A review on laser drilling and its Techniques

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Abstract
Drilling is one of the most important and successful applications of industrial lasers. Laser drilling emerges as a viable and successful substitute for holes less than 0.25mm in diameter that are otherwise difficult to drill mechanically, especially for hard and brittle materials, such as ceramics and gemstones. Laser drilling of metals is used to produce tiny orifices for nozzles, cooling channels in air turbine blades, etc. For direct hole drilling, the quality of the laser beam, wavelength, intensity, pulse duration, pulse repetition rate are all important parameters. Yet many issues remain to be solved when high quality holes are to be drilled in various material. These include cracks, large taper size, unsatisfactory shape etc. In the present paper, the technologies, applications and techniques that lead to the solution of aforesaid problems are highlighted

Keywords
Drilling, Lasers, wavelength, cracks, applications, techniques

Introduction
Machining refers to the removal of material from a work piece in the form of chips. It is also called "metal cutting" when referring to metal. There are three main categories of machining:

Abrasive
These include grinding, polishing which cause material removal by the action of rubbing propelled by the release of abrasive particles.

Cutting
These processes include milling, turning, drilling which remove metal by the action of a rotating tool against a stationary work piece or vice-versa.

Nontraditional
These use nontraditional techniques like electricity, chemicals, lasers, or water to cut away material

Laser is the acronym of Light Amplification by Stimulated Emission of Radiation. Laser is light of special properties, being very different from normal light in that it is coherent having low beam divergence and high energy content, and thus creates heat upon striking a surface. This heat is utilized in machining of various kinds of material. Laser machining means material removal accomplished by laser material interaction. What it does is use ultra-fast laser pulses of very short duration to remove material in layers from the surface of the work piece. Machining depths per layer vary from one application to another. [1,2]

Generally speaking, Laser Machining processes include laser drilling, laser cutting and laser grooving, marking or scribing. Laser machining is not programmed like traditional cutting/milling equipment requiring speeds and feeds, but instead is driven directly from digital CAD data

Laser drilling is one of the oldest applications of laser machining processes. A well-known example of laser drilling is the drilling of airfoil cooling holes in components of aircraft engines. Another application is drilling holes for fuel filters for automobile manufacturing. Laser hole drilling in ceramic, silicon and polymer substrates is widely used in electronics industry. [3]

Usually Nd: YAG lasers with pulse length of several tenths of milliseconds are used to drill such holes when a certain degree of inaccuracy of diameter and shape as well as thin recast layer can be tolerated. In cases where higher accuracy is required, laser drilling with millisecond pulses does not meet the requirement. The means to increase precision then include reduction of pulse length and improval of machining techniques.

Advantages of Laser Machining
Laser machining processes transport photon energy into target material in the form of thermal energy or photochemical energy, they remove material by melting and blow away, or by direct vaporization/ablation. On the other hand, traditional machining processes rely on mechanical stresses induced by tools to break the bonds of materials. This basic difference in material removal mechanism decides the advantages and disadvantages of LMP compared with traditional machining processes.

Contact
Laser machining is localized, non-contact machining and is almost reacting-force free, while traditional machining usually has direct mechanical contact and need devices to balance the machining force, i.e. work piece needs clamping. The forces in laser machining are of micro scale. The photon pressure on target material is negligible for bulk material.
Delicate Machining
LMP can remove material in very small amount, while traditional machining remove material in macro scale. LMP are said to remove material "Atom by Atom". The depth of laser drilling can be controlled to less than one micron per laser pulse and shallow permanent marks can be made with great flexibility. In this way material can be saved, which may be important for precious materials or for delicate structures in micro-fabrications

Heat Affected Zone (HAZ)
Heat Affected Zone (HAZ) in laser machining is very narrow, usually there is a very thin re-solidified layer of micron dimensions, this promises negligible distortion in machining. In traditional machining, large areas of work hardening are almost unavoidable.

Surface Finish
LMP can achieve final quality level machining results in one process, while in traditional machining several processes are commonly used. Laser cutting edges can be made smooth and clean, no further treatment be required. High aspect ratio holes can be drilled using lasers. Dross adhesion and edge burr can be avoided, geometry precision can be accurately controlled

Material Choice
LMP can be applied to any material that can properly absorb the laser irradiation, while traditional machining processes have to choose suitable tools for materials with different hardness or abrasiveness. It is difficult to machine hard material or brittle material such as ceramics, laser is a good choice for solving such difficulties.

Laser Drilling- An overview
Holes less than 0.25mm in diameter are difficult to drill mechanically, laser drilling offers an excellent alternative for small hole drilling, especially for hard and brittle materials, such as ceramics and gemstones. Large holes can be drilled by trepanning, i.e., by overlapping and drilling the circumference of a circle to form a large hole. High throughput of hole drilling are realized by mask projection and automation.

Table 1 compares laser drilling with electrical discharge machining (EDM) and traditional mechanical drilling. EDM is limited to electrically conductive materials, on the other hand drill wear and breakage is a big concern as regards mechanical drilling. Laser drilling is highly effective for small hole drilling and can be flexibly automated.

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<tr>
<th>Advantages</th>
<th>EDM</th>
<th>Mechanical drilling</th>
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<td></td>
<td>No taper, large</td>
<td>Large diameter,</td>
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For direct hole drilling, the quality of the laser beam, wavelength, intensity, pulse duration, pulse repetition rate are all important parameter. For the process to be precise and more predictable, modeling and simulation is necessary.

Laser drilling has rapidly become an inexpensive alternative to outdated mechanical hole drilling methods. Micro hole laser drilling offers alternatives to CNC, punching, wire EDM, broaching or other popular destructive hole drilling methods. Laser drilling offers a panacea of manufacturing solutions.

Laser hole drilling in materials such as ceramics, copper, nickel, brass, aluminum, borosilicate glass, quartz, rubber and composite materials offer high-accuracy, repeatability and reproducibility for the medical device industry, semiconductor manufacturing and nano-technology support systems.

Laser drilling provides consistency for manufacturing specifications relying on tight tolerances for high depth-to-diameter ratios. Laser drilled hole sizes vary depending on laser power, motion control and galvo systems. Rapid prototyping is particularly adaptable to wide range of hole sizes. Laser drilling can provide dynamic, “on-the-fly” “changing of hole diameter, hole depth and edge quality.

Laser drilled holes usually have tapers, i.e. the hole is not perfectly straight. Also a redeposition area may exist around the hole, because laser drilling is realized through violent phase change. Thus the material becomes melted, ablated, cools down and becomes solid state again. Redeposition is serious for long pulses (i.e. for pulse duration > 10 nanosecond). Tapering and redeposition can be lowered by suitably choose shorter wavelengths and pulse durations. For direct hole drilling, the quality of the laser beam, wavelength, intensity, pulse duration, pulse repetition rate are all important parameter

Techniques in Laser Drilling

Figure 1 illustrates various drilling techniques[4], Single pulse drilling, Percussion drilling, Trepanning and Helical Drilling.
Single Pulse Drilling
Single-pulse (shot) drilling tackles high-speed production of blind or through holes and delivers aspect ratios typically below 15:1. High-production throughput, however, is a trade-off with tolerances generally above 10% compared to trepanning. For many applications, this is acceptable where cycle time is more important than quality.

An example of single-pulse drilling is found in the automotive industry, where it creates a scribed guideline for breaking off (cracking) a connecting rod for diesel engines. Scribing, in effect, drills blind holes close enough to create a notch. Another single-pulse drilling application in the automotive industry is in manufacturing filters.

Percussion Drilling
Percussion drilling delivers successive laser pulses to the same spot and is the best trade-off between throughput and hole quality. The process has become standard for creating cooling holes in turbine-airfoil blades. Laser percussion drilling is favored over the older drilling techniques and the other laser drilling techniques because it is by far the quickest. However, it still suffers from some drawbacks.

Recast layer: The first drawback is a recast layer, that is, resolidified material remaining at the wall of the hole. Some resolidified material can normally also be found at the entrance and exit of the hole, in which cases it is called spatter and dross, respectively.

Tapering: Tapering refers to the decrease of hole diameter with depth. Nowadays, one does not necessarily see this tapering as a disadvantage any more, however, control of the taper angle and reproducibility is needed.

Bellow shape: Finally, occasionally the hole resulting from a laser percussion drilling process shows barreling or a the local increase of hole diameter.

These terms are illustrated in Figure 2.

Fig 2: Defects of Percussion Drilling

Trepanning
Trepanned laser drilling is a method used to remove a cylindrical core, or circular disc from a substrate. Trepanning is the standard technique for large holes, e.g. 500 micron holes in turbine blades. It is essentially a percussion drilling process followed by a cutting procedure. The application of nanosecond pulses to trepanning can increase the quality of the hole. But the drawbacks of percussion drilling remain. The advantages of trepanning include large holes, consistency and ability to drill shaped holes. Trepanning also reduces the holes taper.

Unlike percussion laser drilling, the position of the beam or substrate is moved in conjunction with a predetermined laser beam “overlap” to achieve the desired edge quality and production throughput. Less overlap trepanning laser drilling increases throughput but produces a more jagged edge quality. On the other hand, more overlap creates finer hole resolution and edge quality. Laser drilling utilizing the trepanning method can also produce proportionately larger exit holes by “tilting” the laser beam within an already drilled entrance hole. This method of trepanning laser drilling is achieved through the special use of optics.

Helical Drilling
A new technique, called Helical Drilling, makes use of the breaking up of the process into a multitude of ablation steps in order to enhance the accuracy. In contrast to trepanning, the helical drilling reaches the breakthrough only after many turns of spiral describing the path of the ablation front. Helical drilling has the following favorable effects on drilling accuracy: more deviation from circular geometry can be reduced than trepanning; the load on the opposite walls is minimized; and most importantly, recast layers as observed in percussion drilling using nanosecond-lasers can be greatly reduced or completely avoided.

The beam path is not limited to circular geometry. With suitable optical systems like scanners or by movement of the work piece, any shape can be formed. This means helical drilling can be applied to laser micro machining when high accuracy and high machining quality is required. Helical
drilling is a technique that is efficient when the helical diameter is close to the focal diameter of the laser beam. Trepanning and helical drilling is much more costly expensive and time consuming than percussion drilling. Although Laser percussion drilling and laser trepanning can produce through-holes, the choice comes from the hole size we need. Laser percussion drilling makes holes of diameter normally less than 50 mm. The laser trepanning holes are larger. Laser trepanning is a method by which the laser beam cuts in a circular pattern, taking advantage of high-speed beam positional scanner. There is a limit to the depth of material that can be cut in a single pass, so a number of passes has to be made. Researchers and manufacturers are seeking new ways to optimize the process, with particular focus on achieving better quality holes while keeping the drilling speed high at economical costs.

Quality Control in Laser Drilling by Beam Modulation

An increasing demand for quality assurance in laser drilling requires checking of the laser beam-the central tool in laser drilling processes. ISO 11146 includes a standard for laser beam characterization, which states the basic parameters to describe a laser beam as

Laser power and pulse energy
Power meters can measure laser power and pulse energy. The measurement is done reliably by thermopile or by calorimetric devices. There are also a lot of methods and devices to measure the beam position, dimension and beam propagation factors, but most of the devices do not allow measurement in full power. Measuring devices for high power lasers in industrial environment have been studied in [1]

Profile of the unfocused laser beam
This is of vital essence to the final shape and finish of the hole. A continuous visible beam from a laser using a gas, such as the helium–neon combination, provides a nearly ideal straight line for all kinds of drilling operations. The beam from such a laser typically diverges by less than one part in a thousand, approaching the theoretical limit

Profile of the focused laser beam
The benefits of lasers in drilling (and various other applications) stem from properties such as coherency, high monochromaticity, and capability for reaching extremely high powers. For instance, a highly coherent laser beam can be focused down to its diffraction limit, which at visible wavelengths corresponds to only a few hundred nanometers. For example, a frequency doubled neodymium yttrium aluminum garnet (Nd:YAG) laser emitting 532 nanometer (green) light at 10 watts output power is theoretically capable of achieving a focused intensity of megawatts per square centimeter. In reality however, perfect focusing of a beam to its diffraction limit is somewhat difficult to achieve.

Polarization and beam quality parameter M²
In many, although not all cases, the output of a laser is polarized. This normally means a linear polarization state, where the electric field oscillates in a certain (stable) direction perpendicular to the propagation direction of the laser beam. However, some lasers (e.g. many fiber lasers) do not generate a polarized output. Optical devices are used for conversion of the same. The M2 factor, also called beam quality factor or beam propagation factor, is a common measure for the beam quality of a laser beam. According to ISO 11146, it is defined as the beam parameter product divided by \( \lambda \pi \), the latter being the beam parameter product for a diffraction-limited Gaussian beam with the same wavelength. The M2 factor of a laser beam limits the degree to which the beam can be focused for a given beam divergence angle, which is often limited by the numerical aperture of the focusing lens.

Errors in laser drilling may be caused by any of the following reasons. The gas pressure may be set up incorrectly, the laser power or thickness of the material being cut may vary, defocusing, or limitations in robot maneuverability. An ideal sensing system should be able to monitor and discriminate between all of these possible errors, however the currently available sensors can only monitor or control individual parameters. This necessitates the use of certain techniques related to beam modulation that ultimately lead to conformity as regards quality. The techniques include

Focus Control
The Laser Beam must focus completely on the hole to be drilled. For this purpose, many methods for laser focus control have been developed. An ideal focus control system should have high spatial resolution and should operate in real time.

Capacitance measurement: Focus control can be realized by monitoring the capacitance between the work piece and the nozzle [7]. This is an established technique and in practice as well but has its limitations. The shape of the work piece as well as damage to the nozzle can change the capacitance, thus giving incorrect focal measurement. Furthermore, the system does not work with a non-conductive work piece.

Physical contact and Optical triangulation: Two other methods are beam control through physical contact and optical triangulation. Physical contact methods may use some sort of roller or lever attached to the nozzle, which detects the surface. For the triangulation methods, a 'stripe' of light from a laser diode is scattered from the surface of the work piece and monitored with a detector array. Knowing the distance between the emitter and receiver, the angle of incidence of the light one is able to calculate the distance to the work piece. These methods work well for flat plates but give incorrect messages for non-flat surfaces.

On-axis monitoring technique: A schematic of the optical sensor system is shown on next page. The high-powered laser light is delivered through an optical fiber and imaged onto the work piece. Multi-band light is generated by the heating up of the work piece, part of which is collected and imaged onto the output end of the delivery fiber where it counter-propagates back along the fiber and into the laser head. This light can then
be coupled into a second fiber from behind one of the turning mirrors in the laser head, filtered as required and then imaged onto a detector. The chromatic aberrations are used in order to detect focal errors. If the lenses are achromatic, all light would be imaged on the fiber. But since the lenses are not achromatic, the focal position varies according to the wavelength. The magnitude difference of the infrared radiation and the visible radiation serves as error signal for focus control. When the work piece is at the focus of the laser system, the sensor system is adjusted to have equal magnitude for the infrared radiation and visible radiation. When the work piece deviates from the focal location, the error signal is non-zero, and has different sign if the deviations are different in direction. This system of focus is non-intrusive, it is also on-axis, so it is convenient in industrial life. The error signal reflects the real time focus change at the machining position corresponding linear increase in laser power. On the other hand, normal percussion drilling use the same pulse parameters repeatedly throughout the drilling train of pulses. The reduced taper in SPDPC can be explained in the following manner. Consider the fact that the material removal in laser drilling with intensities somewhere about $10^7$-$10^8$W/cm$^2$ has strong liquid melt ejection. This generates a recoil force in the opposite direction such that the liquid melt is pushed out of the interaction zone. This further induces melting of additional solid material on the hole-wall during laser drilling. The interaction time between the melt and the hole wall is the greatest at the entrance of the hole and reduces with depth. Due to this variation in whole wall erosion throughout the hole-path, a hole taper is formed with the entrance end being enlarged. Also, the laser pulse intensity would subsequently be reduced with hole propagation. This is due to the increasing beam diameter with beam divergence along the laser axis and the absorption of any part of the incident beam at the upper section of the hole. [6]

Thus SPDPC, which focuses on linear increase of laser power with time and depth reached, eliminates the second effect de facto as it maintains the laser energy and insures that beam divergence is minimized. The recoil force too is overcome by the instantaneous increases in Laser energy which tend to balance out each other. The modulation of laser intensity can be realized by software and the laser controlling unit and no extra hardware is needed.

**Future of Laser Drilling**

The nature of the laser beam used in laser drilling allows holes to be drilled in the hardest of materials, from aerospace alloys, diamonds, ceramics and even synthetic materials. Through the use of laser drilling, holes can be created in coated materials. And the control of the hole created with laser drilling is exceptionally precise. The main applications are in aerospace where cooling holes needs to be formed. The programmable nature of lasers allows for very high speed drilling applications where many thousands of holes are required in short cycle times. Laser hole drilling outperforms wire EDM, chemical etching, mechanical machining/cutting, electroforming, and other processes because the process is non-contact and flexible.

In addition, there are fewer process limitations, no need for expensive waste disposal, and tooling costs are reasonable. High quality cuts with exceptional positional and feature size tolerances are achieved. LLTI developed laser-based hole drilling technology to satisfy the growing need for smaller products.

The use of laser drilling is becoming more and more popular. in providing benefits previously unknown. It allows for greater flexibility in what and where one can drill. Laser drilling is also proving fast to be an affordable alternative.
Conclusion

Not since cable tools gave way to rotary drilling almost a hundred years ago has there been a revolutionary change in drilling methods -- but one may be coming. According to a previous study, 50 percent of drilling time is spent on making hole, 25 percent on tripping and 25 percent on casing and cementing [5]. Thus, major reductions in drilling costs can be achieved by faster drilling techniques and reduction in the requirements for drill bit replacement and setting, casing etc. Laser technology applied to drilling operations has the potential to reduce drilling time, eliminate the necessity to remove and dispose of drill cuttings and improve through bettered perforation operations.

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