

DEEP ENGRAVING OF METALS FOR THE AUTOMOTIVE SECTOR USING HIGH AVERAGE POWER DIODE PUMPED SOLID STATE LASERS

Paper #1901

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Abstract/Manuscript

This paper investigates deep engraving of steel and aluminium by laser. By examination of laser and scanner parameters an optimal balance between feature quality and processing speed is achieved. Material removal rates of up to 20 mm³/min for steel and 40 mm³/min for aluminium are demonstrated up to a maximum engraved depth of 1mm. The effect of feature shape and feature size on the process is also investigated.

Deep engraving of metals using latest generation Q-switched diode pumped solid-state lasers is a developing application across a range of market sectors. One key use is in creating indelible laser milled marks on high value components in the automotive industry for security reasons. These marks must be resistant to tampering, visible after subsequent painting, difficult to reproduce and not affecting the working properties of the component.

Introduction

Q-switched DPSS lasers are particularly suited to laser milling since each nanosecond laser pulse can easily achieve the power density required to cause ablation of the target material [1,2]. The high repetition rate of this type of laser allows accurate and controlled material removal at rates which are industrially attractive. The ablation process forms the basis of many industrial applications and a subset of these are high speed milling applications. High speed laser milling has been developed from in-house laser milling trials and certain parameters have been identified for optimisation.

Milling trials

Laser milling trials were performed on samples of aluminium grade 5251 (NS4) and stainless steel grade 316. The results of these trials are presented in the following section.

The laser milling tests used a Starlase AO2 Nd:YAG Q-switched DPSSL at the fundamental wavelength of 1064 nm. This pulsed laser offers average powers up to

220 W at a range of repetition rates and pulse durations between 3 to 50 kHz and 30 to 200 ns respectively. The output beam power was varied using a proprietary attenuator unit, and then collimated with a Galilean telescope and directed into a galvanometric scanner (ScanLab HurryScan25). During the course of the tests the scanner was fitted with an 80 mm focal length f-theta telecentric objective lens with a working target area of 25 mm × 25 mm which produced at best focus a Ø160 µm focal spot. All of the processing work was performed in air at standard atmospheric conditions and no gas assist was used.

Samples were analysed using a Nikon LM1500 optical microscope with a PC interface via a 12 megapixel camera into Lucia G software. This software allowed microscopic measurements to be made against a Nikon standard. Depth measurements were made using a Mitutoyo dial gauge.

Table 1: Laser pulse characteristics for milling trials

Laser Rep. Rate [kHz]	Pulse Irradiance [W/cm ²]	Output Power [W]	Pulse Energy [mJ]	Pulse Width [ns]
10	$1.5 \cdot 10^9$	179	18	59
20	$5.1 \cdot 10^8$	192	9.6	94
30	$2.4 \cdot 10^8$	201	6.7	137
40	$1.5 \cdot 10^8$	214	5.4	172
50	$1.1 \cdot 10^8$	222	4.4	204

The ablation characteristics of both materials were investigated by a matrix of tests which varied specific laser parameters. And measured material removal rates. Two parameters were changed to produce the matrix: laser pulse repetition rate (prf) and laser output power. The laser maximum output for varying laser repetition rates is shown in Table 1. For each test in the matrix the laser pulse width, irradiance, and ablation

time were recorded. Ablation depth measurements were used to calculate the volume of material removed and removal rate.

Laser Milling Results for Aluminium

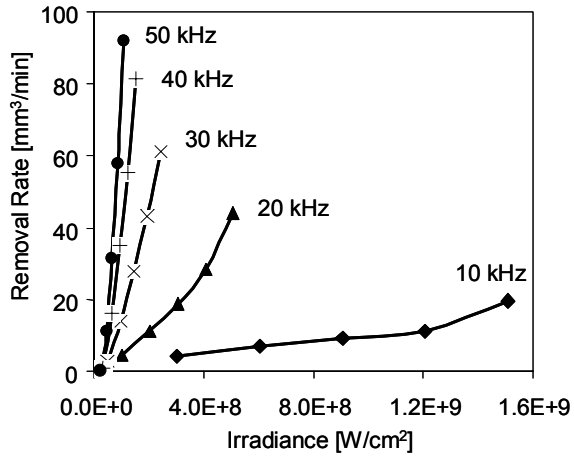


Figure 1. Removal rate of aluminium alloy as a function of pulse irradiance and laser pulse repetition rate.

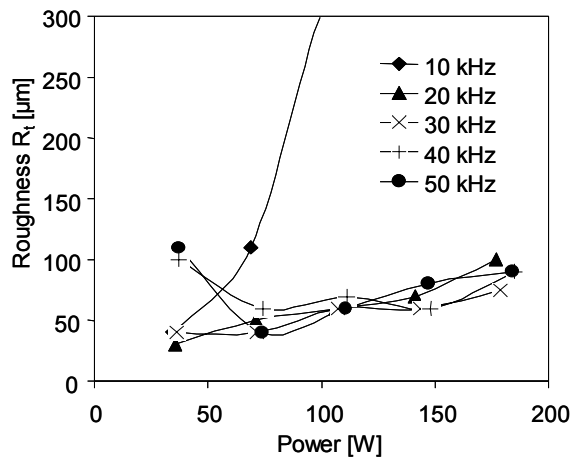


Figure 2. Roughness measurements for aluminium

Figure 1 shows the results of the aluminium laser milling trials. It can be seen that as the repetition rate increases, the removal significantly increases reaching over 90 mm³/min. Note that, for a constant pulse frequency, the removal rate increases with irradiance. However, at 10 kHz, the curve slope is relatively small, and the reason for this will be explained in the next section.

One of the measures of the quality of the laser milling is the variation in base depth, which will be referred to in this paper as roughness (R_a). The results for the roughness measurements for the milling trials are shown in Figure 2. It can be seen from this figure that

roughness is approximately proportional to average laser power with two exceptions: at low laser pulse frequency, 10 kHz, where the roughness reaches 500 μm (not shown in the Figure), and for high repetition rates (40 and 50 kHz) at low power.

Laser Milling Results for Stainless Steel

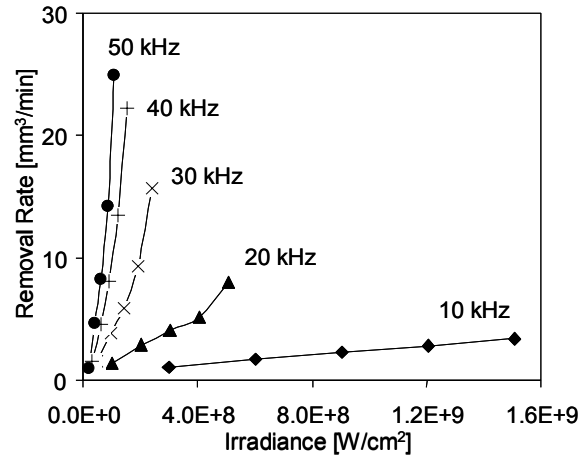


Figure 3. Removal rate of stainless steel as a function of pulse irradiance and laser pulse repetition rate.

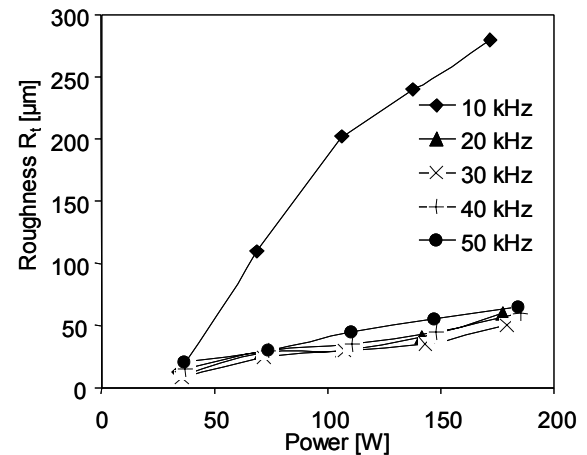


Figure 4. Roughness measurements for stainless steel

Figure 3 shows the results of the stainless steel laser milling trials. The removal rate is smaller than for aluminium alloy, but still very attractive for many industrial processes. Figure 4 shows the roughness measurements for these tests, and it can be seen that although the roughness levels are lower, the general trends are the same as for aluminium, i.e. high roughness at 10 kHz, otherwise increasing with average power. Note that roughness does not increase at high prf at low power, whereas with Al alloy it does increase.

Discussion

For both materials the removal rate increases with laser pulse repetition rate. One of the reasons for this trend is that the average laser power increases with pulse frequency, but this alone can increase the removal rate by ~20%. In order to explain this behaviour, a numerical procedure was developed [3], which shows that the surface temperature plays a very important role in laser milling. It was assumed that every laser pulse act in two stages, first bringing the material temperature up to vaporisation point, and second stage vaporising material. The first part of the pulse, although very important, does not contribute directly to material removal. Thus, for a given pulse duration, higher removal rates will be achieved if the vaporisation stage is extended and heating stage reduced. The time to vaporisation can be calculated as:

$$t_B = \frac{\pi k \rho c_p (T_B - T_0)^2}{4 I_a^2} \quad (1)$$

Where: k – thermal conductivity
 ρ – density
 c_p – specific heat
 I_a – absorbed irradiance
 T_B – vaporisation temperature
 T_0 – initial temperature

The time to vaporisation is proportional to the square of temperature difference, that is the higher the substrate initial temperature, the shorter time to vaporisation and more laser pulse energy is being used to actually remove material rather than just heat it up. This formula can be used to calculate ablation threshold, as there will be no removal if the time to vaporisation, t_b , is longer than the actual laser pulse.

One way to achieve high removal rate is to increase substrate temperature. This can be achieved by overlapping laser pulses so that several consecutive laser pulses will irradiate every point on the surface. Since residual heat from one pulse will cause the surface temperature to be significantly higher when the next pulse arrives, the average surface temperature will rise considerably, it can even be higher than melting temperature; with certain conditions a melt pool is created and material removal is very violent and fast, but the quality is poor and there is thermal damage to the underlying layers.

The surface temperature depends on both material properties and process parameters, which include pulse overlap, pulse repetition frequency and irradiance. These parameters can be easily changed to achieve desired results in terms of material removal rate and

surface roughness. The figures below illustrate how the surface temperature is influenced by these parameters.

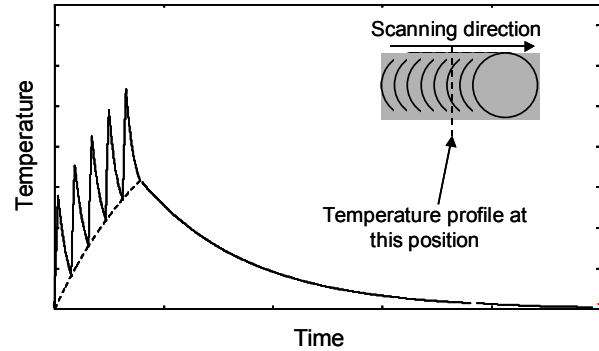


Figure 5. Temperature profile at the surface with 80% pulse overlap. Each point is irradiated by 5 laser pulses. Note that this graph is not in scale.

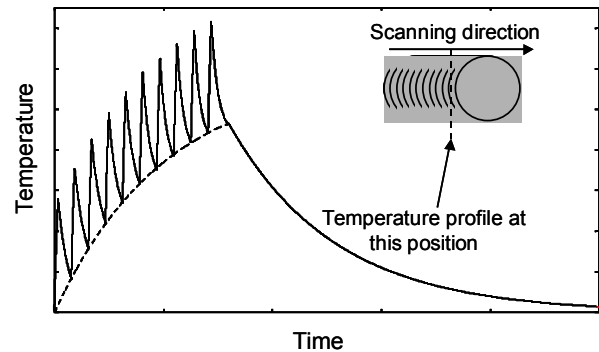


Figure 6. Temperature profile at the surface with 90% overlap. Each point is irradiated by 10 laser pulses. The laser pulse frequency is the same as in Figure 5.

As shown in Figures 5 and 6, each laser pulse will cause a relatively fast surface temperature rise, and much slower cooling. At the beginning of the next laser pulse the surface temperature will be higher, and it will rise with every laser pulse irradiating the same point. Larger overlap will create higher surface temperature, as there will be more pulses hitting each unit area of the target. Note that this process is not linear, as heat flux is higher at higher temperature difference. Effectively, the material removal rate will rise with overlap, but only to a point where the laser beam creates a groove so deep that molten material cannot escape, and is redeposited back onto substrate.

Increasing laser pulse repetition rate at constant pulse duration and irradiance will also increase the substrate temperature, as the cooling time after each laser pulse will be shorter. However, pulses of q-switched solid-state lasers become longer and less energetic with increasing prf. It is thus arguable whether or not the temperature will rise while increasing the pulse

frequency. Nonetheless the removal rate for both materials does rapidly increase with prf (Figures 1 and 3), so this could be indication of material temperature increase, especially that reflectivity of metals decreases with temperature [4]. This increases laser energy coupling into material and further increases the material removal rate.

As mentioned above, the pulse energy decreases and pulse duration increases with frequency, so the irradiance decreases even more quickly. Depending on the focal spot size, the irradiance may be below ablation threshold, especially in the case of highly reflective metals such as aluminium. Surface roughness and removal rate results support this theory. Figure 2 shows that the aluminium alloy roughness increases at 40 and 50 kHz and at low laser power. At these conditions the removal rate is small ($<2 \text{ mm}^3/\text{min}$), and it is believed that the surface does not reach vaporisation temperature, except where there is some localised increase in absorption, for example due to surface imperfections.

This is not observed for stainless steel (see Figure 4). Because optical absorption is much higher and thermal diffusivity lower than that of aluminium, the ablation threshold is lower.

Both materials show high base roughness at laser pulse repetition frequency of 10 kHz. At this frequency and used spot size, the irradiance is very high and the laser beam creates a plasma above material surface. This plasma scatters and absorbs the laser beam reducing removal rate. It has also big effect on the surface roughness, but detailed analysis is beyond scope of this paper. The optimum irradiance in terms of material removal rate is $\sim 10^8 \text{ W/cm}^2$ for aluminium and $6 \cdot 10^7 \text{ W/cm}^2$ for stainless steel.

High Speed Laser Milling

The laser milling process has been optimised, maximising the removal speed whilst maintaining a quality level that is sufficient for the applications in hand. This has been achieved by identifying and optimising the following parameters :

Process Efficiency: The ablation process is much more effective at higher repetition rates, and this is shown in Figures 1 and 3. This is valid for both aluminium and stainless steel.

Focal Spot Size: Within limits, smaller focal spot sizes produce a higher removal rate. A comparison was made between two scanner objective lenses, an 80 mm and a 163 mm focal length. The rest of the system was kept the same, and the same pulse overlap was used for

both lenses. It was found that that the 80 mm FL lens produced a removal rate up to 250 % higher than for the 163 mm lens. It was noted that highest removal rate occurred at the same irradiance of about 10^8 W/cm^2 . For 80 mm FL lens this irradiance is can be achieved at 50 kHz prf, while for the 163 mm FL lens (larger spot size) it could be obtained at only 25kHz. This is with the condition that the irradiance was kept below the plasma blocking threshold, where laser-induced absorption waves block the delivery of the beam [1,2].

Pulse Overlap: Pulse overlap can be considered in 2 dimensions : pulse to pulse overlap, where each pulse overlays the previous pulse by a certain amount, and scan-line overlap, where lines of pulses (each pulse having a fixed pulse to pulse overlap) overlays adjacent lines of pulses by a certain amount. Note that the pulse to pulse overlap governs the amount of residual heat left in the material between pulses, thus the optimum pulse to pulse overlap tends to be material specific. Experimental milling trials have shown that the optimal pulse to pulse overlap is usually in the region 60 to 90 %, whereas the optimal scan-line overlap is much lower, usually in the region 20 to 50 %.

Scan Path: Optimising the scan path creates the least number of mirror movements which means that there are more laser pulses in a given scan time, which results in a higher material removal rate.

Applications of Laser Milling

High speed engraving

A set of applications have been identified that can be achieved with high speed laser milling. These are applications that have the characteristics described in Table 4.

High speed laser milling has many industrial applications in a wide range of areas. There are many reasons for using this technology, including increased speed, increased security, reduced damage to substrate material and improvement to production processes. Possible applications include not only milling 3D shapes but also barcodes and serial numbers. An example application is shown in Figure 7, which is a sample identification plate. This plate has approximately 90 mm^3 of material removed during the milling process, which took 2 minutes to engrave. A variety of depths are achieved between 200 and $800 \mu\text{m}$, which can be seen in the figure as a variation in the shade of the milled areas.

Table 2. Characteristics of High Speed Milling Applications

Parameter	Comment
Removal Rate	As high as possible whilst maintaining a reasonable base roughness
Depth	Typically up to 1 mm deep. Deeper work possible with active focus control
Quality	Some surface dress allowed. Base variation 50 to 100 μm (or 10% of overall depth). Generally quality level sufficient for application in order to maximise removal rate.
Resolution	Comparable with focal spot size, typically $\text{\O}200 \mu\text{m}$

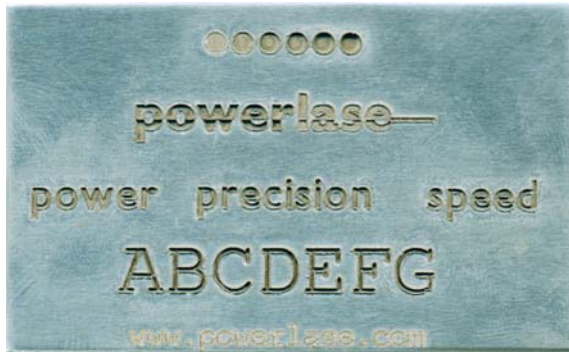


Figure 7. Example of High Speed Laser Engraving

Laser Engraving of Barcodes

Preliminary trials were performed to investigate whether laser engraving could be used to generate barcodes on bare uncoated aluminium. In order for a laser engraved barcode to be readable using a standard industrial barcode scanner, there has to be enough contrast for the “black” and “white” sections of the barcode to be identified. These trials attempted to determine the conditions that allowed a laser engraved barcode to be readable.

How Scanners Work

A simple schematic of a barcode scanner is shown in Figure 8 [5]. The scanner contains a laser diode which is swept across the barcode typically by means of a rotating optic. Light scattered from the barcode is

received by the photo-diode, and the information is interpreted by the decoding electronics.

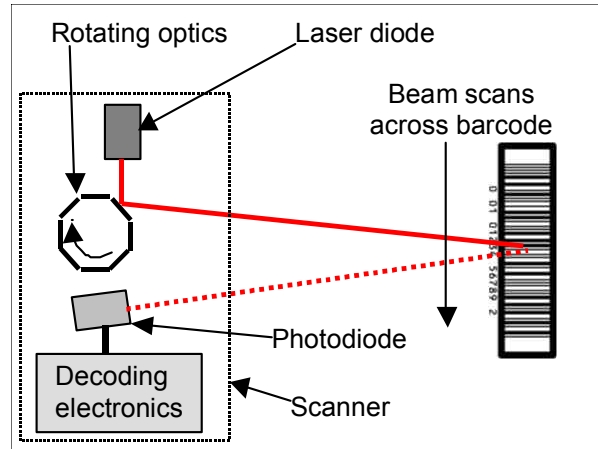


Figure 8 : Barcode scanner operation

The factors that make a bar code readable are: an adequate print contrast between the light and dark bars and having all bar and space dimensions within the tolerances for the symbology. It is also helpful to have sharp bar edges, few or no spots or voids, a smooth surface and clear margins or “quiet zones” at either end of the printed symbol.

Experimental Setup

A set of trials were used to determine whether a barcode engraved on a aluminium plate would be readable with a standard industrial scanner. The readability of any barcode is governed by the scattered light reflected back towards the scanner. Therefore the trial needs to determine this for a typical industrial configuration. The experimental set up is shown in Figure 9.

Note that the light collecting lens had a focal length of 300 mm, and the distance between the laser engraved sample to this lens and the distance from this lens to the photodiode were both set at 600 mm. This lens was put into place to simulate the scanner optics [5].

The laser engraved sample was arranged so that the angle relative to the photodiode could be set at a desired position, and in Figure 9 this angle is shown as θ . Two sets of tests were completed, the first with $\theta = 15^\circ$ and the second with $\theta = 30^\circ$.

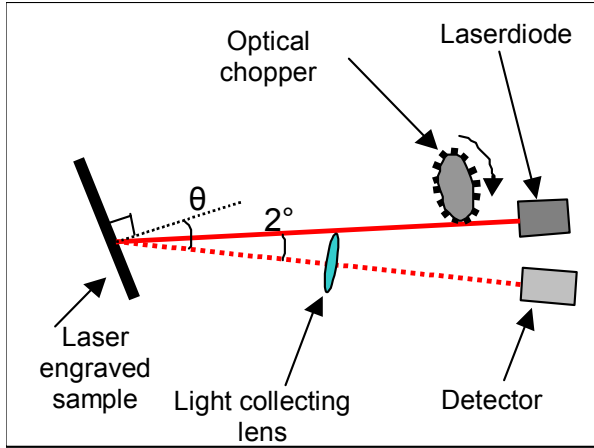


Figure 9: Experimental setup for scatter tests.

Results and Discussion

The laser engraved sample plate used for these trials is shown in Figure 10. It is an uncoated aluminium plate which has been laser engraved with a grid of 2 mm × 2 mm squares. Each square was produced with a single pass and the time to produce a single square was 100 to 400 milliseconds depending on overlap. Typically the depth of any square is 100 to 200 μm. Two parameters are varied within this grid; laser pulse repetition frequency (from 20 kHz to 50 kHz) and overlap (from 75% to 95%)

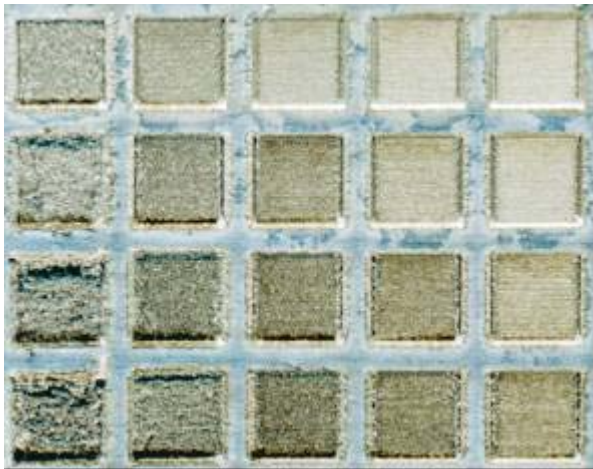


Figure 10 : Laser engraved sample plate

Figures 11 and 12 show the results of the two sets of trials. Note that before each of the sets of trials a piece of white paper was placed at the same angle as the laser engraved sample in order to assess the maximum scatter that could be expected. For the 15° trial this measured 14 on the “Reflected Scatter” scale, and for the 30° trial it measured 12.

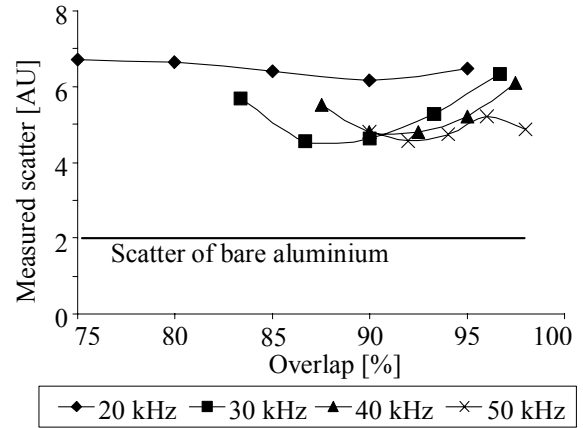


Figure 11. Results of reflected scatter trials with engraved sample set at 30°.

For the 30° trial there is less scatter with bare aluminium than for the engraved samples. The difference between the scatter of the bare aluminium and the engraved samples is quite clear. However, within the engraved samples there is some difference in scatter but not a great deal. It was noted that the highest measured scatter was obtained with the set of 20 kHz squares, and the result was similar across the range of overlap.

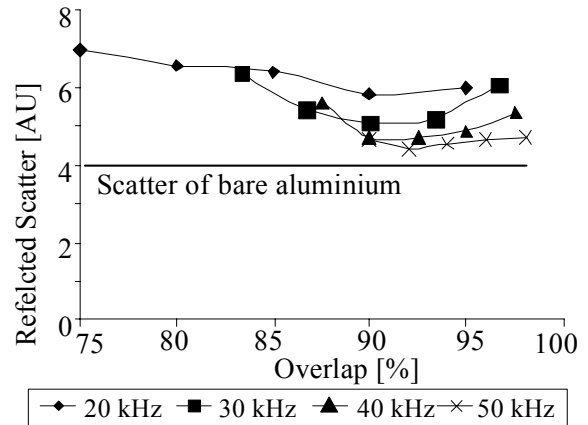


Figure 12. Results of reflected scatter trials with engraved sample plate set at 15°

For the 15° trial there is also less scatter with bare aluminium, but the difference between the engraved and bare aluminium is harder to discern. Similarly to the 30° trials, the squares engraved at 20 kHz produced the best scatter measurements.

Therefore, for a laser engraved barcode that has the clearest difference between the “black” and “white” parts of the barcode, these results indicate that a good distinction could be made using bare aluminium and

single pass engraving at 20 kHz, using 75% overlap as this produces the fastest results. Note that if the natural finish of the aluminium is not sufficient to produce the required scatter, it is possible to create an improvement by laser polishing.

Conclusions

Q-switched DPSS lasers can be used to enhance many different applications, and this paper reports on two such applications that require high removal rates and surface modification. The material removal rates achieved, which are 90 mm³/min for aluminium alloy and 25 mm³/min for stainless steel, are very attractive for industrial applications.

High Speed Laser Milling has been developed through the identification and optimisation of particular laser parameters that enable the process to operate at high removal rates. A set of applicable areas for industrial use have been indicated, and one application of this milling method has been shown.

The surface roughness can be controlled during the milling process, and this can be used to change optical properties of the target. This paper show that it is possible to achieve good contrast which is needed for

barcode marking on bare metals. Further experiments are now in progress to make this process industrially viable.

References

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