hand, molten material deposition decreases as

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**Figure 8.** Entrance (a) and exit (b). Molten material deposition and splashes on entrance and exit for assisting gas pressures (0.5, 0.6, 0.7, 0.8 bar).

**Figure 9.** Recast layers at hole entrance and exit for oxygen gas.
increase in defocusing distance. In case of number single pulse, material deposition on entrance of the whole is recorded increasing with increasing in defocusing while for 2 pulses and 3 pulses this trend seems random. For double and triple pulses increase in molten material deposition was investigated as first increasing till 1.5 mm and after that decreasing. It was evaluated that every new added pulse will add more molten material splashes.
which cause more material deposition around entrance of key hole. At exit of the hole material deposition gradually decreases with increase in defocusing distance and slight decrease with increase after 1 mm defocusing.

The essential cause of cleaner exits and less material depositions is the increase of new pulse in total energy which accounts for the high amount of pulses. When the defocus gap rises for all currents values, a slow and steady addition in material deposition is observed. On the other hand when the current escalates the alteration in material deposition and resolidification on hole entrance is slightly increased. On all positive defocusing points the cleanest hole entries are detected for 300 amp currents. For high currents hole exits are shaped exquisitely. When the current falters because of high energy the material deposition is enhanced. Around openings of holes molten material deposition is low for higher frequencies in contrast to lower frequencies. The cleanest hole entrance and the worst exit for all defocused points with reference to material solidification was observed at 10 Hz frequency. Thermal diffusivity of material and high thermal stresses during laser drilling affect internal recast layer to a great extent (see figure 11). Material cooling rate will be higher if material’s diffusivity is high but the amount of debris is comparatively small (see figure 12). The temperature of concerned material increases during laser drilling which is the major drawback of this process. Change of currents at various defocused
positions revealed major debris and internal recast layers which was the reason of increase and decrease of pulse energy and temperature dissipation around machining area. Higher temperatures and heat conduction adversely affected, causing cracks and change of structure, walls of many holes and drilling area around the material as it was observed after cutting cross section of hole.

Debris formation is an unavoidable phenomena and still need to address during laser drilling with millisecond laser systems. Debris forms because of condensation of high super cooled vapors collisions with ambient gaseous molecules, especially in the gas phase. The majority of the vapor first ejected then deposit on the ablation pattern surface, entrance surroundings and inside the hole, as demonstrated in figure 12. The main disadvantage of debris formation is deteriorated the feature quality, reduces ablation rate because debris can block the laser-beam for the next scan. Debris formation seems dominant within the hole walls but some surface debris were also found on entrance. Results shown in above figure are without treating the debris removal methods such as chemical etching.

4. Conclusion

It is revealed that there is a clear observation of increase in hole entrance diameter with the increase in defocusing distance during experimental investigation. While moving below the focal point the said increase in diameter recorded smaller as compared to moving above the focal point. Dynamics of hole shape at the entrance and exits does not have linier relationships with the operating parameters. The hole exit diameter decreases up to 1 mm defocusing while after that it start increasing in many cases. Overall the entrance to exit diameter ratio remains close to constant. Material deposition, debris formation have different trends of increasing and decreasing with respect to different defocusing positions. Most of experiments showed that heating effects at entrance and exits are remained opposite in all cases.

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