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High Aspects Ratio Micro-drilling of Super-alloys Using Ultra Short Pulsed Laser

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Abstract

The demand for high aspect ratio micro holes is growing day by day. Functional micro-holes are necessary for application areas in aeronautic, automobile, semiconductor and biomedical industries for turbine blades, fuel filters, surgical needles and micro-fluidic devices. The applications require holes with high contour accuracy and minimum thermal damage. Further, the materials used in these applications are alloys, super alloys and composite materials, which are treated as difficult to cut due to their poor machinability. Although, a regime of processes exploiting chemical energy to beam energy are available, laser machining has demonstrated outstanding capability to generate high precision micro features. In recent past, the development of femto and picosecond lasers has provided a precise method for micro and nano-scale fabrication.

In this paper, micro-hole drilling was carried out using a 12W, Ti-sapphire 50-100 fs laser. Examples of micro-hole drilling are analyzed for hole size and shape. The effect of pulse duration was analyzed for three different materials: SS-316L, Inconel-718 and Ti6Al4V. The geometry and morphology were characterized by optical and scanning electron microscopy. Further, the experimental analysis investigates effect of laser drilling techniques like percussion, trepanning and helical drilling on hole quality characteristics. Therefore, with proper control on beam positioning, beam energy and pulse width one can achieve high quality holes using ultrafast lasers.

Keywords:ultra short pulse, aspect ratio, micro drilling, femto and pico-second laser.

1. INTRODUCTION

Functional micro holes and micro features are becoming necessary for biomedical, aerospace, semiconductor etc. applications. Further, these micro holes with high aspect ratio are required in aerospace applications for injection, cooling, diffusion, transpiration etc. Although, many processes have been developed in the recent past which will satisfy these need but laser micro drilling seems to be promising out of all.

Applications for laser micromachining in manufacturing have been growing in recent years aided by the new developments in the field of ultrashort pulsed lasers. In addition to economy factors such as processing time and cost of production, the quality of the features produced via laser micromachining has been important for process exploitation. Extensive studies have been conducted on the optimization of laser micromachining correlating feature quality improvement by beam monitoring, beam control and modeling [1].

A smart tradeoff between nanosecond (*ns*), picoseconds (*ps*) and femtosecond (*fs*) is always desired in case of processing micro features. The material removal mechanics by ultrashort laser pulses (*ps*, *fs*) is quietly different than by millisecond (*ms*) and nanosecond (*ns*) regime laser processes. As per characteristic durations of laser interaction with metals, nanosecond pulses are too long. The material is heated comparatively slowly, thereby causing quick energy diffusion into the surrounding area. The affected spot is heated enough for the material removal resulting into large heat affected zone (HAZ) [2].

In fact, higher fluences, i.e. under a strong ablation, induce alterations and irregularities, which compromise the quality of the hole comparable to those obtained by means of nanosecond lasers.Whereas in case of ultrashort pulses (*fs*), thermal contribution is extremely reduced due to pulse duration lesser than the time of electron-photon relaxation (0.5-50 *ps*). Fluence below 10 J/cm^2 and gentle ablation produces high-precision micro machining. [3].

Furthermore, issues like large taper, error in roundness, getting through hole and formation of recast layer need to be addressed while micro-drilling of difficult to cut materials like aerospace alloys. Due to laser beam and material interaction during processing, tapering and error in roundness is bound to occur. However, in this paper attempts are made to minimize it to certain level. Micro holes are drilled in 1mm thick SS316L, Inconel 718 and Ti6Al4V sheets using Clark MXR Ti:Sapphire fired ultrashort pulsed laser (50-100 *fs*). A comparative investigation between percussion, trepanning and helical drilling has also been reported here.

2. LITERATURE REVIEW

Laser drilling has become the accepted economical process for drilling thousands of closely space holes in several applications. Therein, parameters that play vital role are quality of the laser beam, wavelength, intensity, pulse duration, pulse repetition rate. In order to optimize the process,lot of researchers has worked in this area in recent past.

In order to improve the performance of laser micro-drilling, Lazare and Tokarev [4] developed a laser beam model to predict the hole diameter and depth using KrF excimer laser on PET (Mylar D). The term "laser brilliance" was coined which was responsible for deep micro drilling provided that beam has low divergence. It relates the geometry of the micro-hole to the experimental parameters including the laser source parameters like pulse energy and divergence. Taper formation, production of non-circular holes and spread of HAZ are characteristic of the laser micro drilling operation, as laser machining is based on the interaction of a laser beam with inherent focusing characteristics [5]. Modeling of the process is required in order to control these important characteristics. Developing a physical model for laser percussion drilling is very complicated since a large number of parameters involved in the process.

Biswas et. al. [6] have tried to address the problem of hole tapering. They considered circularity of the hole at exit and the hole taper while micro drilling of gamma-titanium aluminide

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using pulsed Nd:YAG laser. Tan B [7] suggested multi burst pulse train to resolve this problem. Holes with 20 μm diameter with nearly straight sidewalls in a 250 μm thick silicon substrate have been demonstrated by him. This was achieved by using DPSS Nd YAG UV laser with 25 μm spot diameter.

It was observed that femtosecond machining has a physically different material removal process. It predominantly involves a transition from solid to vapor or smaller atomic clusters with minimum droplets from the molten phase. Femtosecond machining is reported to be more advantageous for hard materials and deeper holes than for thin and relatively low melting point metals. In the similar domain, Huan Huang et. al. [8] performed drilling of transparent and nontransparent materials like glasses (soda lime glass), metals (stainless steel) and tissues (bovine bone and tendon). A 750 *fs* pulse duration fibre laser with 1030 nm wavelength was used for investigation.

For smallest features and the least amount of heating and collateral damage, pulse lengths of femtosecond are almost as efficient as their picosecond alternative and lead to the same morphologies inside the hole [9].

In micro-hole drilling and cutting using *fs* fiber laser (1030*nm* wavelength and 750-*fs* pulse duration), Huang et. al. did not observe any cracks or collateral thermal damage for both hard and soft tissues [10].

Picosecond lasers offer high power for industrial scale fabrication and their pulse length adapt for metal fabrication because the characteristic durations of lattice heating are in the region of several to several tens of picoseconds [11].

Femtosecond lasers do not yet rival picosecond systems in delivered power, but with their parameters and industrial robustness improving steadily, they seem destined to reach maturity in industry in the very near future. In fact, the technical advances in femtosecond laser technology are making laser machining of thin metallic coatings or foil a feasible solution for high-quality, deep drilling. Femtosecond laser pulses provide a micromachining tool with high-quality material processing and large area patterning of solids [2,12].

As given in literature, many authors have tried to use ultrashort pulsed lasers for micro machining. However, a detailed experimental analysis for difficult-to-cut materials still needs to be addressed. Therefore, this paper attempts to give thorough experimental analysis for use of ultra short pulses for micro drilling by using various drilling techniques like percussion, trepanning and helical. This paper can give a guideline for the researchers in this field for selection of laser source, process parameters and drilling techniques in order to achieve desired results.

3. EXPERIMENTAL PLAN & PROCEDURE

Micro holes were drilled using Clark-MXR (12Watt) Ti-Sapphire femtosecond pulsed laser with wavelength of 800nm, repetition rate 10000Hz and pulse width ranging between 50ps-100fs. Gaussian beam profile was used during experimentation.

This work not only analyses micro drilling by percussion but also by trepanning and helical drilling techniques. Experiments were carried out on 1mm thick test specimen of SS316L, Inconel 718 and Ti6Al4V sheets to study hole quality like hole diameter, ovality and taper.

Some initial feasibility experiments revealed that number of passes for percussion, trepanning and helical drilling strategies have significant impact on hole characteristics. Hence following processes parameters (Table 1) were observed.

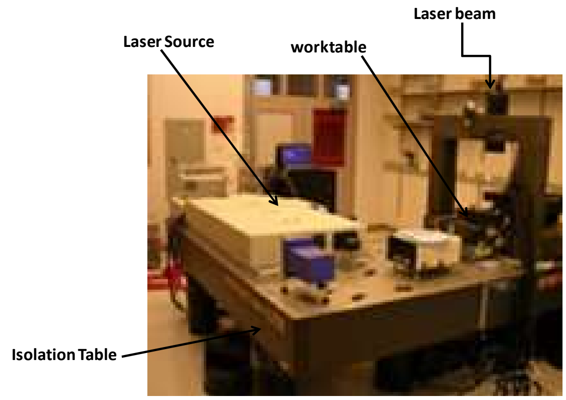

Fig. 1. Ultrafast Laser Setup

Table 1. Process parameters

Drilling Method	No. of pulses/No. of passes
Percussion	200000
	500000
	1000000
Trepanning	500
	750
	1000
Helical	100
	200
	300

4 RESULTS & DISCUSSION

Optical image analysis and measurement of hole diameter of all the three materials was carried on Conation Tech microscope. It is evident from fig 2 that there are negligible traces of heat affected zone and recast layer near the hole area.

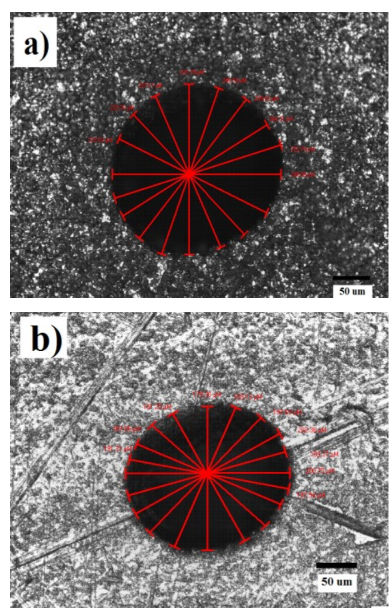

Fig.2. Optical images of (a) Inconel 718 and (b) and Ti6Al4V drilled by femtosecond laser

4.1 Analysis of Hole Diameter

Fig 3. a depicts effect of number of pulses on the hole diameter. As number of pulses increase from 2 lakh to 10 lakh, average hole diameter decreases from 209 μm to 202 μm.

However, the error bar shows that effect of pulses is not statistically significant and shows an average difference of only 6 μm.

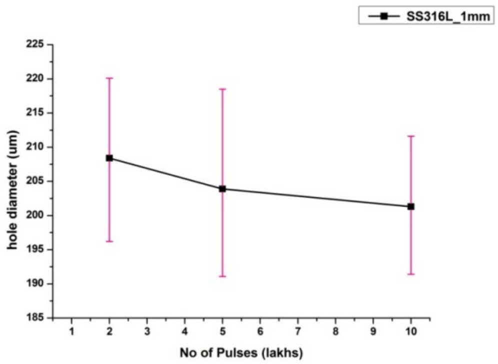

Fig.3 a. Effect of No. of Pulses on hole diameter

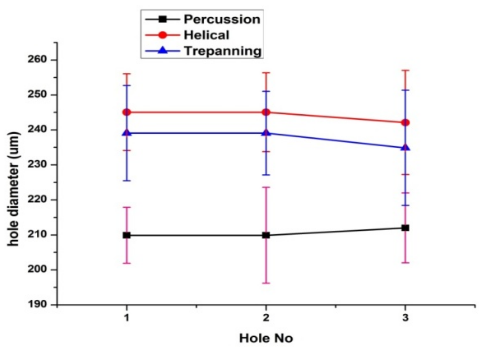

Fig. 3. b. Effect of drilling techniques on hole diameter

While studying the effect of different drilling techniques on the hole diameter, it was observed that minimum hole diameter is achieved in percussion followed by trepanning and helical (see fig. 3b).

This may be due to the fact that for helical drilling, initial pilot hole is drilled by percussion and followed by enlargement by helical drilling accurately to the required size. However, this results in slightly oversize hole which also is likely to depend on the spot diameter of the laser. Moreover, in case of trepanning, the laser beam moves in spiral direction radially outward from the hole centrewhich again leads to larger diameter. Whereas in case of percussion, laser beam is focused at a spot and repetitive pulses are triggeredresulting in with hole of minimum diameter. Hence, to achieve minimum hole diameter, percussion drilling is recommended compared to helical and trepanning.

4.2 Analysis of Ovality

Since hole ovality is greatly affected by incident energy and contact time, effect of number of pulses on ovality in percussion drilling of SS316 material has been shown in fig. 4.a.

As number of pulses are increased from 2 Lakh to 10 Lakh, ovality decreases. This happens because repetitive pulses focusing on small area of drilling are useful in finishing of hole edges and achieve better ovality. Therefore, to minimize ovality higher number of pulses in the range of 8 Lakh to 10 Lakh are recommended.

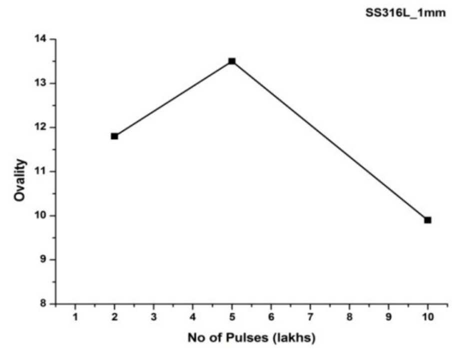

Fig. 4. a. Effect of No. of Pulses on hole ovality

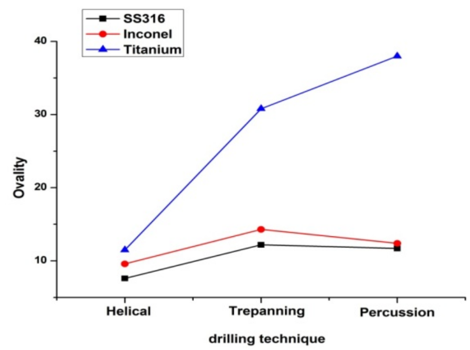

Fig. 4. b. Effect of drilling techniques on hole ovality

It has also been observed that, ovality is least in SS316L followed by Inconel 718. However, ovality of TI6Al4V is larger due to low absorptivity of titanium and lower focusing efficiency.

At the same time, effect of drilling techniques shows that helical drilling gives better ovality (refer fig.4. b.) than percussion which is justified by its way of machining. Helical drilling cuts a pilot hole and subsequent laser pulses finish the hole to the required size.

4.3 Analysis of Hole Taper

Fig.7 shows the scanning electron microscope (SEM) micrographs of the percussion drilled hole. It represents sectional view of SS316L (Fig 7 a & c) and Inconel 718 (Fig b) along the axis of the drilled hole, showing entry and exit diameter. Holes drilled by this technique resemble to conical shape for both the materials.

Since, barreling effect is unavoidable in laser beam machining therefore, one must find other ways to reduce it further. One of the way might be sandwiching the workpiece between some coatings and them removing coating after drilling. By this method taper can be reduced from 10° to 4°.

Fig.7 shows effect of material on the hole taper. It is observed that hole taper is minimum in Ti6Al4V compared to SS316L.This may be due to lower thermal conductivity of

Ti6Al4V which causes concentration of energy on specific localized region that minimizes the spread of entry diameter and minimum difference between entry and exit diameter.

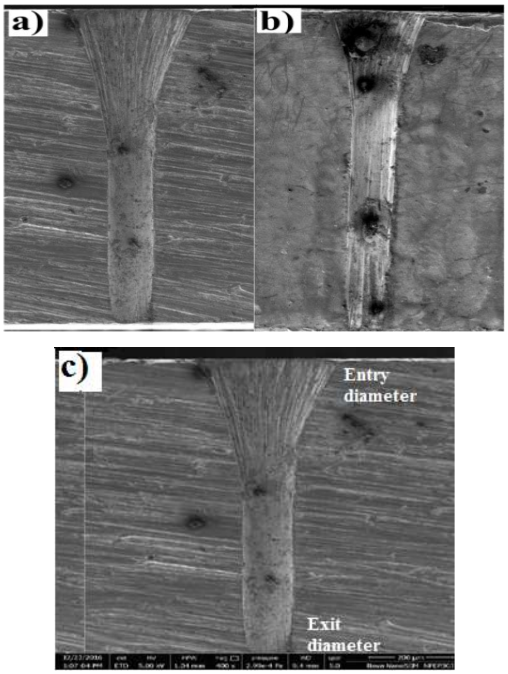

Fig.5. a.SEM Micrograph showing transverse section showing holetaper

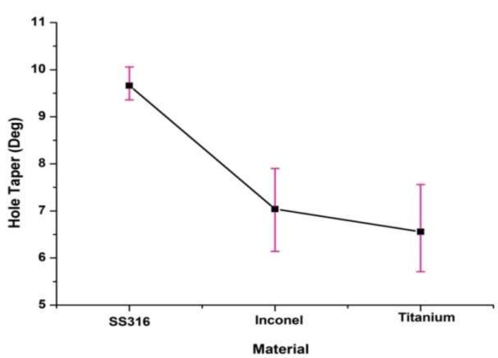

Fig.5. b.Hole taper in various materials

Therefore, in case of Ti6Al4V, average taper of 6° can be obtained which is 10° in case of SS316. Fig. 7, SEM images of SS316 (fig.5a) and Inconel 718. From fig. 5.b. it is observed that in order to minimize taper of SS316, entry and exit diameter variation must be minimized.

5 CONCLUSIONS

The three drilling techniques - percussion, trepanning and helical have been successfully tried independently on three aerospace alloys SS316L, Inconel 718 and Ti6Al4V. Recast free holes with negligible heat affected zone have been observed.

After investigating all the three techniques, percussion drilling was found to be most suitable technique to achieve smaller hole diameters followed by trepanning and helical drilling ($200\mu m$ - $215\mu m$). A better control over ovality (~$10\mu m$) is possible by increasing the number of pulses for SS316L, Inconel 718 and Ti6Al4V respectively. For all cases, helical drilling yielded perfect round holes (ovality ~$10\mu m$)as compared trepanning and percussion (Ovality ~30-38μm).

Transverse sections of holes revealed that due to poor thermal conductivity of Ti6Al4V compared to SS316L, laser energy readily reached till the deep bottom of the hole removing material consistently to shape a relatively less taper hole (4^o-6^o).

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