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INVESTIGATION OF THE EFFECT OF ASSIST GAS PRESSURE AND PULSE FREQUENCY ON SELECTED HOLE CHARACTERISTICS IN Nd:YAG LASER PERCUSSION DRILLING

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ABSTRACT

Laser drilling has been widely used in many applications especially in aerospace industry for drilling cooling holes in gas turbine engine components. Spatter formation is one of the inherent defects associated with laser drilling. It is formed around the hole rim due to the deposition of the molten or vaporized material that is expulsed from the workpiece during drilling. Hole taper is another problem facing laser drilling. The manufacturers usually use a gas jet (assist gas) in tandem with laser beam when material removal by laser. In this study an investigation of the effect of oxygen pressure -as assist gas- on the spatter deposition area, inlet diameter, and taper of holes drilled on superalloy is carried out. The effect of laser pulse frequency on the same hole characteristics is also presented. A trial to find the effect of assist gas pressure and pulse frequency on the total volume removed from the laser-drilled holes is also done. The drilling operation was carried out by a fiber-optic delivered 400 W pulsed Nd:YAG laser system. Scanning electron microscope (SEM) was used to capture images of the laser-drilled holes at the workpiece surface. An image processing software was employed to measure both spatter deposition area and inlet hole diameter. Exit hole diameter was measured by digital optical microscope. It was found that the increase of assist gas pressure could increase the spatter deposition area, inlet hole diameter, and hole taper. The increase of pulse frequency may lead to the same results. Continuous increase of gas pressure and pulse frequency could decrease spatter deposition area.

KEY WORDS

Laser drilling, Assist gas, Pulse frequency, Spatter, and Hole taper.

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1. INTRODUCTION

Lasers have been used in many scientific and engineering applications since their discovery in 1960. The capability of lasers as a tool for materials processing has been demonstrated. However, laser material processing techniques are increasingly finding their way in industry with a wide range of applications. The ability of lasers to deliver a high energy density make them useful in manufacturing operations like welding, cutting, and drilling [1].

Laser drilling can be understood to be a hole making technique that utilizes laser beam's capability of being focused to a small spot at power densities sufficient to melt and vaporize the metal. Laser percussion drilling is a series of laser pulses with specified properties that are directed onto the same spot to form a through hole [2]. Superalloys are used in gas turbine engines manufacturing. These materials are hard to be machined with conventional machining methods, so laser drilling has become a trademark in making arrays of fine cooling holes in such industry.

A gas jet (usually called an assist gas) passes through a nozzle, which is coaxial with laser beam, is usually used in such drilling (Fig.1). The prime reason for this jet is to protect the focusing optics from being contaminated by the expulsed material removed from the workpiece during drilling [3].

In laser cutting of steel with oxygen as assist gas, it has been calculated that the laser contributes only around 40% of the energy to the cutting zone, the remaining 60% of energy is supplied by exothermic reaction between Fe & O_2. The gas also blows the molten metal from the cutting zone. For laser drilling the effect of assist gas is less dramatic, since most of the material is removed from the top of the hole and so opposed by gas flow [3].

Little work has been done to investigate the effect of assist gas on the drilling process and the hole characteristics. French et. Al. [3] found by using a high speed filming technique during laser percussion drilling process that at the end stage of hole formation small liquid droplets are ejected from the hole. This particular ejection type was only observed when oxygen assist gas pressure (2-4 bar) was used, indicating the importance of assist gas flow and pressure in determining the final hole configuration.

Laser percussion drilling suffers from some defects; spatter and hole taper are from. Spatter is the ejected molten or vaporized metal that is not completely ejected but resolidifies and adheres around the periphery of the hole. Spatter formation is undesirable especially in drilling of cooling holes aero-engine components, whereby the flow and efficiency of cooling is crucially dependent on the characteristics of holes. In addition, removal of spatter needs more cost and time. The characterization of spatter is done by identifying its deposition area and its thickness around the drilled holes [2]. Hole taper is another problem facing laser drilling. It is mainly due to the nature of the spatial distribution of the laser beam intensity (5).

Pulse frequency is one of the effective parameters in laser drilling. It has a clear effect on liquid metal expulsion during laser drilling. Basu and DebRoy [6] found that when workpiece is irradiated with multiple laser pulses, only at high frequency (10 Hz at pulse width of 0.5 ms) region liquid metal expulsion occurred. This may because preventing cooling of liquid metal between subsequent pulses. Low et. Al. [2] measured the spatter area at frequencies of 10 Hz and 190 Hz at ~ 0.5 ms pulse width. They found that the spatter area decreased at the higher pulse frequency more than the lower one. It was said that the dissimilar spatter characteristics could be due to the presence of interaction between successive laser pulses with the ejecting material.

In the present study, the effect of oxygen pressure as an assist gas, also the effect of the pulse frequency on spatter formation and hole taper was investigated during laser percussion drilling of a superalloy.

2. EXPERIMENTAL SET-UP

2.1 Laser drilling system and parameters

Laser drilling was carried out by a JK 700 GSI Lumonics 400 W pulsed Nd:YAG laser emitting ay 1.06 μm wavelength. The laser beam was delivered by means of 6 m long, 600 μm core diameter optical fiber. The beam exit through a delivery head that held the necessary optics and the conical assist gas nozzle. Nozzle used was 1.5 mm diameter. The delivery head was mounted on z-axis of three-axis CNC table. Four holes were percussion drilled at the same setting parameters with a hole pitch of 6 mm (to avoid overlapping of spatter) such that the final values were taken from their average dimensions. Identical train containing standard rectangular pulses with pulse energy of 3.65 joule and width of 0.5 ms were used. Stand-off distance (distance between nozzle and workpiecs surface) was 1.9 mm.

The laser beam was focused with a lens of 120 mm focal length. The focal plane position was placed at material surface giving a beam spot diameter of 0.55 mm. Oxygen as assist gas was used with pressure values of 1,2, 3,4 bar. Pulse frequency range was from 10 to 70Hz.

2.2 Material used

The material used was a superalloy (2.5 mm thickness) having the following chemical composition (according to EDS analysis made by (SEM)):

Si	Cr	Fe	Co	Ni	MO
0.907	19.335	24.818	13.957	13.173	27.809

2.3 Hole characteristics measurements

In order to measure the spatter area, image processing of the laser-drilled substrate was done using Matlab 6 software. The hole is captured after laser drilling by (SEM) and transferred to a digitized image, which is kept in the computer memory. A developed program was employed to measure the spatter and hole dimensions. The program allows the calibrated measurement of laser drilled hole surface features. The computer based measurement process used a threshold function to find the edges of the hole and spatter. This thresholding depends mainly on variation of intensity of each of object of interest (drilled-hole, spatter, and workpiece surface) along the hole profile (see Fig. 2). The defined edges automatically converted into area measurement. The calibrated measurement of laser drilled hole and its associated features were finally exported to Microsoft Excel for analysis and graph plotting.

The indication of the hole taper is made by measuring the inlet and exit hole diameters to get the ratio between them. The same image processing procedure was employed to measure the entrance hole diameter. Digital optical microscopy (made by Mitotoyo) was used to measure the exit hole diameter.

3. RESULTS

3.1 Spatter deposition area evaluation

The effect of increasing pulse frequency on spatter deposition area was studied at the different increments of gas pressure. Fig. 3 shows that for assist gas pressure of 1&2 bar the spatter deposition area increases with increasing pulse frequency up to 40 Hz. When increasing pulse frequency up to 60 Hz; the spatter area shows approximately constant values with little variations. The maximum spatter deposition area is obtained at frequency of 70 Hz for the same two pressure increments. For gas pressures of 3&4 bar a different behavior is observed; at these two pressures the spatter area initially increases with increasing pulse frequency up to a threshold value (depends on the oxygen pressure value) at which the spatter deposition area starts to decrease until reaching the maximum frequency used (70 Hz). An observation obtained from Fig.3 is that for constant pulse frequency the spatter deposition area increases with increasing oxygen pressure up to 3 bar. Continuous increase of the assist gas pressure up to 4 bar, spatter area will have lower values than that obtained when using a pressure of 3 bar. Fig.4 shows the images that captured by (SEM) to the inlet hole at different pressures and pulse frequencies.

3.2 Evaluation of inlet and exit hole diameters

The influence of increasing pulse frequency on the inlet diameter of the laser-drilled holes is investigated at the same different assist gas pressure values as shown in fig 5. It is noticed that the entrance hole diameters are proportionally increasing in an approximately linear manner with increasing pulse frequency for all the assist gas pressure values until it reached a threshold value (50 Hz) at which these diameters started to decrease slightly or remained constant.

The effect of gas pressure on the inlet diameter is easily predicted from fig 5. When increasing the assist gas pressure the entrance hole diameters increased except at the minimum and maximum frequencies used (10 and 70 Hz respectively) where there is little mutation about the latter results.

The exit hole diameter shows little response to both pulse frequency and gas pressure changes, which make these changes ineffective. Figure 6 shows a SEM image the exit of laser-drilled hole.

3.3 Inlet to exit diameters ratio

The ratio between the inlet and the exit diameters are shown in Fig.7. As the exit hole diameter does not greatly affected by both pulse frequency and assist gas pressure; it can be said that hole taper decreases at both low gas pressure and low values of pulse frequency, and increased at high pressures and frequencies. There are exceptions at high values of pulse frequency (60 and 70 Hz).

4. DISCUSSION

Vaporization and melt ejection are two material removal methods that occur during laser drilling of metals. The latter arises due to the rapid built up of vapor pressure in the hole as evaporation occurs [7]. This type of drilling usually occurs when laser intensity in the region of 10^5 to 10^7 W/cm^2 [5]. The used intensity in this study is $3x10^6$ W/cm^2.

When increasing pulse frequency the time between successive laser pulses decreases. This leads to that the drilled hole material has not enough time to be cooled [6], so the expulsed liquid temperature increases with each coming pulse. This may increase the amount of vapor inside the hole, and causes an increase in vapor pressure, which could give more kinetic energy to the expulsed material, so the spatter deposition area increases. Another reason for increasing spatter deposition area with increasing pulse frequency could be detected from increasing the entrance hole diameter as the pulse frequency increases. This may cause more metal removal and consequently more spatter area.

The experimental work shows that the spatter deposition area also increases when increasing the assist gas pressure up to 3 bar. It could be a result from a supplementary kinetic energy that may be supplied to the expulsed liquid metal (produced when laser drilling) from the assist gas.

When the gas pressure reached the value of 4 bar, the spatter deposition area decreased approximately up to the values associated with 2 bar pressure. That area decrease could be related to the use of oxygen as assist gas. Low et Al [8] found (using high speed filming) that when using oxygen in laser percussion drilling of Nimonic alloy, the mechanism of metal removal is characterized with increased liquid particle ejection coupled with volatile burning and vapor ejection, so when the gas pressure reaches 4 bar this volatile burning rate may increase and little material is resolidified around the hole rim. The fraction of the downward material ejection when increasing the assist gas pressure should be examined to find a relation between them. This may be another reason for the decrease of spatter deposition area when the gas pressure reaches the value of 4 bar.

The increase of the inlet hole diameter when increasing the pulse frequency may be due to the rapid heating of the workpiece surface, which could lead to more thermal damage around the laser interaction region at the substrate and consequently more inlet hole diameter. The increase of oxygen pressure as an assist gas may have a chemical or a mechanical effect or both on the same region that leads to enlargement of the entrance hole diameter.

The ratio between the inlet and exit holes shows the same behavior as the entrance hole variations for the exit hole has a little response to the changing of the pulse frequency and assist gas pressure.

A trial to find the effect of pulse frequency and assist gas pressure on the volume of metal removed inside the laser drilled hole is done by considering the hole as a cone has a maximum and minimum diameters of inlet and exit hole respectively and finding its volume. It is presented in Fig. 8. It is clear from this figure that the assist gas pressure could have an effect on the volume of metal removed so the pulse frequency.

5. CONCLUSION

The pulse frequency (in the used region) and pressure of oxygen as assist gas may have considerable effects on the spatter deposition area, inlet hole diameter, hole taper, and volume of metal removed in laser percussion drilling of the superalloy used:

- Generally when increasing pulse frequency the spatter deposition area, inlet hole diameter, hole taper, and volume removed from the hole increase.
- The increase of assist gas pressure will also increase the spatter deposition area, inlet hole diameter, hole taper, and total volume of metal removed from the hole. Continuous increase of assist gas pressure may decrease the spatter deposition area.
- Pulse frequency and assist gas pressure have no considerable effect on exit hole diameter.

6. REFERENCES

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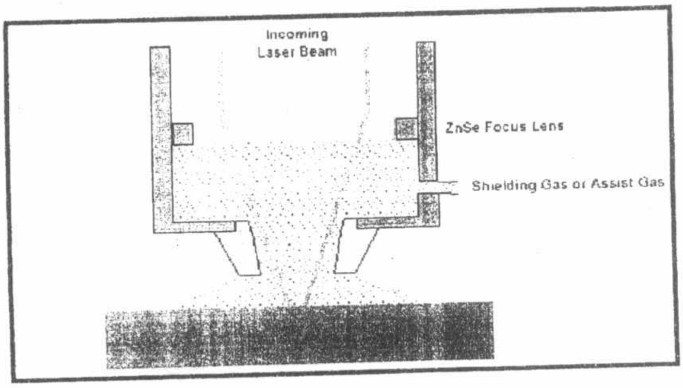
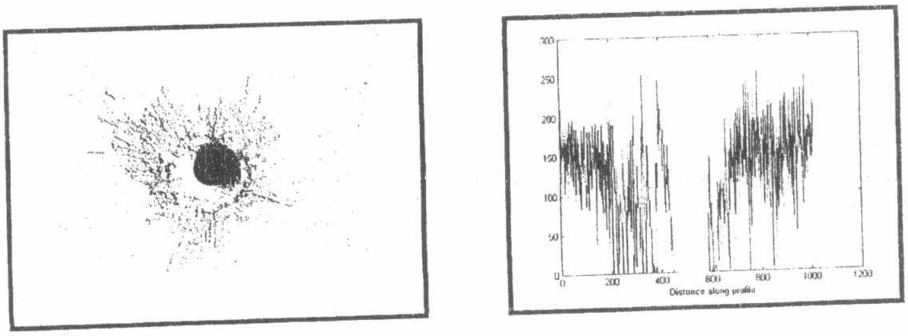


Fig. 1. Laser material processing head (4)



(a) (b)

Fig.2. (a) SEM gray-scale image of laser-drilled hole with spatter; (b) Gray-scale intensity distribution along the image profile

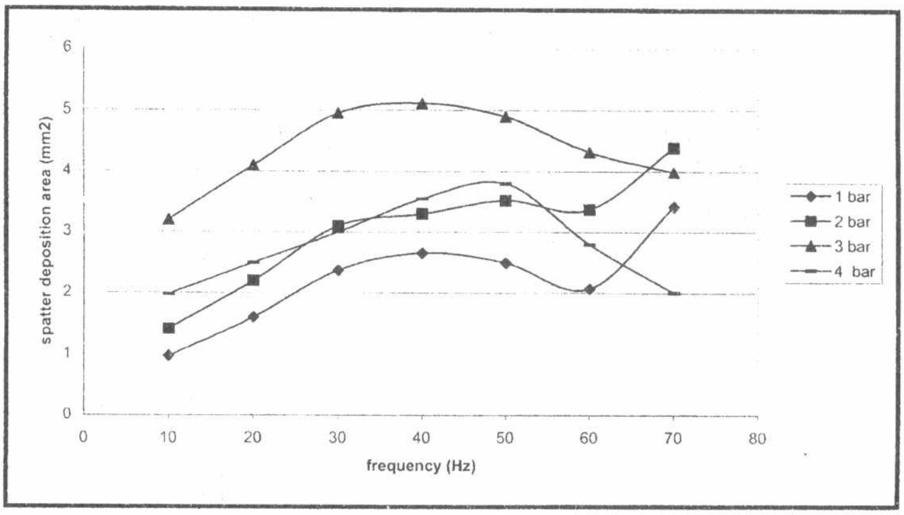


Fig.3. Spatter deposition area with different pulse frequencies at various assist gas pressure

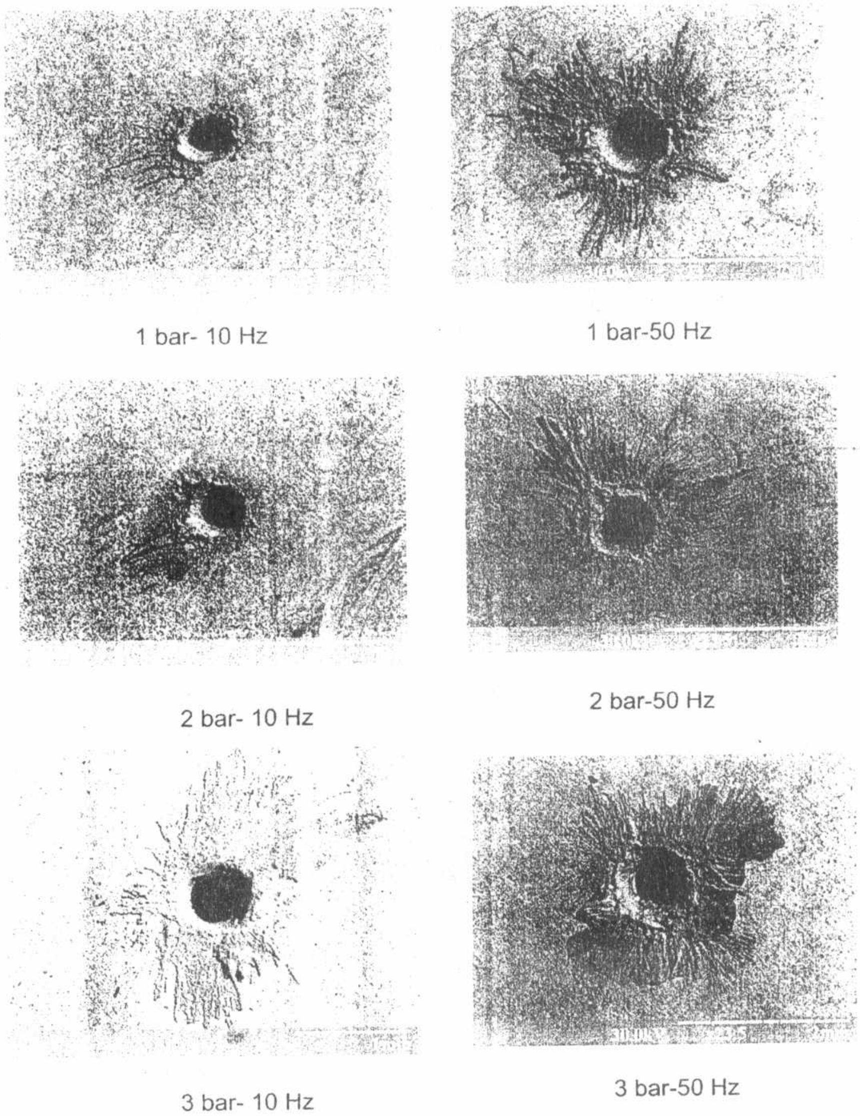


Fig. 4. Laser–drilled holes with their associated spatter at different setting parameters

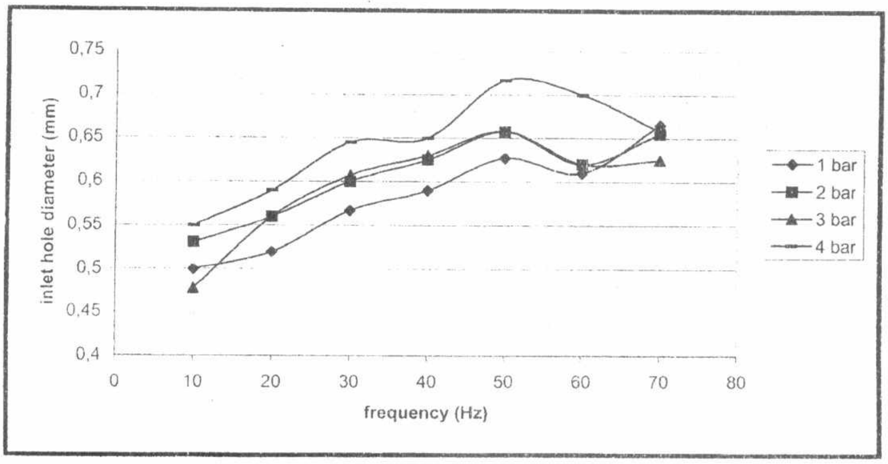


Fig.5. Inlet hole diameter with pulse frequency at different assist gas pressures

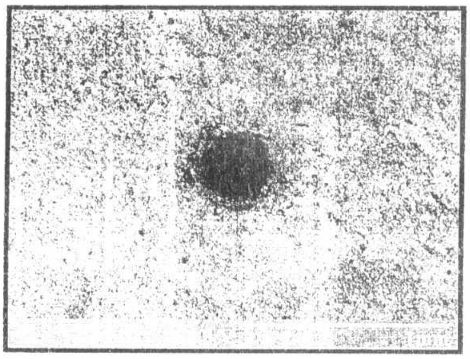


Fig.6. SEM image of exit diameter of laser-drilled hole

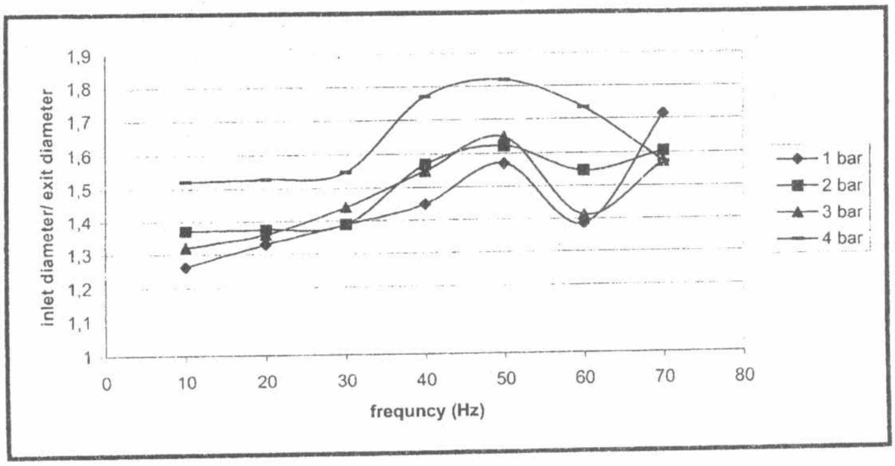


Fig.7. Effect of pulse frequency and assist gas pressure on the inlet to exit diameter ratio

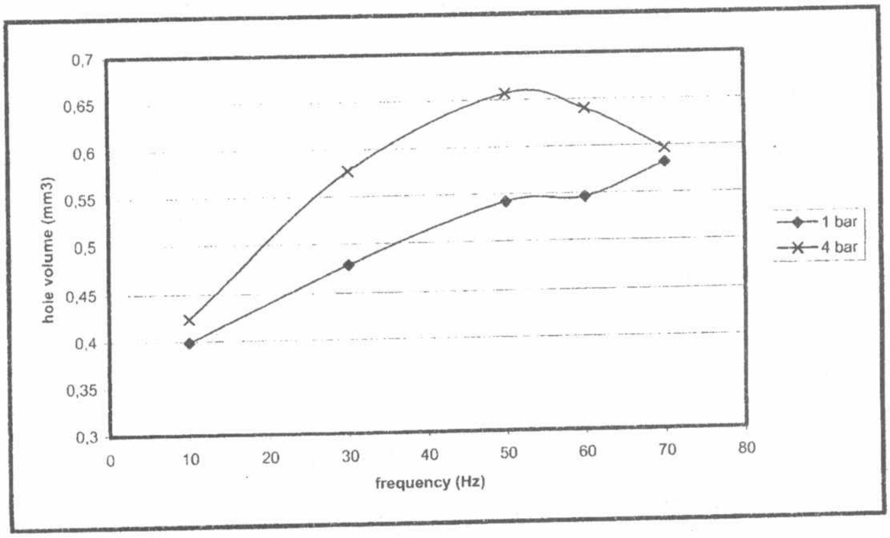


Fig.8. Volume of metal removed with pulse frequency at 1 and 4 bar assist gas pressures