Laser Milling – A Practical Industrial Solution for Machining a Wide Variety of Materials

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Abstract

Laser milling of diverse materials has been demonstrated with short pulse lasers ranging from microsecond to femtosecond pulse durations, and with wavelengths from the far infrared to vacuum ultra-violet. In all cases a balance between quality, throughput and cost of ownership must be struck in order to determine commercial relevance. Latest generation Q-switched Diode Pumped Solid State Lasers offer the potential to enable the industrial uptake of laser milling for a wide variety of materials including aerospace alloys, thermal barrier coatings, tool steels, diamond and diamond substitutes. This paper will investigate these practical applications of laser milling with reference to comparative laser and non-laser processes.

Keywords: laser, q-switched, diode pumped, milling, machining, ablation, nanosecond, steel, aerospace, diamond

1. Introduction

The field of laser milling is extremely diverse as virtually all commercially available high power lasers have applications for which they are particularly suited. This suitability is a function of laser wavelength, pulse duration, required feature size, material properties, output power and critically process rate and cost-of-ownership. It is necessary to weigh up alternatives in terms of acceptable cost, productivity and quality when investigating laser milling as a manufacturing technique both in terms of the different laser sources available as well as competing conventional techniques.

This paper provides a brief overview of laser milling from the point of view of the different laser sources available and their benefits and shortcomings. It also details some of the latest laser milling achievements using high power Q-Switched Diode Pumped Solid State Lasers (DPSSL).

2. Laser Sources & Their Process Characteristics

There are a wide range of laser sources available which are suitable for laser milling. Each specific application and material dictates which is most appropriate. The two key elements in laser choice are wavelength – from far infrared (IR) to deep Ultra-Violet (UV) – and pulse duration – from continuous wave (CW) to femtosecond (fs). These elements are key to the success of a milling application, and there are trade offs to be considered which are discussed below.

2.1 Wavelength

High power industrial lasers suitable for milling have a wide spectrum of wavelengths to choose from. The two most common are CO_2 in the Far IR and Nd:YAG in the Near Infra-Red. Ti:Sapphire lasers also lase in the Near Infra-Red, but this medium is used to create fs pulses where the wavelength is of less significance. In the visible there are two alternatives Copper Vapour Lasers (Cu:Vap) and 2nd harmonic Nd:YAG. In the UV range, 3rd and 4th harmonic Nd:YAG lasers offer Near and Deep UV; whilst Excimer lasers can produce a wide range of UV wavelengths from Near UV to Vacuum UV.

As can be seen in table 1, a general trend is less available power at shorter wavelengths. Excimer lasers offer relatively high outputs in the UV, but are complicated lasers that use Halide gases particularly F_2, these present serious safety concerns as well as lifetime issues for the cavity containing such corrosive elements. Also, Excimer lasers produce high M^2 asymmetric beams due to cavity configuration and excitation methods – this requires subsequent homogenisation and masking in the optical train for effective use in milling. As a consequence the laser industry is moving to the use of frequency converted solid-state lasers to achieve UV wavelengths.

Efficiency is a key component in cost-of ownership, typical wall plug efficiency for the following lasers would be; CO2 12%, Nd:YAG (DPSSL) 12%, 2nd Harmonic Nd:YAG 6%, 4th Harmonic Nd:YAG 3% and KrF Excimer 0.5% [5,6]. Therefore it is clear that shorter wavelengths are more costly to achieve and offer less available average power for processing. However, for many applications shorter wavelength laser light is essential to achieve the required results. There are three reasons for this, detailed in the subsequent sections.

Table 1 Typical laser characteristics [1,2,3 & 4]

Laser Type	Wavelength (nm)	Medium	Typical Pulse Duration	Typical Average Power (W)	Notes
			IR		
CO2	10600	Gas	CW or 100s ms	100-8000	Electrically Excited
Nd:YAG	1064	Solid state	CW	100-4000	DPSSL
			1-0.1ms	200-600	Flash lamp pumped
			5-200ns	10-450	DPSSL Q-switched
Ti:Sapphire	780	Solid State	≈100 fs	2	Mode-locked regenerative amplifier
			Visible		
Cu:Vap	578, 511	Metal Vapour	15-60ns	20-100	High temperature cavity
2nd Harmonic Nd:YAG	532	Solid State	5-100ns	3-90	DPSSL Q-switched
			UV		
3rd Harmonic Nd:YAG	355	Solid State	<50ns	2-7	DPSSL Q-switched
XeCl	308	Excimer (Gas)	15-30ns	200	Hazardous gases
4th Harmonic Nd:YAG	266	Solid State	<25ns	2	DPSSL Q-switched
KrF	248	Excimer (Gas)	15-30ns	180	Hazardous gases
ArF	193	Excimer (Gas)	15-30ns	<100	Hazardous gases
F_2	157	Excimer (Gas)	15-30ns	20	Hazardous gases

2.1.1 Feature Size

Laser wavelength affects the size of the spot that the laser beam can be focussed down too. This spot has to be small enough that the desired feature size can be achieved during laser milling. The theoretical spot size achievable from a given laser can be calculated from the well-known equation below.

$$d_{min} = \frac{4M^2 f\lambda}{\pi D_L} \qquad (1)$$

Where d_{min} = focussed spot diameter, M^2 = beam quality factor relative to a perfect Gaussian distribution of '1', f = lens focal length, λ = laser wavelength and D_L = diameter of beam at lens. Distribution taken as $1/e^2$.

As can be seen $d_{min} \propto \lambda$. Therefore the shorter the wavelength, the smaller the achievable spot and therefore feature size, illustrated in table 2.

Table 2 Example of achievable spot size for different wavelengths

Laser Type	CO2	Nd:YAG	2nd Harmonic Nd:YAG	4th Harmonic Nd:YAG
Wavelength (nm)	10600	1064	532	266
Comparative Spot Size (µm)	175	17.6	8.8	4.4

Table 2 is based on a near perfect laser M2=1.3, a 10mm diameter collimated incident beam at a lens of 100mm focal length

2.1.2 Material Reflectivity

All materials have different reflectivity at different wavelengths, depending on their atomic structure. The process by which photons are absorbed by electrons in a material is called the inverse bremsstrahlung effect [7]. More efficient processing will take place at laser wavelengths that absorb strongly for a given material, the energy coupling more usefully to lead to material removal. Metals, for instance, are highly reflective at longer wavelengths due to their free electrons. This may make it more efficient to use shorter wavelength lasers for milling steels, for instance. Non-conductors and semi-conductors display complex absorption profiles due to their different intermolecular vibration states and bond state energy transitions at higher photon energies. Therefore, if possible, it is desirable to choose a laser with a strongly absorbing wavelength to process such materials.

Table 3 clearly shows that for metals, at shorter wavelengths, reflectivity decreases. The effect is particularly marked for Copper, a highly conductive metal. Silicon has a more complex reflection profile with no progressive trend.

The subject of laser reflectivity in materials is highly complex; being a function not only of material properties, but also surface roughness, surface oxidation, temperature, angle of incidence and changing workpiece topography, see [8] for a more comprehensive discussion.

Table 3 Example material reflectivity (%) at standard laser wavelengths at ambient temperature and normal incidence[6,7,8,9]

	Wavelength (nm)			
Material	*10600*	*1064*	*532*	*355*
Iron	88	75	50	40
Copper	99	97	61	42
Nickel	95	73	60	43
Silicon	75	30	42	60

2.1.3 Energy Absorption Mechanism

Use of shorter wavelengths of light tend towards less thermal mechanisms of material removal. There are two reasons for this; the penetration depth of the laser light and the potential for direct photochemical machining with high energy therefore short wavelength photons. Penetration depth for a material is a function of the laser wavelength and its extinction coefficient.

$$W = \frac{\lambda}{4\pi k} \qquad (2)$$

Where W = penetration depth, λ = laser wavelength and k = extinction coefficient [9].

Therefore at shorter wavelengths, the laser energy is absorbed within a smaller volume of material localising the interaction region being heated and therefore reducing the potential for thermal conduction. Thus, if the laser milling application has stringent requirements for low HAZ or recast due to melting then a shorter wavelength laser may be applicable.

This is particularly true for UV lasers and non-metals, where the high photon energies approach the dissociation energies of chemical bonds. This can result in material removal by the photochemical breakdown of covalent bonds – a non-thermal process, which can achieve very fine features and no Heat Affected Zone (HAZ). Table 4 below displays photon energies of different laser wavelengths and dissociation energies of common chemical bonds.

Table 4 Photon energies and dissociation energies of chemical bonds [6,11,12]

Wavelength (nm) & Photon Energy (eV)				Bond Dissociation Energy (eV)		
10600	1064	532	248	C-C	C-N	C=C
0.12	1.17	2.33	5.00	3.62	3.04	6.40

2.2 Pulse Duration

The pulse duration of a laser is also key to its suitability for a laser milling application. Industrial lasers are available with pulse durations from CW, 100s ms (10^{-1}s), ms (10^{-3}s), μs (10^{-6}s), ns (10^{-9}s), ps (10^{-12}s) and even fs (10^{-15}s). Great efforts have been made to move to ever-shorter pulse durations, however usually at the expense of average power and increased complexity and cost, see Table 1. By reducing the laser interaction time the thermal load on the workpiece is lowered; which will reduce melting and HAZ. This is described by equation (3) below:

$$D = (4kt)^{1/2} \qquad (3)$$

Where D = thermal penetration depth, k = thermal diffusivity of the material, and t = pulse duration [9].

As pulses shorten the thermal penetration depth will near that of the optical absorption depth, see equation (2) minimising bulk thermal damage. In addition as pulses shorten the power density or irradiance (W/cm^2) for each pulse will rise, this will improve the vaporisation/melt ratio, also reducing thermal damage, as higher irradiance will induce a more rapid phase change. This ratio has been empirically modelled and related to material removal rate for laser milling in the ns regime by Harrison et al [12], although plasma blocking at high irradiances can impede processing.

This relationship is true until pulse durations of 10s of ps are reached [14], after which laser irradiances are so high that a new non-linear material removal mechanism takes hold. This mechanism is called avalanche ionisation, and is a result of high intensity pulses 10^{12} W/cm^2 causing ionisation in the material, the resulting free electrons propagate through the material, causing further ionisation and creating a local plasma, which is rapidly expelled from the workpiece by recoil pressure and ion repulsion. This mechanism take place several orders of magnitude faster than thermal conduction and so thermal effects can be avoided altogether [15].

3. Examples of Laser Milling

From section 2 it is clear that finer, more detailed and higher quality processing is possible using lasers with shorter wavelength and/or shorter pulse durations. Unfortunately this is at the expense of average power and therefore productivity. A balance must be struck between the required tolerances and process rate of the application; and the most appropriate laser source chosen accordingly. Table 5 below details a number of laser milling applications for various lasers.

Table 5 Examples of Laser Milling Applications

Laser	**λ (nm)**	**Power (W)**	**Pulse (ns)**	**Freq. (kHz)**	**Material**	**Removal Rate (mm^3/min)**	**Feature size (µm)**	**Notes**	**Ref**
Far IR & Hybrids									
CO$_2$	10600	$\leq$1000	-	CW	Mild steel	100-1400	200-400	Laser Assisted Vortex Machining (LAVM) – melt removed by dual nozzle turbulent gas flow system	16
CO$_2$ & Nd:YAG	10600 & 1064	44 & 53	-	CW	Alumina Al$_2$O$_3$ (ceramic)	9	400	Hybrid process – YAG causes precise cracking, defocused CO2 propagates cracks. 60µm roughness	17
Near IR, Q-Switched DPSSL									
Nd:YAG	1064	3-90	200+	1-50	Steel	4	40	Use of a Q-switch DPSSL laser to vaporise material, employs a scanning technique with overlapping pulses, analogous to EDM, to remove small craters of material per pulse. Surface quality can be optimised at lower power and material removal rate. Figures of 6µm Rz are obtainable	18
					Copper	3			
					Al	21			
					Brass	12			
					Oxide Ceramics	2			
					Nitride Ceramics	4			
					Carbon	28			
Nd:YAG	1064	<100	100+	1-50	Steel	4-6	100	Same process as previous, but larger spot and feature size. Surface roughness 1µm	19
Visible									
Copper Vapour	511, 578	15	25	10	Stainless steel	0.32	30+	Cu:Vap, results calculated from reference, roughness 20µm at overlap	20
Copper Vapour	511, 578	10-100	50	6.5	Fused silica	0.05	30+	Results derived from single pulse ablation rate & known spot size	21
					CVD Diamond	1.65	30+		
Nd:YAG	532	11	15	10	Silicon	0.24	100+	DPSSL 2nd harmonic	22
UV - DPSSL									
Nd:YAG	355	2.2	15	10	Silicon	0.01	40+	DPSSL 3rd harmonic	22
Nd:YAG	355	5	12	50	Silicon	0.04	20+	DPSSL 3rd harmonic	23
UV - Excimer									
Laser	**λ (nm)**	**Power (W)**	**Pulse (ns)**	**Freq. (kHz)**	**Material**	**Etch Rate* (µm /pulse)**	**Feature size (µm)**	**Notes**	**Ref**
KrF / XeCl	248 / 308	200	>15	<4	Al$_2$O$_3$	0.1	10	Photochemical material removal, surface roughness <1µm	11
					Polymers	1	10		
KrF	248	<200	15-30	0.01-1	Poly carbonate	0.54	3+	Excimer processing is well established and this is a small sample of the many materials that have been examined. Excimers most suit polymer processing, but also non-metallics. Material removal is slow but quality is unsurpassed – no HAZ and surface roughness <0.5µm	21
XeCl	308				Kapton	0.63			
KrF	248				PMMA	4.20			
F$_2$	157				Teflon	0.3			
XeCl	308				Silicon Carbide	0.32			
ArF	193				Fused Silica	0.33			
KrF	248				Silicon	0.32			
Short Pulse – Pico and Femtosecond									
Nd:YAG	1064	1	0.06	0.250	CVD Diamond	0.032	20+	Mode-locked laser, ps pulses but simpler and cheaper than fs lasers	24
Nd:YAG	266	0.5	0.06	0.250	Silicon	1	10+		
Ti: Sapphire	780	1	120fs	1	Steel	0.5	10+	Fs mode-locked regenerative lasers, recast <0.5µm	21

*Excimer processing typically involves illumination of a mask which is then imaged to a workpiece, as a consequence efficiency of material removal is defined as an etch rate/pulse into the substrate; image and mask size vary by application making volumetric comparison difficult. Short pulse milling has also adopted this convention.

It becomes clear by application that as you progress to shorter wavelengths and pulse durations that achievable feature size decreases and that quality increases; but that this is at the expense of material removal rate. It is in fact because the application of energy is so precise for both fs and UV processing – each pulse removing fractions of a µm of material that such resolution and quality can be achieved. Conversely if the commercial imperative behind the application requires higher volume material removal, then longer wavelength, more thermal processing may be more appropriate.

Q-switched DPSSL Nd:YAGs at 1064nm offer a good compromise between feature size, quality and removal rate; offering 10s µm resolution, a few microns roughness and removal rates of several mm^3/min for a wide variety of materials.

4. Use of High Average Power DPSSLs in Laser Milling

In the last few years high average power Q-switched DPSSLs have reached the market. These lasers can offer power levels exceeding 400W at 1064nm; and are extremely versatile tools offering pulse energies up to 60mJ, with pulse duration ranging from 5-200ns and frequencies from 3-50kHz, with tailored M^2 from 1.1 to 27. These lasers are highly applicable to laser milling [25].

Previous work [26] reports milling of the Nickel superalloy Hastalloy X for flow control enhancements for turbine blades in aerospace and power generation markets. It is shown that there is an optimum irradiance (I) at which high volume high quality machining is achieved. This is identified as 4x10^{7}W/cm^2, and attributed to the control of plasma formation to achieve a high Material Removal Rate (MRR) with a high geometric quality.

Figure 1a
I=6.7x10^{8}W/cm^2
MRR=2.5mm^3/min

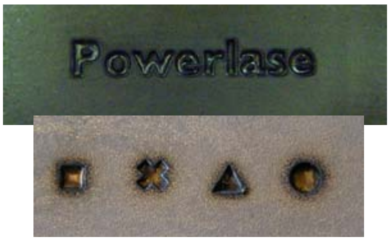

Figure 1b
I=4x10^{7}W/cm^2
MRR=23mm^3/min

Figure 1c
I=1.2x10^{7}W/cm^2
MRR=49.4mm^3/min

Figure 2
Thermal Barrier Coat
(TBC) Milling

Figures 1a-c demonstrate the effect of different irradiances when laser milling Hastalloy X; 1a shows high geometric accuracy but low removal rate, 1c shows poor geometry but a high removal rate and 1b shows an optimal balance. Figure 2 shows milling of TBC; this is particularly attractive for turbine blade manufacture because 3D shapes can be created in TBC coated Nickel superalloys in a single pass (unlike EDM which cannot process the insulating ceramic TBC layer).

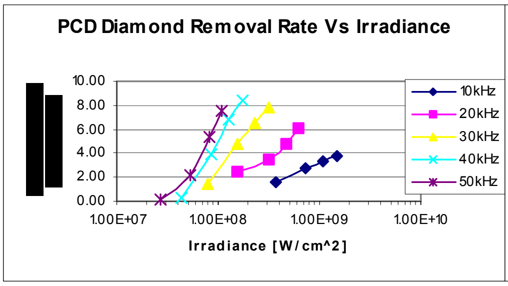

Figure 3: MRR vs. I for PCD

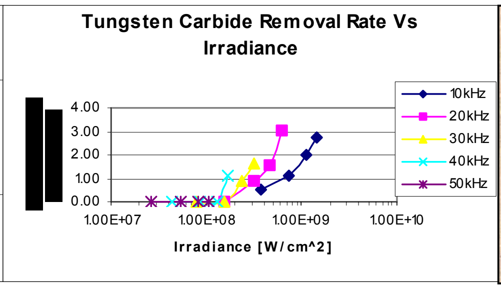

Figure 4: MRR vs. I for WC

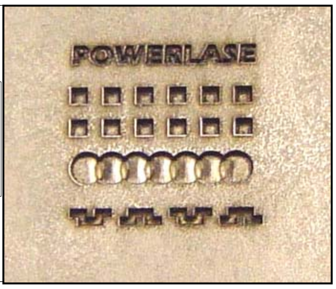

Figure 5: SS Milling

Using the same principle of finding an optimum irradiance the authors have investigated milling Polycrystalline Diamond (PCD) and Tungsten Carbide (WC) both hard materials notoriously difficult to mill by conventional methods.
Figures 3 & 4 show how MRR can be optimised through the ranges of Irradiance available with a given DPSSL. In this case PCD can be milled at 8.5mm^3/min at 40kHz rep. rate with I = 1.7x10^{8}W/cm^2, whilst WC can be milled at 3.05mm^3/min at 20kHz rep. rate with I = 6.2x10^{8}W/cm^2.

Harrison et al have modelled the material removal of WC and stainless steel (SS) [13]. It is found to be possible to achieve a MRR for SS of 11mm^3/min with $I = 9.4 \times 10^7 W/cm^2$. Figure 5 displays features possible in SS. Table 6 displays the latest laser milling parameters achieved with high average power Q-switched DPSSLs.

Table 6: High Average Power DPSSL Laser Milling Applications

Laser	**λ (nm)**	**Power (W)**	**Pulse (ns)**	**Freq. (kHz)**	**Material**	**Removal Rate (mm^3/min)**	**Feature size (µm)**	**Notes**
Nd:YAG	1064	192	55	15	TBC (Ceramic)	>30	150+	No cracking or delamination
		180	120	35	Hastalloy X	23		Recast <40µm
		155	120	40	PCD	8.5		Super hard material
		148	63	20	WC	3.05		High boiling temp 5930°C
		140	160	50	Stainless Steel	11		Achieve a polished finish

5. Conclusion

Laser milling is an extremely versatile process capable of creating complex structures in virtually any material. The critical choice is the right laser for the application. Short pulse and UV lasers offer very fine feature sizes and high quality finishes, but at low processing rates. Longer wavelength and long pulse lasers can offer more rapid processing but at the expense of resolution and quality. A balance must be struck between quality and productivity and the most appropriate laser chosen accordingly. Latest generation high average power Q-switched DPSSLs offer an excellent compromise between quality and material removal rate, and in the work presented shows them to be applicable for milling nickel superalloys, ceramic thermal barrier coatings, steels and hard materials such as diamond and tungsten carbide.

References

[1] J. Ready, LIA Handbook of Laser Materials Processing, 1st Edition, Magnolia Publishing Inc, Ch 1

[2] J. Ready, Industrial Applications of Lasers, 2nd Edition, Academic Press Ltd, Ch3

[3] Coherent website www.coherentinc.com/products/index.cfm

[4] Lambda Physik website www.lambdaphysik.com

[5] W. Steen, Laser Material Processing, 3rd Edition, Springer-Verlag Ltd, Ch1

[6] Unpublished Powerlase internal data

[7] W. Steen, Laser Material Processing, 3rd Edition, Springer-Verlag Ltd, Ch2

[8] J. Ready, Industrial Applications of Lasers, 2nd Edition, Academic Press Ltd, Ch12

[9] J. Ready, LIA Handbook of Laser Materials Processing, 1st Edition, Magnolia Publishing Inc, Ch 5

[10] Liming He, Yoshiharu Namba, Yuji Narita. Wavelength optimisation for machining metals with the harmonic generations of a short pulsed Nd:YAG laser. Journal of Precision Engineering & Nanotechnology (2000) **24** pp245-250

[11] Rainer Paetzel. Comparison Excimer Laser – Solid State Laser. Proceedings of ICALEO 2002.

[12] W.W. Duley, UV Lasers–effects and applications in materials science, 1st Edition, Cambridge University Press, Ch5

[13] P. M Harrison, M Henry, I Henderson and M Brownell. Laser Milling of Metallic and Non-Metallic Substrates in the Nanosecond Regime with Q-Switched Diode Pumped Solid State Lasers, Proceedings of High Power Laser Ablation 2004.

[14] J. Fieret. Observations section. The Industrial Laser User (March 2004) **34**, pp40

[15] Clark MXR website, http://www.cmxr.com/Industrial/Handbook/Introduction.htm

[16] W. O'Neill, M. Vogslanger, A. Elboughey and W. Steen. On the selective removal of steel by laser-assisted vortex machining. Proc Instn Mech Engrs (2000) **Vol 215** Part B, pp1051-1064

[17] Chwan-Huei Tsai and Hong-Wen Chen. Laser Milling of cavity in ceramic substrate by fracture-machining element technique. Journal Materials Processing Technology (2003) **136** pp158-165

[18] Michael Kuhl. From Macro to Micro – the development of laser ablation. Proceedings of ICALEO 2002.

[19] D.T. Pham, S.S. Dimov, P.V. Petkov and S.P. Petkov. Laser Milling. Proc Instn Mech Engrs (2002) **Vol 216** Part B, pp657-666

[20] M. El-Bandrawy et al. Copper vapour laser micromachining of 304 stainless steel. Journal of Laser Applications (2003) **15**, no 2, pp101-106

[21] J. Ready, LIA Handbook of Laser Materials Processing, 1st Edition, Magnolia Publishing Inc, Ch 13

[22] Udo Klotzbach et al. Processing of silicon by Nd:YAG-laser with harmonics generation. Proceedings of ICALEO 2002

[23] Mingwei Li. Effect of laser parameters on semiconductor micromachining using diode pumped solid state lasers. Proceedings of ICALEO 2003

[24] G Raciukaitis et al. Picosecond lasers in micromachining. Proceedings of ICALEO 2002

[25] Powerlase website www.powerlase.com

[26] M. Henry, P. Harrison, I. Henderson, I. Mercer and T. Nowell. Emerging application enabled by high power nanosecond diode pumped solid-state lasers. Proceedings of ICALEO 2003