An Investigation into whether the Laser Drilling Capabilities of a 2kW Fibre Laser Can Be Enhanced Using Pulse Train Shaping

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Abstract

In long, ms, pulsed melt ejected based laser drilling of metals pulse train shaping has previously improved drilling efficiency. This work investigates if pulse train shaping can be exploited in the laser drilling of 0.8-2 mm mild steel with a 1070 nm wavelength 2kW IPG 2000S fibre laser. Single pulse drilling at a range of powers is used to determine the minimum pulse length, and thereby energy input, required for through hole generation. The effect on this minimum penetration energy of using pulse trains of identical 1 ms pulses, as well as pulse trains with a progressive increase in pulse power, was investigated. Drilling efficiency was improved by both multiple 1 ms pulses and progressively increasing pulses, with the multiple pulses having a greater effect, typically increasing efficiency by 35%. Cross-sections showed not all molten material was fully ejected, indicating that further efficiency improvements are possible for the conditions considered.

Keywords: laser drilling; pulse train shaping; melt ejection; fibre laser; process optimisation; percussion drilling;

1 INTRODUCTION

Laser drilling is a non-contact manufacturing technique that covers a wide range of materials, lasers and techniques that are used across the aerospace, automotive and electronic manufacturing industries [1]. Due to its ability to be effectively used with conventionally difficult to machine materials and complex geometries, laser drilling is being increasingly used throughout industry.

The most widely used drilling techniques are single pulse drilling, percussion drilling and trepanning. Trepanning provides the best hole quality by drilling around the circumference of the desired hole shape; however, this is a much more time expensive process when compared to the single/percussion drilling techniques. During single and percussion drilling, there is no relative motion between the workpiece and the laser beam, and the laser is either pulsed once (single pulse) or continually fired in series of pulses (percussion) until a hole is produced.

The substrate material is removed via two main processes: vaporisation and melt ejection. The material removal mechanism is dependent on the laser pulse width; nano and femtosecond pulses generally result in removal by vaporisation [2]. In laser drilling of metals using millisecond pulses, as used in this work, melt ejection is the dominant and more efficient material removal process, requiring approximately 25% of the removal energy when compared to vaporisation [2]. Once the laser pulse has started, the substrate material will heat up, melt and, with further irradiation, vaporise. When the material vaporises, a recoil pressure is generated that exerts a downward force on the melt pool. This forces the molten material to move radially outwards and upwards out of the hole. As material is continuously removed from the hole in this way, the melt front can quickly advance downwards into the material, until breakthrough is achieved [2, 3] as demonstrated in Figure 1. This means that the laser drilling process is at its most efficient when just enough vapour pressure is produced to expel all of the molten material generated.

This method of drilling is of great importance to the aerospace and automotive industry due to its ability to produce high aspect ratio holes in close proximity at relatively low cycle times [4]. A key application of melt ejection based laser drilling of metals is in the aerospace industry for the drilling of cooling holes in Ni superalloy gas turbine blades [5], modern jet engines can require over 1 million holes drilled, hence apparently small process improvements rapidly scale up to provide significant benefits [6].

However, the role of molten material introduces potential hole to hole variability in this laser drilling process, resulting in a body of work on documenting and improving reproducibility. There are various different parameters used to determine hole quality including entrance and exit hole diameters; taper angle; extent of any recast layer; as well as the variation of each of these parameters.

The desire for low cycle times and repeatable holes with correct hole characteristics has resulted in research into pulse shaping as a method of achieving these goals. Pulse shaping is a technique that manipulates the way in which the energy is delivered to the workpiece by the laser beam. Grad *et al.* [7] ultimately concluded that if a melted pool is formed during the laser drilling process, then laser pulse shaping can be used to enhance the laser drilling process. The research community agrees with the conclusions drawn by Ng *et al.*[8], that a lower entrance hole diameter standard deviation and, therefore, better hole repeatability, can be achieved by drilling with a combination of higher peak powers and shorter pulse widths. This is due to a more uniform distribution of melt ejection as a result of a higher peak power and a reduced interaction time between the molten material and the substrate parent material due to a reduced pulse width. Mishra [9] confirms these relationships, and concluded that hole taper decreases with increasing sheet thickness, indicating that pulse shaping can successfully be utilised to produce better quality holes with lower variance. Roos [10] demonstrated that efficiency increases when comparing a multi-pulse shape and a single pulse, whilst Durr [11] highlights that such efficiency increase relies on the temperature remaining high between pulses. Low *et al.* [12] used, what they termed as, Sequential Pulse Delivery Pattern Control (SPDPC), that is, a pulse train of equally spaced pulses of equal width, but with linearly increasing peak power. It was demonstrated that using SPDPC allowed for controlled hole taper because it generates a smaller entrance hole than a multi-pulse shape of constant peak power and generated an increased fraction of downward ejected material.

Millisecond length pulse based laser drilling of metallic materials has been dominated to date by solid state lasers, mainly Nd:YAGs. More recent research has focussed on exploiting the higher average powers available from fibre lasers [13, 14]. The authors are not aware of any previous report of the use of pulse shaping with fibre lasers. The present work investigates the effect of temporal pulse shaping on the laser drilling capabilities of a 2kW IPG YLR 2000S fibre laser.

2 EXPERIMENTAL PROCEDURES

A 2kW IPG YLR 2000S fibre laser with a wavelength of 1070nm was used. A 200 µm diameter fibre delivered the beam to a head with a 125mm collimation length and a 120mm focal length lens to produce a 200 µm diameter focussed spot on the top surface of the substrate. Argon assist gas was supplied at 1 bar co-axially with the laser beam. All experiments were conducted with the laser beam being delivered vertically incident to the substrate surface. The substrates used were mild steel sheets with thicknesses 0.8, 1.2 and 2 mm, used in the as received state. Holes were drilled with a separation of at least 2 mm, large enough so that the molten material ejected from the hole that gets deposited around the hole entrance (spatter) did not affect the drilling of the next hole.

Three different pulse shapes were used in this work: single pulse; multi-pulse; linear ramping up pulse (Figure 2).

2.1 Single Pulse Experiment

Initial values starting point parameter combinations were obtained from previous work carried out with the laser used in this study [3]. For mild steel sheet of thickness of 0.8, 1.2 and 2 mm and for pulse widths of 4, 6 and 25 ms, the minimum power required to produce breakthrough, defined as 10 out of 10 through holes being produced, was determined. This was done progressively reducing the power in steps of 12.5 W. A total of 10 holes per parameter set were drilled to allow for hole to hole variation to be studied.

2.2 Multi-Pulse Experiment

For this study, the multi-pulse is defined as using a constant power, pulsed at a frequency of 1 Hz with an equal 'on' and 'off' pulse segment width of 1 ms. The minimum number of 1ms pulses at the corresponding power found in the single pulse experiment to achieve 100% breakthrough for 10 holes was then found. This allowed the minimum input energy required for a multi-pulse to generate a through hole to be compared to that required for the single, square, pulse.

2.3 Linear Ramping-Up Pulse

The geometry of the linear ramping-up pulse (LRUP) shape was selected to start at 50% below and finish at 50% above the corresponding power found in the single pulse experiment, thereby initially matching the energy input of the corresponding single pulse. The total input energy of the pulse was then decreased in 5% iterations whilst maintaining the pulse shape geometry to determine the limit for which 100% breakthrough for 10 holes was achieved.

2.4 Measurement of Hole Quality

The entrance and exit diameters of the appropriate holes generated were measured using an optical microscope and measurement software, shown in Figure 5. An average diameter of the hole was calculated from a horizontal and vertical measurement. For the exit holes, the diameters were measured by focusing the microscope onto the surface of the steel, and using a light source from beneath the sample to show the hole boundaries more clearly. The standard deviation of the diameters of the 10 holes was calculated and defined as the hole variance.

From the entrance and exit hole diameters, the taper angle and volume removed per unit energy can also be calculated. For this study, the shape of the drilled hole was assumed to be a conical frustum and its volume was calculated accordingly. Figure 6 and Equations 1, 2 & 3 show how these values were calculated.

$$Taper\ Angle = \tan^{-1}\left(\frac{D-d}{2t}\right) \qquad (1)$$

$$Volume\ removed = \left(\frac{\pi t}{12}\right)\left(D^2 + d^2 + \left(D^2 d^2\right)\right) \qquad (2)$$

$$Volume\ removed/unit\ energy = \frac{Volume\ removed}{Total\ input\ energy} \qquad (3)$$

Volume removed per unit energy is readily used throughout literature as a metric for drilling efficiency [16].

To produce cross-sections, samples were initially roughly sectioned and then mounted in a 30mm diameter resin block. Using the diameter measurements previously made and a grinding wheel, a cross section through the centre of the hole was exposed to approximately ±15µm. The samples were then polished using ferrous diamond grinding wheels, finishing with a 1µm pad to give a mirror like finish. To expose the microstructure, the samples were then etched using nital for approximately 10 seconds.

3 RESULTS

All holes measured in this study were through holes that were created close to the threshold of the minimum energy required for breakthrough for given pulse widths, pulse shapes and powers. Hole entrance and exit diameters varied from 429 to 714 µm and 131 to 295 µm respectively using laser powers from 325 to 1625 W. Figure 5 shows the typical appearance of the drilled holes. The presence of spatter around the drilled holes confirmed melt ejection as the material removal mechanism for the parameters used in this study. The majority of the spatter around the entrance hole was consistently to the same side of each drilled hole whilst the spatter around the exit holes was randomly orientated, suggesting that the assist gas was not delivered perfectly coaxially. Table 1 summaries the minimum power required to achieve 100% breakthrough for 10 holes for a single pulse with a given pulse width and mild steel sheet thickness.

3.1 Drilling efficiency

For each different thickness and pulse shape, the minimum energy required for breakthrough increases as power decreases at an increasing rate. For each mild steel sheet thickness, the multi-pulse shape required the least amount of energy to achieve 100% breakthrough for 10 out of 10 holes and is therefore the most efficient pulse shape. The LRUP is also more efficient than the single pulse with and average improvement of 15%, performing slightly better on the thicker steel samples. Figure 7 shows how the improvement in drilling efficiency of the multi-pulse compared to the single pulse increases as steel thickness decreases and power used decreases. The greatest increase in drilling efficiency is 56% when comparing the single pulse to the multi-pulse is for 0.8mm steel at 325W when compared to the 25ms single pulse. The increase in multi-pulse drilling efficiency for the 2mm steel at 788W is 36% with an overall average increase of 35%. To plot the LRUP results for Figure 8

& 9, the average power of the pulse shape that produced a through hole with the minimum input energy was calculated and plotted.

Figure 8 shows how the volume removed per unit energy varies for pulse shape, steel thickness and power used. In all cases, apart from for the multi-pulse for 2mm steel, the volume removed per unit energy input increases as the power used increases. Therefore, drilling efficiency increases as power increases. The benefit from using a higher power increases as steel thickness decreases.

3.2 Hole quality

For each thickness of mild sheet steel and pulse shape, the entrance diameter decreased with increasing power used (Figure 9). There was no apparent correlation between pulse shape and entrance diameter size. For the majority of pulse shapes and steel thickness, entrance diameter variation decreases as the power used increases apart from for the LRUP for 1.2mm and 2mm steel. The single pulse provided the best overall performance with an average variance across all samples of ±22.3µm with the lowest hole variance of ±13µm for 4ms pulses for 0.8mm and 1.2mm steel samples, while the multi-pulse gave the highest average variance of ±25.7µm. The 4ms LRUP pulse for the 2mm steel sample generated holes with the highest variance of ±49µm with an overall average of ±24.6µm. Whilst the single pulse hole entrance diameter variation remained almost constant for each steel thickness, for the LRUP and the multi-pulse it increased with increasing steel thickness.

The taper angle of the laser drilled hole across all steel thicknesses and pulse shapes is seen to decrease with increasing power (Figure 10). Only 1 out of the 9 pulse shape comparisons between steel thickness and pulse width where the LRUP does not give the highest taper angle. The hole with a highest taper angle of 17 degrees was produced by a 25ms LRUP at 788W in 2mm thick steel and a 4ms single pulse at 525W produced the hole with a lowest taper angle of 8.5 degrees in 0.8mm thick steel. It can also be observed that the taper angle variance increases with both increasing steel thickness and power.

Recast layer and heat affected zone (HAZ) thickness of the holes drilled by multi-pulse and single-pulses are remarkably similar. The recast layer thickness of the multi-pulse and single pulse are 25µm and 24µm respectively. The HAZ thickness of the multi-pulse and single pulse are 87µm and 92µm respectively. The LRUP has a thicker recast layer and HAZ thickness of 47µm and 99µm respectively. This means that the LRUP is the poorest performer in the regard as the recast layer should be minimised.

4 DISCUSSION

4.1 Pulse shape comparison

The results obtained by the present study show that pulse shaping can be used to increase the drilling efficiency of laser drilling. LRUP's and multi-pulses require on average 15% and 35% less energy for breakthrough respectively when compared to single pulses of the same average power. LRUP's and multi-pulses also remove on average 20% and 63% more material respectively for an equal energy input compared to the equivalent single pulse. The material removal mechanism that occurs during laser drilling involves heat transfer, fluid flow and phase change interactions that can make it difficult to be certain of how the process differs between parameter sets and pulse shapes.

In an attempt to aid this understanding, cross sections of drilled holes with the same power and equal input energies delivered with a single and a multi-pulse were produced (Figure 11). The differences in energy efficiency are attributed to the different pulse shapes effecting the way in which the material is removed. It is important to note that the cross sections do not reflect directly what is happening during the laser pulse but still allow the progression of the melt front and the extent of retained, i.e. non-expelled, molten material to be observed.

At an input energy of 2.7 J with a 2 ms single pulse and two 1 ms pulses (multi-pulse), it can be observed that the multi-pulse melt front has progressed much deeper into the 2 mm steel sample than the single pulse. This suggests, with further evidence from the 4.1 J input energy cross sections, that the multi-pulse is more effective at removing the molten material generated. This allows the melt front to progress further into the material and achieve breakthrough more efficiently, as if the melt is completely ejected as it is created, the hole can continue to get deeper whilst less energy is used in making the hole wider.

The efficiency gained by using a multi-pulse compared to a single pulse was also larger for the lower power and longer pulses. The gain in efficiency could potentially be due to each pulse of the multi-pulse ejecting a higher proportion of all of the material it melts, whereas for a single pulse, where continuous heating occurs may form a larger melt pool where more force is required to either eject the entire melt pool or overcome the surface tension of the molten material. Just enough vapour pressure being generated to eject all of the molten material represents the ideal ratio, and the multi-pulse may be operating closer to it than the single pulse. An interesting experiment would be to determine the magnitude of vaporisation of each pulse shape by comparing the volume of material ejected to the volume removed, also known as the melt eject fraction investigated by Voisey et al. [2], from the drilled sample. The mass ejected per pulse could be calculated and therefore also be used to identify the effectiveness of each stage of the LRUP.

Generally, from Figures 7 & 8 we can conclude that drilling efficiency decreases with decreasing power. This relationship can be due to a similar reason for why the multi-pulse is more efficient than the single pulse, that the lower powers do not generate a high enough ratio of vapour pressure to molten material to for complete melt ejection.

A recast layer is still present on the multi-pulse drilled hole, this means that material has been melted and then not ejected, thereby showing that the efficiency of the process can still be improved, forming the basis for future study. An optimisation study could be carried out investigating the effects of the multi-pulse frequency on drilling efficiency and hole quality as this could highlight the effect that progressive heating and re-solidification have on the multi-pulse drilling mechanics.

The LRUP also exhibited an increase in energy efficiency compared to the single pulse. This indicates that increasing the input power to match the increasing input energy requirement as the hole progresses is a successful method for increasing energy efficiency. However, to investigate this, the LRUP shape was modified so that it is pulsed and termed as a linear ramping-up multi-pulse (LRUMP) (Figure 12), similar to Low's [12] SPDPC, and tested in the same way as the LRUP. The minimum energy required for breakthrough for a LRUMP did not exceed an equivalent single pulse for any of the cases. This suggests that the rate of volume removed/hole progression is not proportional to power or input energy. This also suggests that the LRUP is reliant on progressive heating whereas the multi-pulse is not as the LRUMP inputs the same energy in the same way but with 1ms of cooling time between each pulse and does not achieve breakthrough, where the LRUP does. An optimisation study on the LRUP could be performed to determine a more efficient pulse shape geometry. Due to the LRUP shape geometry and the 1ms pulse shape resolution of the laser operating software, progressive cross sections of the LRUP drilled hole at equal energies to the single and multi-pulse could not be produced, therefore prohibiting a similar direct comparison. However, it would be interesting to use a similar process to investigate what happens during the low powered start to the LRUP pulse.

It can also be observed that in many of the cases the increase in volume removed per unit input energy decreases as power increases. The laser pulse width resolution of the laser operating software being limited to 1ms can impact the accuracy of the result. For example, in the case of a 1625W single pulse for 2mm steel, if breakthrough is achieved at 3.5ms instead of the 4ms noted, then an additional 0.82J is input into the material, which is 12.5% of the measured total input energy. In the case of 788W for 2mm steel, if breakthrough is achieved at 24.5ms instead of the measured 25, there is only a 2% total energy input difference, making the effect more significant at higher powers. Therefore, energy is being input into a through hole and not removing material, thereby decreasing its volume removed per unit input energy.

A key observation is that both the minimum amount of energy required for breakthrough and the volume removed per unit energy improve with increasing laser power used. So with regards to industrial application, using the highest power possible will yield the best drilling efficiency results, and the findings of this study would allow a lower powered fibre laser combined with pulse shaping techniques to match the efficiency capabilities of a higher powered fibre laser using a single pulse pulse shape. This means that cheaper, smaller peak power lasers can be used instead and thereby possibly reducing the cost of purchasing a fibre laser or expand the capabilities of a fibre laser already owned by manufacturers.

4.2 Hole quality comparison

Ng et al. [8] found that for single pulses, using shorter pulse widths and higher powers resulted in a reduced hole variance. The results gained from the single pulse experiment, shown in Figure 9, reflect the same findings. French et al. [4] concluded that a ramping-up pulse, a pulse that starts with a constant low power and then finishes with a step change to a higher constant power, that is the most comparable pulse shape to the LRUP studied in literature, performed more consistently with regards to hole variation when compared to a single pulse. This improvement was attributed to a more ‘controlled coupling’ between the laser beam and the workpiece material in their further work [16]. This is the opposite to what was found in the present study, however, in this case, the mechanics between a ramping-up pulse and a LRUP may be to dissimilar to compare. These discrepancies could also be arising from the difficulty in measuring the drilled hole diameters using an optical microscope, due to the deposited spatter that makes it difficult to clearly identify the hole boundaries.

For each thickness and pulse shape the entrance diameter increased with increasing input energy and pulse width. Knowledge of this relationship can be valuable when drilling many holes in close proximity, as they regularly are in the aerospace industry, as holes drilled too close together can offer an easy crack propagation path, leading to a component ‘unzipping’.

As both the single pulse and multi-pulse entrance diameters increased in a similar way, progressive heating can be discounted as the reason for the diameter increase. However, in both cases the hole side walls would be exposed to flowing molten material for longer, causing more erosion than what would occur in the shorter pulse shapes, meaning that pulse width has a larger impact on entrance diameter than total input energy. The erosion of the side wall could also potentially explain why the thicker samples exhibit larger entrance diameters also, as the material on the inside of the hole near the hole entrance would have a higher volume of molten material flowing over it than in the thinner samples, increasing the magnitude of the melt erosion effect, as investigated by Low et al. [17]. Comparing single pulse, multi-pulse and LRUP shapes appears to have no effect on the magnitude of the entrance diameter.

There is no single aim for a taper angle with regards to hole quality. The drilled hole taper angle can have differing effects on fluid flow dynamics, so the aim changes with component requirements, so it is important to understand the effects of different pulse shapes on the taper angle, instead of aiming to maximise a positive, negative or zero taper angle. LRUP consistently produced holes with the largest taper angle. This could be due to the initial low power section of the pulse shape producing a large, when compared to the start of the single and multi-pulse pulses, and wide non-ejected melt pool that is then later ejected by the higher power section. Li et al. [18] was able to manipulate SPDPC to control the taper angle of the holes. An interesting investigation would be to study the effect of different LRUP shape geometries on the taper angle of drilled holes. Single and multi-pulse pulses exhibited similar, but lower, taper angles when compared to the LRUP. It can be observed that all pulse shapes demonstrated larger taper angles for longer pulse widths and decreasing laser power, potentially for the same reason as discussed for why the entrance diameter also increases.

The largest source of error for this investigation is believed to be the measuring of the entrance and exit diameters of the drilled holes due to the spatter than forms on the surfaces of the steel. To mitigate this, ten holes were drilled for each parameter set and a standard deviation was calculated and defined as the hole variance.

5 CONCLUSIONS

The following conclusions can be drawn from the present study.

- Pulse shaping has been successfully used to increase the drilling efficiency of a 2kW fibre laser.
- It was found that on average the single pulse produced holes with the smallest entrance variation and recast layer thickness. As these are the most critical hole qualities, it is concluded that pulse shaping does not enhance the capabilities of laser drilling with regards to hole quality.
- The multi-pulse pulse shape was the most efficient pulse shape in terms of energy required for breakthrough and volume removed per unit energy.
- The decrease in energy required for breakthrough for a multi-pulse compared to a single pulse increases with decreasing material thickness.
- Due to the presence of a recast layer, drilling efficiency can still be improved further.
- Volume of material removed per unit energy increases with material thickness.
- Taper angle increases with mild sheet steel thickness, regardless of pulse shape.

- Drilling efficiency with regards to minimum energy required for breakthrough and volume removed per unit input energy decreases as the laser power used decreases.

Pulse width and power have a larger effect on the drilled hole entrance diameters than the single pulse, multi-pulse and LRUP shapes.

ACKNOWLEDGEMENTS

Thanks to Mr Stuart Branston for his help and assistance with the operation of the laser throughout the investigation.

NOMENCLATURE

D	entrance diameter (m)
d	exit diameter (m)
t	sample thickness (m)
θ	taper angle (degrees)

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TABLE 1
Results summary - Minimum powers required to achieve 100% breakthrough for 10 holes for a single pulse of a given pulse width and mild steel sheet thickness.

	Pulse width (ms)		
Mild Steel Sheet Thickness (mm)	4	6	25
0.8	525W	463W	325W
1.2	838W	713W	475W
2	1625W	1363W	788W

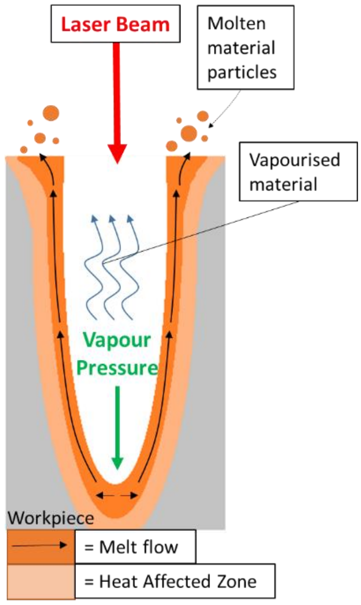
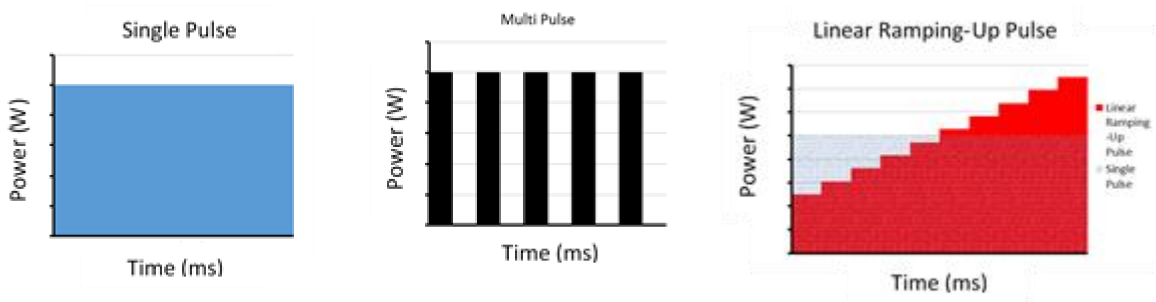


FIGURE 1
A schematic representing the material removal mechanism during the millisecond laser drilling of mild steel.



a b c

FIGURE 2
Schematic representations of the pulse shapes. a) Single Pulse, b) Multi-Pulse, c) Linear Ramping-Up Pulse with a superimposed single pulse schematic.

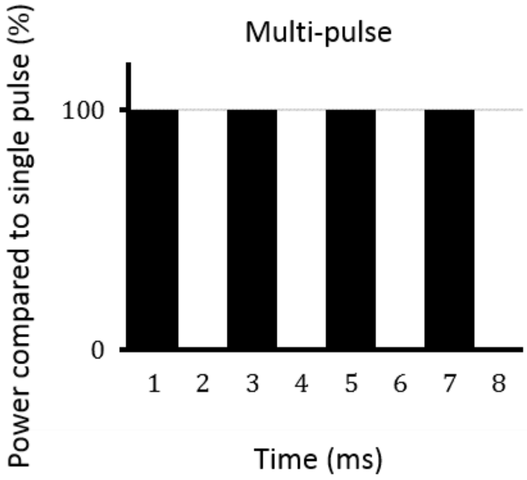


FIGURE 3
Multi-Pulse schematic used in this study. Constant power pulsed at a 1 Hz frequency with equal 'on' and 'off' pulse widths of 1 ms.

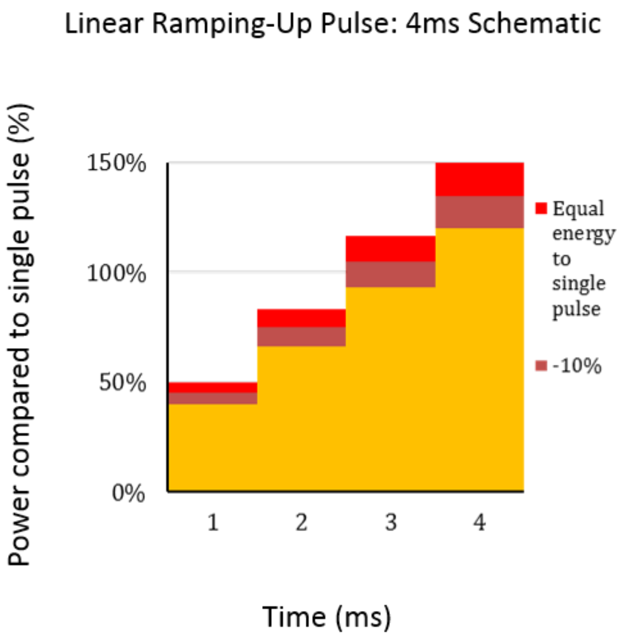
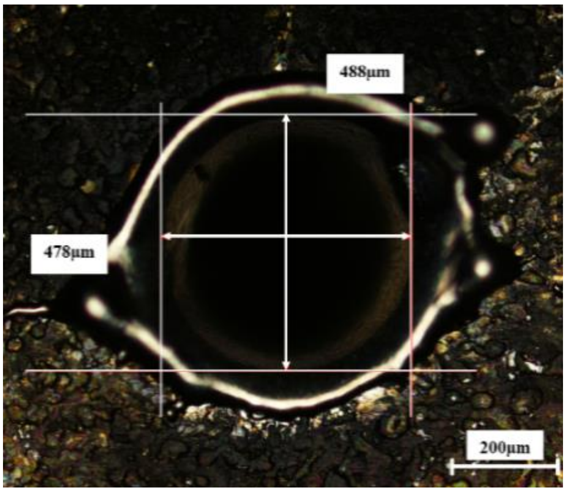
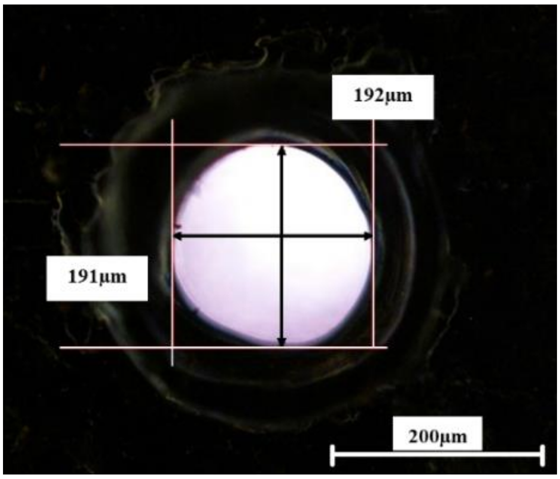


FIGURE 4
Linear Ramping-Up Pulse schematic showing how the energy is decreased in 10% increments whilst maintaining the same geometry.





a b

FIGURE 5
Optical micrographs of hole drilled with single Pulse, 475W, 6ms. Entrance (a) and exit (b) hole diameter measurements.

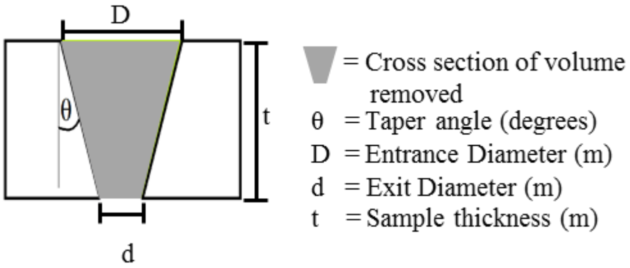


FIGURE 6
Schematic of a laser drilled hole cross-section.

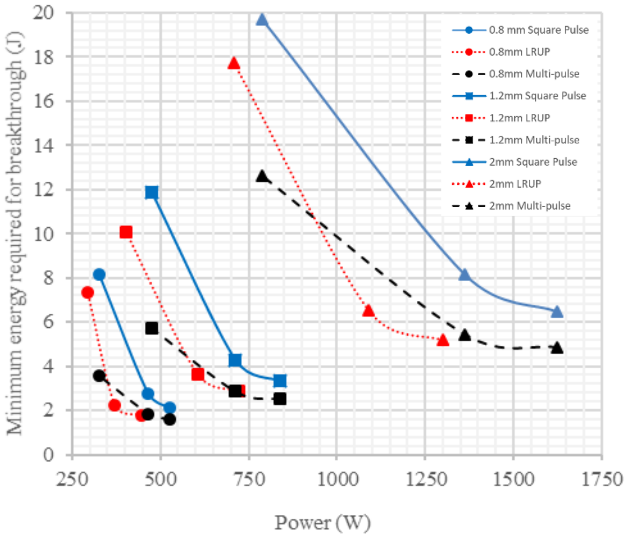


FIGURE 7
The minimum energy required for breakthrough for given drilling parameters.

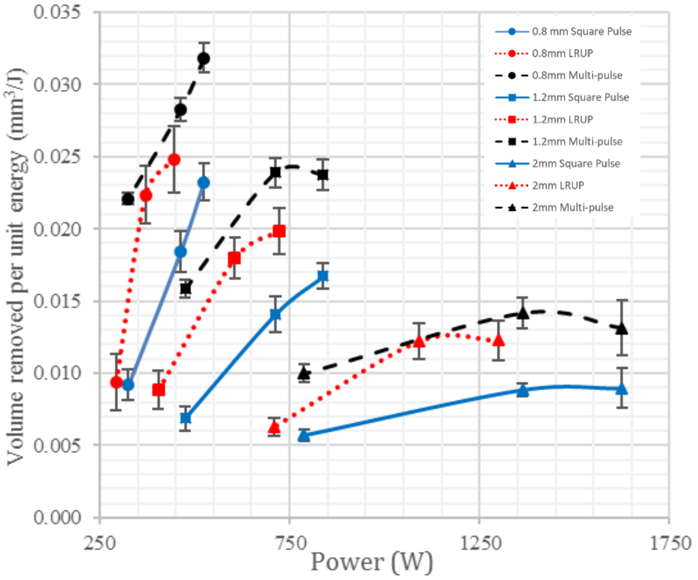


FIGURE 8
The volume removed per unit input energy for given drilling parameters at the breakthrough threshold.

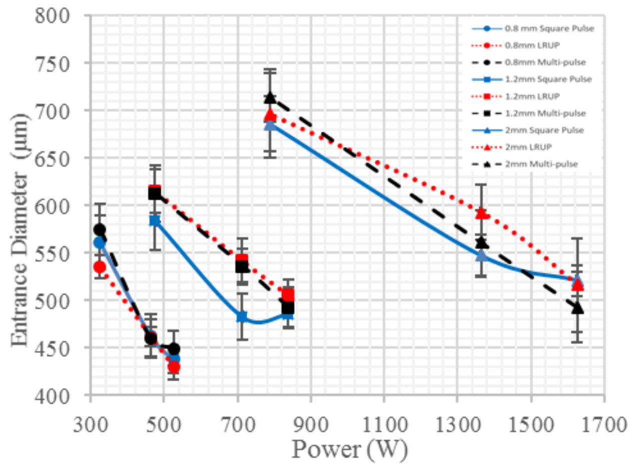


FIGURE 9
Measured entrance diameters shown as a function of drilling parameters, error bars show the standard deviation.

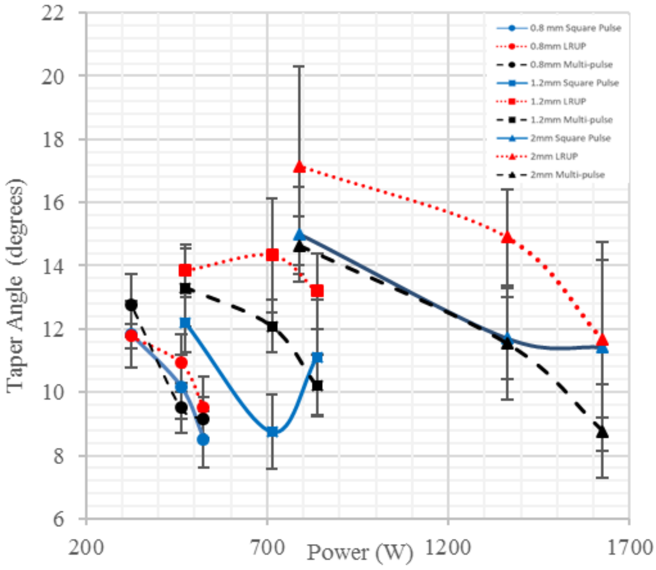


FIGURE 10
Taper angle as a function of drilling parameters, error bars show the standard deviation.

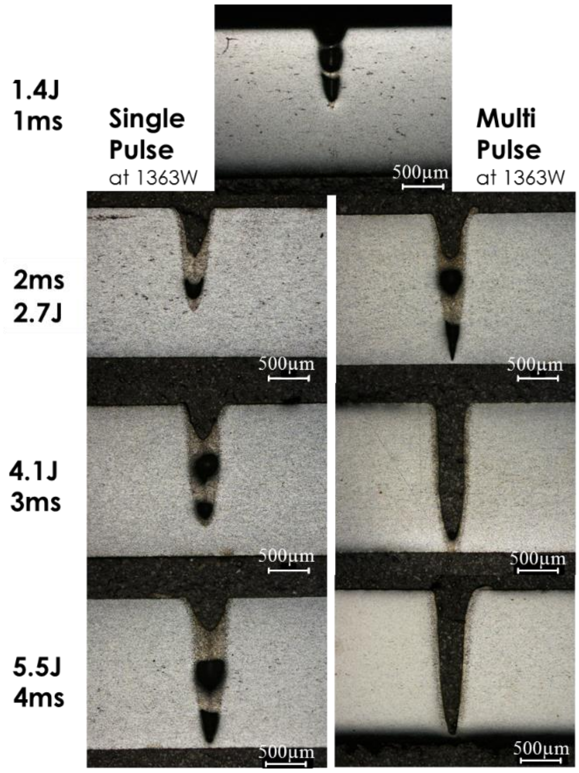


FIGURE 11
Optical micrographs showing the hole progression for a single pulse and a multi-pulse at stages of equal input energy at the same power. The multi pulse is observed to achieve breakthrough before the single pulse.

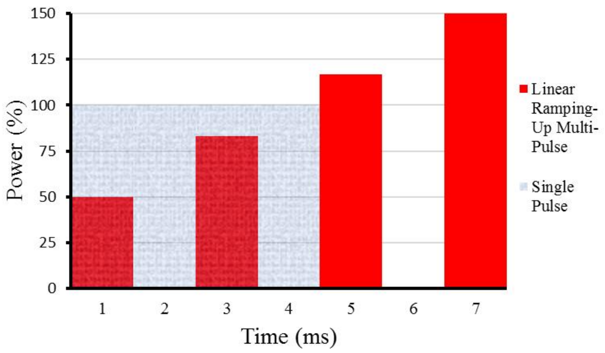


FIGURE 12
A schematic of a linear ramping-up multi-pulse used to investigate the linear ramping-up pulse. A single pulse overlay is present for comparison.