

Laser Drilling for Medical Device Manufacturing

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Abstract

Despite its proven capability in drilling small holes for various industrial applications, laser drilling is not being widely used in medical device manufacturing. New laser sources as well as improvements in the control of more traditional sources are leading to improved quality of laser drilled holes.

This paper presents a current view of capabilities and trade-offs associated with laser drilling of small holes in metals and non-metals using pulsed solid state lasers.

Introduction

Laser drilling is applied to a wide range of components in many different materials (metals and non-metals), thicknesses, and shapes. Current industrial applications include drilling cooling holes in aircraft engine components, production of filters, and drilling precision apertures for optical components.

The success of lasers in stent cutting is well documented [1]. Laser drilling leverages the same characteristics that have contributed to this success, providing capability to produce fine ($\leq 100 \mu\text{m}$), precise features (round or other shapes of openings) in difficult to machine materials and at shallow, compound angles to the surface. Recent R&D efforts have been aimed at characterizing the laser drilling process based on current and emerging laser sources and, in doing so, providing means for better controlling the process and the quality of holes produced by it.

Laser Drilling Process

As illustrated in Fig. 1, laser drilling is performed by several different types of lasers having a wide range of wavelengths and pulse durations. The trend in solid state laser source development has been toward shorter pulse lengths because of their ability to produce small holes with low heat input.

Laser drilling capability is rooted in the ability to focus a high power laser to a diameter as small as a few micrometers thereby creating intensities of from 10^6 to more than 10^{12} Watts/cm². As shown in Equation 1, the size of the focused beam is a function of the laser wavelength, diameter of the

collimated beam from the laser, focal length of the focusing optics, and beam quality.

$$d = \frac{4\lambda F}{\pi D} M^2 \dots\dots\dots [1]$$

where:

- d = Focused beam diameter
- λ = Laser wavelength
- F = Focal length of the focusing lens
- D = Beam diameter entering the final focusing lens
- M^2 = Beam quality relative to a Gaussian distribution

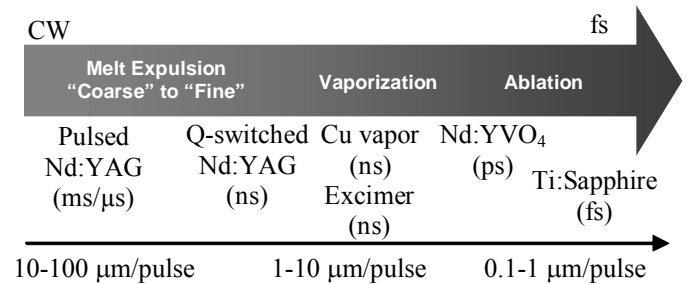


Figure 1: Laser drilling covers a broad range of applications and laser types, from ultraviolet to infrared wavelengths and from millisecond to femtosecond pulse durations.

Absorption of the focused laser beam can produce heating, melting, or vaporization of a material. The specific nature of this interaction depends in part upon the intensity of the absorbed energy. For pulsed lasers, intensity is defined by the following relationship:

$$I = \left(\frac{E}{\tau}\right) / \left(\pi\left(\frac{d}{2}\right)^2\right) \dots\dots\dots [2]$$

where:

- I = Peak power density, or beam intensity, typically expressed in units of Watts per cm².
- E = Pulse energy, Joules
- τ = Pulse duration, seconds
- d = Diameter of focused laser beam at the workpiece, cm.

Material properties with the greatest influence on the interaction are: (1) absorptivity of the material surface at the laser wavelength, (2) melting and vaporization temperatures, and (3) thermal diffusivity.

For metals and ceramics, drilling using lasers with pulse durations in the millisecond through nanosecond range occurs through a ‘melt expulsion’ mechanism. Absorption of the focused laser beam creates a molten pool within the hole (Fig. 2). Once the pressure gradients acting on the surface due to vaporization are sufficiently large to overcome surface tension forces, the molten material is expelled from the hole.

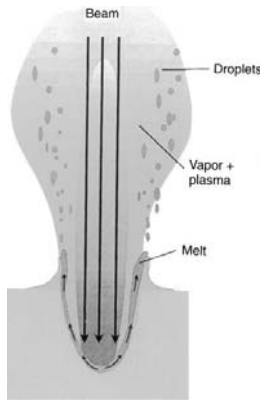


Figure 2: Melt expulsion occurs through pressure gradients acting on a molten layer created by absorption of a focused laser beam. Source: Körner, C., et al [2]

Körner, et al. [2] have shown that the proportion of material removed by melt expulsion increases and the droplet size decreases as intensity increases. However, more recently, Voisey, et al. [3] have shown that the fraction of the material removed by melt expulsion drops when laser energy further increases, suggesting that vaporization becomes more dominant and, therefore, the thickness of the melt layer decreases.

For pulse durations down to 10 picoseconds, reducing pulse duration contributes to lowering the depth of penetration of heat produced by the interaction according to the relationship in Equation 3.

$$D = (4k\tau)^{1/2} \dots \text{for } \tau > 10 \text{ ps} \dots [3]$$

where:

- D = Thermal penetration depth
- k = Thermal diffusivity of the material
- τ = Pulse duration

At pulse durations less than 10 picoseconds, a classical heat conduction model can no longer be used. At these pulse durations, the laser energy is absorbed into the electron structure but not transferred to the lattice. As a result, melt depth is minimized. Nevertheless, a small (few tens of μm) heat affected zone is produced by expansion of the plasma that is formed by vaporization [4, 5].

One important implication of this transition from coarse melt expulsion to fine melt expulsion to vaporization for laser drilling is that the size of particles generated in laser drilling

decreases with pulse duration, which in turn influences the requirement for post-processing.

Drilling Methods

Drilling using pulsed solid state lasers occurs by one of several methods broadly illustrated in Fig. 3. Percussion drilling (Fig. 3a) involves delivering one or more pulses from a laser while it is stationary relative to the workpiece. A variant of this, referred to as drilling on the fly, involves drilling while the laser beam is moving relative to the workpiece.

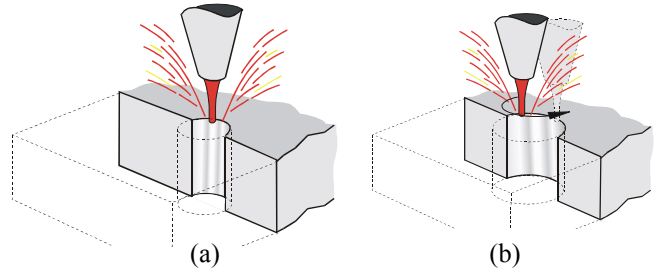


Figure 3: Laser drilling occurs by (a) single or multiple pulse percussion drilling and (b) trepanning (cutting the hole).

Trepanning (Fig. 3b) involves percussion drilling to create a starting hole for the subsequent cutting of the hole. A variation of trepanning, sometimes referred to as helical drilling, involves making multiple revolutions around the hole, with the laser removing a small depth of the material within the hole on each revolution.

One of the major challenges with laser drilling in components having a nearby adjacent surface, such as tubing, is to minimize damage (heating, melting) to the adjacent surface (backwall). Experience has shown that even for ultrashort pulse length lasers, some backwall effects (debris, heating) are evident. Various techniques have been successfully applied to avoid these effects, including filling the tube with a sacrificial material or flowing water through the tube during drilling.

Capability

Medical devices pose stringent requirements on manufacturing processes. Components are generally small, produced from difficult to machine materials, and must in the end be extremely clean (free of debris).

Table 1: Capability of pulsed solid state lasers for hole drilling.

Hole Characteristic	Millisecond Pulse	Ultrashort Pulse
Diameter – percussion	≤1 mm	≤100 μm
Diameter repeatability	+/-25 μm	+/-5 μm
Taper	+/-25 μm	+/-10 μm
Edge Finish	Function of material removed per pulse	
Heat Affected Zone	10s-100s μm	Few 10s μm
Throughput	Holes/second	Seconds to minutes/hole

Table 1 summarizes the capability of laser drilling for two regimes of pulse duration – the traditional millisecond pulse length and that of the recently available ultrashort pulse length.

In general, millisecond pulse duration, flashlamp pumped solid state lasers have a much wider range of average and peak power and energy than ultrashort pulse length lasers. As illustrated in Fig. 4, these lasers can percussion drill holes from a 100 μm to 1 mm diameter in thicknesses up to several millimeters.

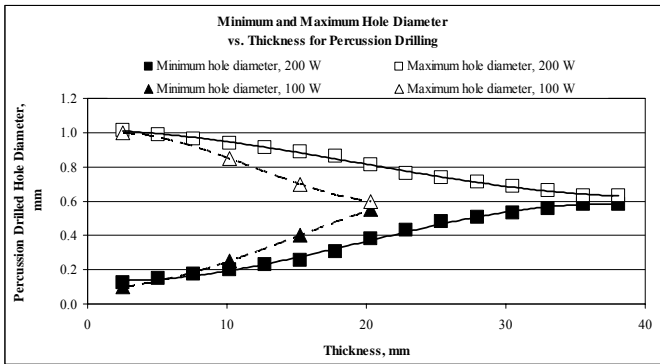


Figure 4: Minimum and maximum hole diameter that can be percussion drilled using a millisecond pulse duration, flashlamp pumped Nd:YAG laser with $M^2 \approx 12$.

Beam quality (focusability and intensity) is a key differentiator among lasers of a given pulse duration. An order of magnitude difference in beam quality translates into two orders of magnitude of intensity and significant reductions in thermal effects. High beam quality (low M^2) lasers in combination with short focal length lenses are capable of producing holes much less than 100 μm diameter in a wide range of metals, polymers, and ceramics.

Precision

The shape of laser drilled holes is controlled by the choice of laser parameters. Fig. 5 illustrates a cylindrical hole (within the limits of taper identified in Table 1) along with holes produced by process conditions that produce non-cylindrical shapes.

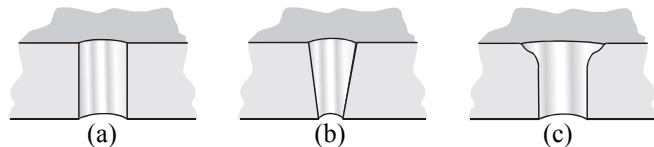


Figure 5: A typical laser drilled hole has a taper less than 2°. However, the choice of laser conditions can produce holes with greater taper (b) or bell-mouthing (c).

With millisecond pulse length lasers, the typical variation of hole size in metals is on the order of +/-25 μm , whereas with ultrashort pulse length lasers, the variation is closer to +/-5 μm .

Precision in percussion drilled holes is determined by localized material removal rate per pulse which is influenced by both the laser process and material factors previously identified. The spatial symmetry and temporal stability of energy within the laser beam and polarization are key factors affecting the shape and consistency of laser drilled holes. Recent work has also suggested that there is an optimal laser beam intensity for a given hole diameter. Intensities either less than or greater than this value result in greater taper than for the optimum value.

For holes produced by trepanning or helical drilling, precision is largely determined by the performance of the mechanism that positions the laser beam relative to the surface. However, as with percussion drilling a linearly polarized laser beam or asymmetrical energy distribution within the beam will also contribute to mishapen holes.

For either process, variations in the local material absorption, bulk composition, and melting and vaporization temperatures also influence hole shape and consistency.

Edge finish

The representative finish of the walls of laser drilled holes is shown in Fig. 6. The material removal rate per pulse is a good predictor of the edge finish that can be achieved, especially for thin (<100 μm) thick materials.

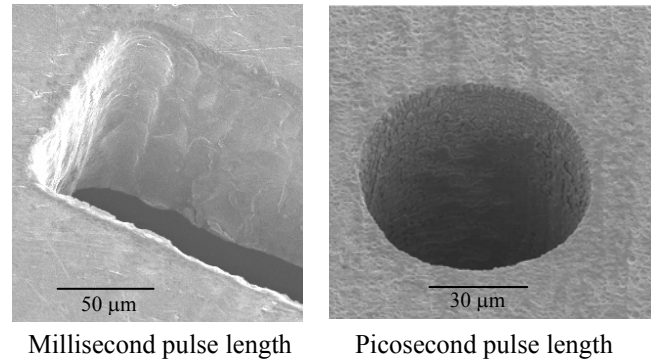


Figure 6: Pulse overlap and material removed per pulse determine key quality aspects of the laser drilled holes. Picosecond pulse length hole picture courtesy of Lumera.

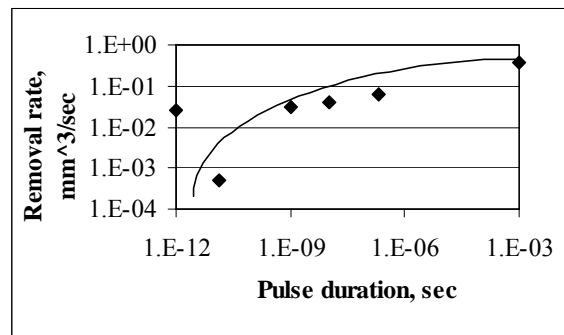


Figure 7: Removal rates for metals vary widely with pulse duration.

Throughput

As indicated previously, reducing pulse duration has the effect of reducing the thickness of the melt layer in the hole wall and, through this, reducing the size of melt particles. As illustrated in Fig. 7, it also reduce the material removal rate.

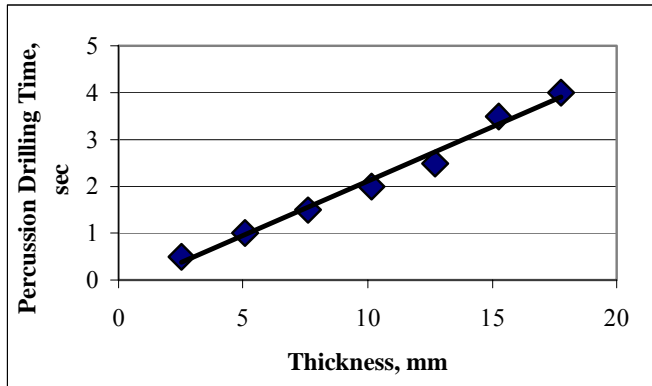


Figure 8: Percussion drilling time vs. thickness for minimum hole size for a millisecond pulse length Nd:YAG laser.

Laser System Developments

A key focus in industrial application of laser drilling has been to increase the consistency of laser drilled holes through process sensing and integrated control of the laser and motion based on the sensor feedback.

As illustrated in Fig. 9, maintaining the laser beam focus range centered on the workpiece surface provides a range over which the hole size is relatively insensitive to workpiece position. Several methods of focus control are available with the most common being capacitance (conductive materials only) and optical (all materials).

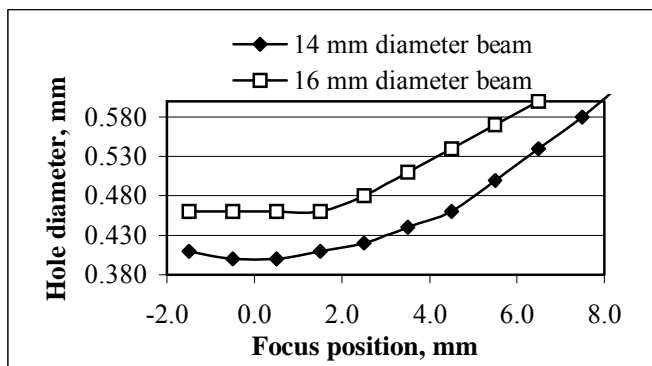


Figure 9: Laser drilled hole diameter vs. focus position (0 = center of focus depth) for two beam diameters and a 200 mm focal length focusing lens.

Another means of improving hole consistency and of reducing thermal effects in general is to incorporate process control sensing that determines when the hole has been produced. As illustrated in Fig. 10, such sensing improves the consistency of hole diameter by compensating for normal process and material (e.g thickness, absorption) variations.

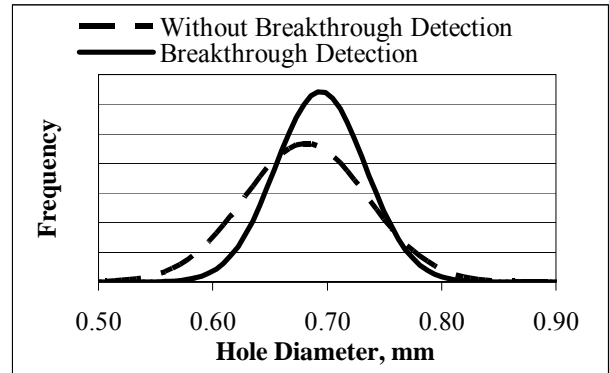


Figure 10: Breakthrough detection produces more consistent holes by compensating for process and material variations. Results are for holes drilled in 3 mm thick Inconel 718 sheet.

Summary

Medical device process engineers have a wide range of laser sources available for use in producing small holes. Longer pulse lengths offer capability for high throughput even in relatively thick metals and non-metals whereas ultrashort pulse length lasers provide a means of producing sub-100 μm diameter holes with little or no heat affected zones.

Modern laser systems incorporate process control sensing to build upon the capability of these lasers by producing more consistent quality.

References

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