Emerging applications for Q-switched DPSS lasers

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Nd:YAG Flashlamp-Pumped Solid State Lasers (FPSSLs) have been widely used in industry for over twenty years, whereas industrially rugged Diode Pumped Solid State Lasers (DPSSLs) appeared only relatively recently. Q-switched DPSSLs are now available at comparable average powers to pulsed FPSSLs, offering pulses with durations of 1-100s of nanoseconds at kilohertz pulse repetition frequency. Typically comparable figures for conventional pulsed FPSSLs are a pulse duration of order 1ms at a repetition frequency of a few hundred Hz.

We believe that the ns - kHz (1ns = 10^{-9}s, 1 kHz = 1000 pulses per second) regime of operation has the potential for much improved processing: short pulses diminishing thermal effects and high peak intensities improving material coupling and process efficiency. Combined with the excellent beam quality, high efficiencies, rugged construction and long diode lifetimes; this makes DPSSLs lasers a very attractive option for both macro and micro scale manufacturing.

In this paper we consider two emerging processes enabled by the latest state-of-the-art Q-switched DPSSLs. The first is laser milling of Nickel superalloys, a process by which complex 3D shapes can be machined in aerospace alloys to improve cooling and therefore performance and lifetime of turbines in both the aerospace and power generation sectors. The second is high aspect ratio, fine hole drilling of stainless steel fuel injectors for the automotive sector; offering the potential to radically improve engine efficiencies by producing ever-finer fuel aerosols from smaller hole sizes. The high peak power densities in the focused beam results in plasma formation when processing metals and an explanation is given as to why we believe this to be critical to the success of both processes.

Laser milling

The laser milling of Hastalloy and other Nickel based superalloys is of increasingly significant commercial interest in the aerospace and industrial gas turbine sectors. It offers, for example, the potential to rapidly machine complex shapes in the leading edges of turbine blades.

With high power DPSSLs complex shapes can be created in times that compete with EDM, with the added advantage that the processing can take place on surfaces that have already had Thermal Barrier Coatings (TBC) applied to them. Cooling vanes have long been drilled by flash lamp pumped solid-state lasers: it is now possible to laser mill 3D shapes at the exit of these vanes, offering improved cooling by more effective flow control.

We have already successful demonstrated the laser milling of ceramic (TBC) with a Q-switched DPSSL, so the potential exists to mill and drill dissimilar laminar materials in a single pass with the same laser e.g. drill cooling vanes and mill alloy turbine blades: a very attractive option for those companies at the forefront of gas turbine technology.

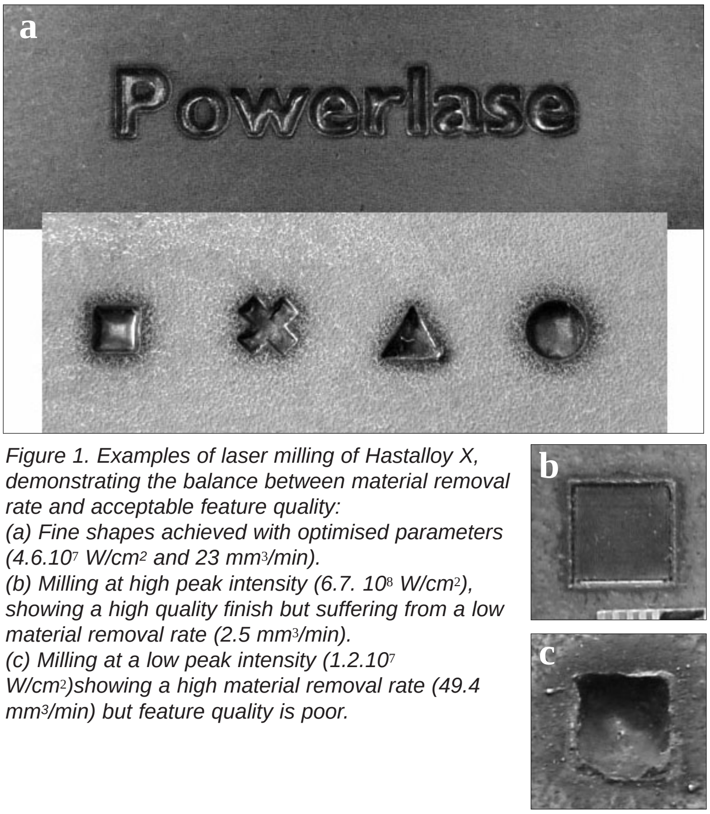

Figure 1. Examples of laser milling of Hastalloy X, demonstrating the balance between material removal rate and acceptable feature quality:
(a) Fine shapes achieved with optimised parameters (4.6.10^7 W/cm^2 and 23 mm^3/min).
(b) Milling at high peak intensity (6.7. 10^8 W/cm^2), showing a high quality finish but suffering from a low material removal rate (2.5 mm^3/min).
(c) Milling at a low peak intensity (1.2.10^7 W/cm^2)showing a high material removal rate (49.4 mm^3/min) but feature quality is poor.

For this laser milling work a Starlase AO4 Nd:YAG Q-switched DPSSL was used at the fundamental (1064nm) wavelength. This laser offers average powers up to 430 W, repetition frequencies from 3-50 kHz and pulse durations of 35-200 ns. The output beam passed through an external attenuator* to provides fine control of pulse energy at the workpiece, was.collimated through a Galilean telescope and directed into a galvanometric scanner (ScanLab HurryScan25) with a 254mm focal length f-theta telecentric lens, a working field of 115x115mm and a maximum velocity of 10m/s. All samples were Hastalloy X.

The performance of the Q-switched DPSSL is such that if average power is maintained constant, the pulse duration increases as the pulse frequency is increased i.e. the peak intensity decreases. In the high pear power regime, material removal rates are found to increase exponentially as power density diminishes, an effect that we associate with plasma shielding of the workpiece (see below) i.e. the density of the plasma increases with increasing incident power density, increasing its shielding effect. This implies that there will be an optimum set of laser parameters for which the material removal rate is maximised. For this removal rate to be commercially attractive, our work suggests operating the laser at higher frequencies, 30-50 kHz, where pulse widths are longest,

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*Such an attenuator is necessary to control pulse energy, for unlike FPSSLs, Q-switched DPSSLs have distinct stability regions that are optimised by reference to the diode drive current, which means that, stable power output cannot be controlled simply by adjusting power input. Fine power control is better achieved externally.

120-200 ns, in order to reduce the ratio of peak intensity to average power and thereby reduce plasma shielding effects.

A further consideration is surface quality. It is observed that at high power density, material is removed in the form of a fine molten spray. This produces the finest surface finish. At a constant average power, the molten spray becomes denser and the surface quality deteriorates as the the power density diminishes. Clearly a balance must be struck between material removal rate and acceptable feature quality. Figure 1 above demonstrates this balance. It may be possible to combine different regimes to improve laser milling: for example, a two-stage process could involve low intensity processing for bulk material removal, followed by high intensity processing to produce fine features and surface quality. Indeed, it can be argued that plasma effects are beneficial if appropriately controlled, acting as a balance between quality and milling rate.

Plasma effects

At focused beam intensities of between 10^7 and 10^{10} W/cm^2 at a metal workpiece, typical for DPSSL processing, plasma formation occurs. Understanding the effect of the plasma is therefore critical in controlling the metal removal process.

Such effects are already well documented in the field of laser welding; for example, plasma suppression is essential for consistent keyhole welding, where CW lasers in the kW range achieve focussed intensities approach 10^7 W/cm^2.

Laser plasmas from metal substrates are produced predominantly via multiphoton ionisation and the inverse bremsstrahlung mechanism, by which free electrons can extract energy from the laser beam. The effect of the plasma is three-fold: (i) some of the incident laser beam will be absorbed, heating the plasma and being partially conducted through to the substrate, and some of the absorbed power will be re-radiated via bremsstrahlung emission; (ii) the laser beam will suffer optical distortion as it passes through the plasma, serving to defocus the beam– the so called ‘plasma lensing’ effect; (iii) when the plasma reaches a critical density, a value set by the laser wavelength, it will act as a ‘plasma mirror’serving to reflect the beam. This critical density is inversely proportional to the square of the laser wavelength i.e. the density at which the plasma becomes a mirror to teh laser beam is one hundred times higher for a Nd:YAG (1.06 µm) than for CO_2 (10.6 µm) laser. A consequencxe of this is that deeper hole formation is achieved in metals by using shorter wavelength lasers.

The plasma is rapidly formed at the surface, and expands away from the substrate. The substrate at the plasma-solid interface is heated by conduction and the plasma pressure causes material ablation at the interface. As the plasma expands away from the substrate its temperature rises and its density falls. Incident light begins to be reflected away at the point at which the critical density is reached in the plasma.

The plasma density that is achieved will affect processing, and its value is proportional to the peak laser power density at the workpiece. It is therefore proportional to pulse energy and inversely proportional to pulse duration and spot size. Controlling these parameters will control plasma density and its effects upon processing.

Fine hole drilling

Laser drilling of cooling vanes in aerospace and industrial gas turbines with flash lamp pumped Nd:YAG lasers is one of the great success stories in the field of laser materials processing. The emergence of high power industrial DPSSLs opens up new and exciting markets for laser drilling, particularly automotive, where the need for ever more efficient engines drives the demand for improvements in fuel injector design.

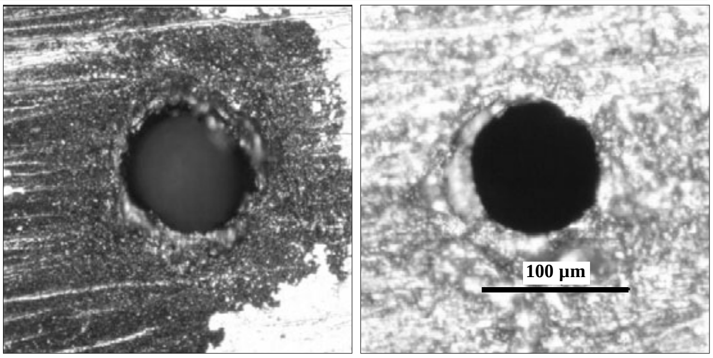

Figure 2 Comparison of percussion (left) & trepan drilled entrance holes, demonstrating the unsuitability of the former for fuel injection holes.

In order to improve engine efficiency, fuel injectors are required to produce ever-finer fuel aerosols in the cylinder. This can be accomplished by reducing the diameter of the holes through which the fuel is volatilised. Conventional manufacturing methods such as EDM are unable to produce holes small enough for the next generation of engine designs, particularly diesel engines. Therefore the challenge for the laser industry is to meet and exceed these exacting standards for high aspect ratio hole drilling.

The current industry target is to drill <100µm diameter holes in 1mm thick 316 stainless steel. These holes must be devoid of dross, demonstrate consistent circularity throughout their bore, have an acceptable level of recast, and have a taper as close to zero as possible - reverse taper may be desirable for flow control if possible. High quality holes have been successfully demonstrated using both harmonic wavelengths (532 & 355nm) and femtosecond lasers, but not at commercially attractive process rates. The challenge is to successfully apply fundamental wavelength Q-switched DPSSLs and meet hole quality requirements at a commercially interesting process rate.

The choice of laser for this work was dictated by automotive industry research that suggests that sub-20ns pulse durations are an enabling parameter for this application. A Starlase EO12 Q-switched DPSSL was used: this laser offers >30W average power output at 1064nm, at a fixed pulse repetition frequency of 3.5 kHz and pulse duration of 10ns, at near diffraction limited beam quality. A precision Cartesian XYZ motion stage was employed with linear drives offering micron accuracy at high velocities (up to 2m/s). As for the laser milling work, pulse energy at the workpiece was controlled by an external attenuator.

It would offer significant advantages if it were possible to percussion drill these holes whilst meeting hole quality requirements, since then hole diameters and process times could be significantly reduced. however, the accepted wisdom is that trepanning offers superior quality over percussion drilling, so both methods are examined. As figure 2 shows, the quality of percussion-drilled holes was found to be unacceptable.

As in laser milling discussed above, plasma shielding is also found to play a primary role in fine hole drilling. In this application pulse width is fixed and therefore intensity can only be adjusted by external attenuation. Again, a bright plasma is observed at the workpiece, and hole dimensions and taper are found to be a function of the incident laser intensity. Figure 3 shows that how intensity is critical in controlling hole quality.

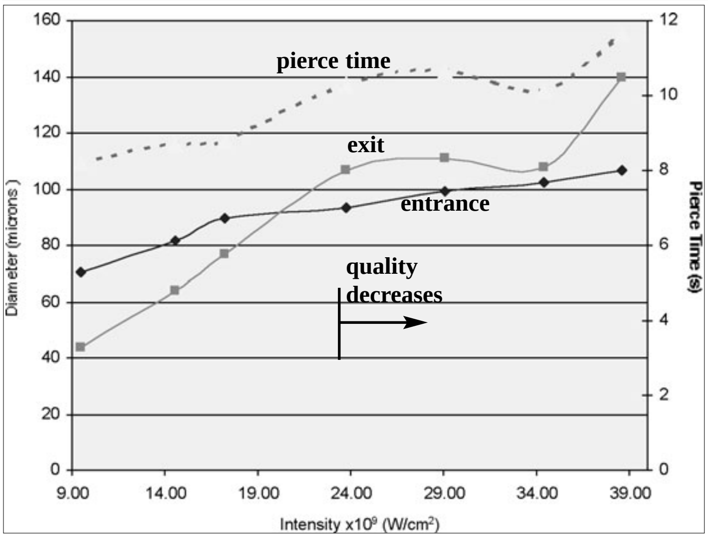

Figure 3 Entrance and exit hole diameter and pierce time in stainless steel as a function of power density. Focused spot size, trepan diameter and exposure time were held constant at 20s throughout.

Since focused spot size, trepan diameter and exposure time were held constant in figure 3, the data suggests that the plasma effects (defocusing of the beam combined with plasma heating) may be responsible for the general trend of increasing entrance and exit hole diameters with increasing laser power density. During the drilling the plasma sinks into the forming hole, widening the hole it as it goes and thereby accounting for the absence of a strong positive taper. If so, the drilling is at least in part a plasma machining process and could explain why the taper diminishes and eventually reverses as power density increases. This interpretation is consistent with the pierce time increasing with power density and with the strong correlation between pierce time and exit diameter.

Figure 3 suggests an optimum power density for creating a sub-100µm hole with minimal or negative taper.of around $2x10^{10}$ W/cm^{2}. Unfortunately, hole quality deteriorates as power density increases much above this threshold: circularity diminishes and dross formation becomes uncontrollable. So simply increasing power density is not in itself a solution for achieving reverse taper.

Figure 3 shows data relating to holes drilled with a constant exposure time of 20s, yet the maximum pierce time is <12s. The reason for this is that it was found that additional exposure to the laser after piercing is required in order to minimise taper. Data for this is shown in figure 4.

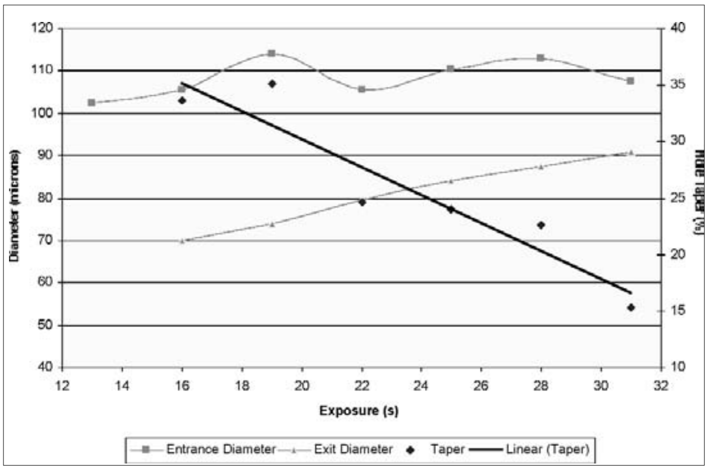

Figure 4. Fine hole characteristics in stainless steel vs. exposure duration

Figure 4 shows clearly that as exposure time increases so taper diminishes, the exit diameter increasing consistently whilst entrance diameter remains relatively constant. Therefore in order to achieve minimal taper, it is necessary to expose the substrate for a number of seconds beyond initial penetration to allow the laser to 'bore out' the hole.

By choosing an appropriate power density, exposure duration and trepan diameter it is possible to achieve high quality holes in stainless steel with highly repeatability, as illustrated in figure 5.

Each hole in figure 5 is drilled in 20s; taper is <10%, hole circularity is better than 5%, and maximum variation is 6%. In this example, only 20% of the available laser power was used, so by beam splitting it would be possible to drill four to five holes simultaneously, offering a throughput of >12 holes per minute.

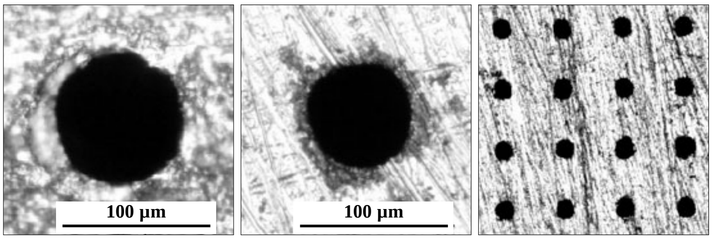

Figure 5. Sub-100 µm holes drilled in 1 mm stainless steel; and (right)grid of holes on a 250 µm pitch

Conclusion

High quality laser milling of Nickel-based super-alloys can be achieved using 1064nm Q-switched DPSSLs; offering fine surface finish and high resolution detail at commercially attractive material removal rates.

Laser milling is critically dependant upon plasma formation. Above the optimum power density, plasma shielding reduces the material removal rate, but results in fine quality machining. Below the optimum power density, the material removal rate is higher, but machining quality deteriorates. At the optimum power density laser milling becomes a robust process, and offers a good compromise between feature quality and process rate.

Fine hole drilling of steel is possible with 1064nm Q-switched DPSSLs. It is possible to drill high aspect ratio holes >10:1 in 1mm steel at commercially attractive rates of >12 holes/minute. Highly repeatable holes of diameter <100µm can be produced with low or negative taper, good circularity at both entrance and exit and negligible dross. Fine hole drilling is also found to be influenced by plasma formation: for a given hole diameter an optimal processing power density must therefore be identified. At high power densities it is possible to achieve reverse taper, but in such regimes hole quality quickly diminishes and hole diameter becomes excessive. Taper reduction in fine drilling requires overexposure of the hole.

The latest generation of high power Q-switched DPSSLs are industrially robust tools capable of commercially enabling the important industrial applications of super-alloy milling and fine hole drilling. With proper process understanding they can match and exceed the performance of alternative technology solutions such as EDM, and can significantly better the performance of flashlamp systems.

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