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Material Processing Applications for Diode Pumped Solid State Lasers

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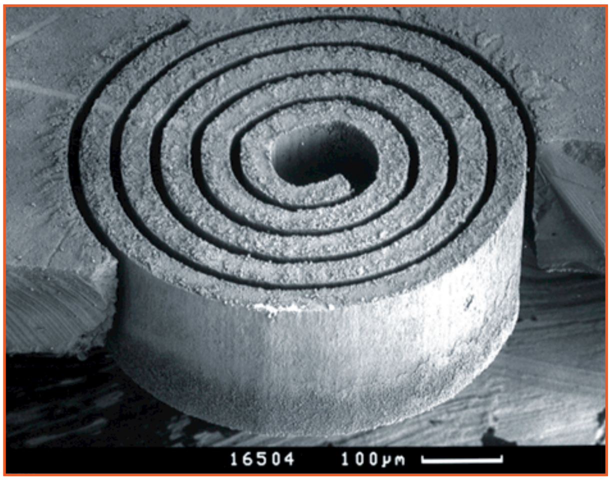

Figure 1: Cuts in 250 μm Al_2O_3 ceramic Sapphire.

Due to their high pulse energy, short pulse duration, and excellent beam quality, diode pumped solid-state lasers are gaining recognition by the industrial community as viable sources for material processing applications such as precision drilling and cutting. An efficient frequency conversion of the fundamental infrared wavelength to the visible and ultra-violet range enables these laser sources to process a broad range of materials, including metals, ceramics, glasses, and plastics. In this paper, a survey of applications for diode pumped solid-state lasers is reviewed to demonstrate their potential application in the field of micro- and precision engineering.

Introduction

The radiation in short pulse, diode pumped solid-state lasers (DPSSL) results in beam and pulse characteristics which make these lasers a versatile tool for precision engineering. With a Gaussian power distribution and a beam quality factor of $M^2=1.1$, the laser beam can be used for nearly diffraction-limited resolution. A pulse peak power in the gigawatt range can be achieved on the sample, using a Lambda Physik DPSS laser with pulse energies in the range of 10 mJ at pulse lengths of 10 ns. The excellent beam quality also guarantees an efficient frequency conversion, providing more than 50% of the fundamental output power for the second harmonic, about 30% for the third harmonic, and about 10% for the fourth harmonic. Metals are ideally processed at wavelengths of 1064 nm and 532 nm, while ceramics, glasses, and polymers are processed with low thermal influence by applying UV-laser radiation. Applications that relate to these laser parameters include precise cutting and drilling, and percussion and trepanning in micro-systems.

Ceramics

For precise machining of ceramics and avoidance of thermal induced cracking, the third and fourth harmonic of a short pulse DPSSL can be used for micro-cutting and micro-drilling. However, due to the lower pulse energies of the fourth harmonic, this wavelength can compete in only a few applications with the third harmonic. The short absorption length of most ceramics, such as Al_2O_3 and AlN, and the high energy density on the sample result in a process which is primarily characterized by spontaneous vaporization, with little heat transfer into the material. The reduction of thermal stress leads to a crack-free cut, allowing structures in the range of only a few microns. As shown in **Figure 1**, structures of 20 μm with cutting gaps between 10 μm and 20 μm can be achieved in a 250 μm thick Al_2O_3 ceramic.

DPSS Laser For 'Real-World' Industrial Applications

Top European industrial research facilities have been solving real world micro-drilling and micromachining applications using the new generation of DPSS-Nd:YAG lasers at the fundamental and harmonic wavelengths. Ceramics, steel and nickel alloys, and diamond can be laser processed using high pulse energies, short pulse duration (low nanosecond range) and shorter wavelengths (532 nm, 355 nm and 266 nm).

High aspect ratio hole drilling (5 μm – 50 μm dia.) with exceptional accuracy (± 0.5 μm roundness) in thick ceramics (up to 1 mm) is discussed in a report from Fraunhofer Institute for Laser Technology (ILT). Results of a high quality helical drilling technique are discussed in a paper presented by IFSW, University of Stuttgart. Laser Zentrum Hannover demonstrates ceramic, stainless steel and plastic component micromachining with short pulse Nd:YAG second, third and fourth harmonics. Lambda Physik USA, Inc. also includes a paper, comparing wavelength (1064 nm, 532 nm and 355 nm) and pulse duration (15 ns) on drilling speeds and hole quality for high aspect ratio drilling of stainless steel and carbon steel.

These articles conclude DPSS lasers with high peak powers, short pulse duration and shorter wavelengths are ideal tools for micromachining hard materials, for industrial component applications.

Metals

The fundamental or the second harmonic wavelengths are usually used for drilling metals. The energy coupling is relatively effective due to the high absorption coefficient. However, absorption of the incident laser radiation in the plasma plume is significant due to the high plasma density that results in high peak intensity of the laser pulses. In this example, the green laser ablation has improved energy coupling because of the reduced absorption of laser induced plasma compared to IR-wavelength. The drilling process can be done either by percussion or trepanning. With ns-pulses, heat-conducting effects cause a melting of the layer beneath the surface where the laser beam is absorbed. The vapor pressure inside the via drives the molten material radially to the perimeter of the hole and then towards the hole entrance where the droplets of liquid material solidify, leading to a formation of a non-reproducible recast layer at the hole's edge. In the case of percussion drilling, the aggregate effect was burr formation on the laser beam entrance side of the hole. Better results are achieved by trepanning the hole with lower pulse energy and a number of repetitions. In this situation, the relative movement between the laser beam and the material avoids the pressure accumulation in a blind via and therefore reduces the burr formation on the surface. In **Figure 2**, a 260 µm diameter trepan-drilled hole in stainless steel is shown.

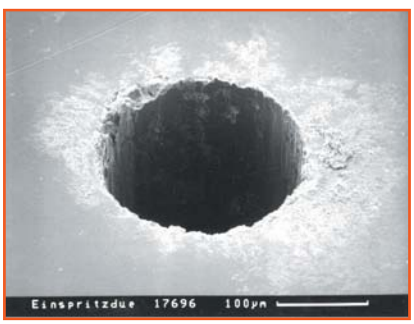

Figure 2: Trepan-drilled in stainless steel.

For processing copper, mainly in the field of printed circuit board drilling, the third harmonic laser has become a widespread tool. The advantage of such a system is the feasibility of machining the copper as well as an underlying dielectric layer. High pulse energies are used to expose the dielectric layer, which will be removed with low energy densities. In case of fiber-reinforced dielectrics, the third harmonic leads to a lower process quality. Here, the combination of the frequency converted DPSSL with a TEA-CO_2 laser for processing the dielectric layer is a promising alternative.

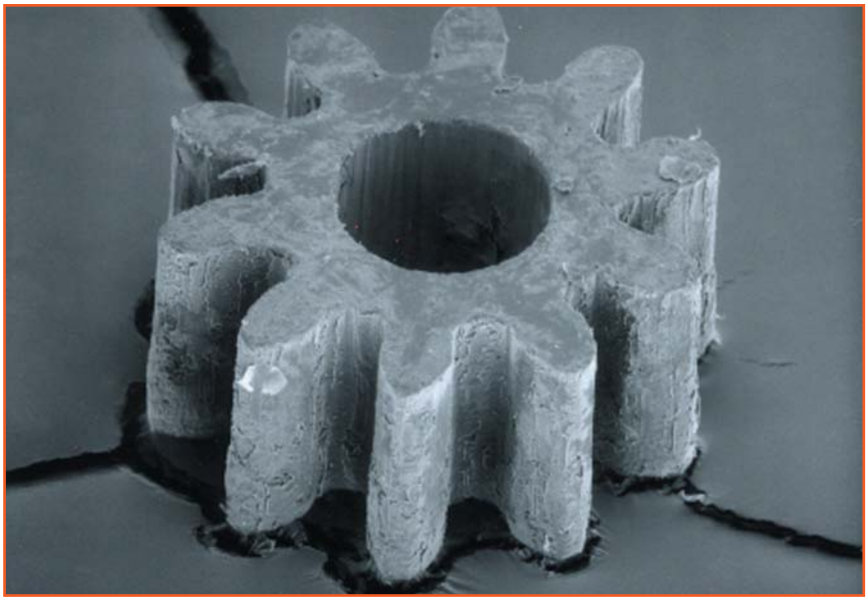

Figure 3: Sapphire gearwheel.

Sapphire

For micro-optical components, e.g. in medical devices, sapphire is a widely used material. Its mechanical properties also expand the list of applications to include the field of micro-mechanical applications such as watch-bearings. By using 355 nm radiation, this transparent brittle material can also be machined at high precision with negligible thermal influence to the component. **Figure 3** shows a sapphire gearwheel used in fluid sensor devices. The quality has been achieved by repeated cutting at low energy densities.

Plastics

With a wide variety of plastics now available, the machinability of these plastics with laser radiation is also varied. However, with the UV-wavelength of 355 nm or 266 nm, many kinds of plastics can be processed. Depending on the material and the wavelength used, the process is either dominated by thermal or photochemical ablation. As the processed catheter in Figure 4 shows, a DPSSL can also be used for medical components that demand high material integrity and purity.

Summary

As explained in this paper, a diode pumped solid-state laser can be applied in various applications for material processing. With wavelengths from the ultra-violet to the near infrared, a broad range of materials like metals, ceramics, and plastics can be machined.

While the feasibility for many applications in the field of micro-technology is discussed, the installation in mass production is primarily determined by economic considerations.

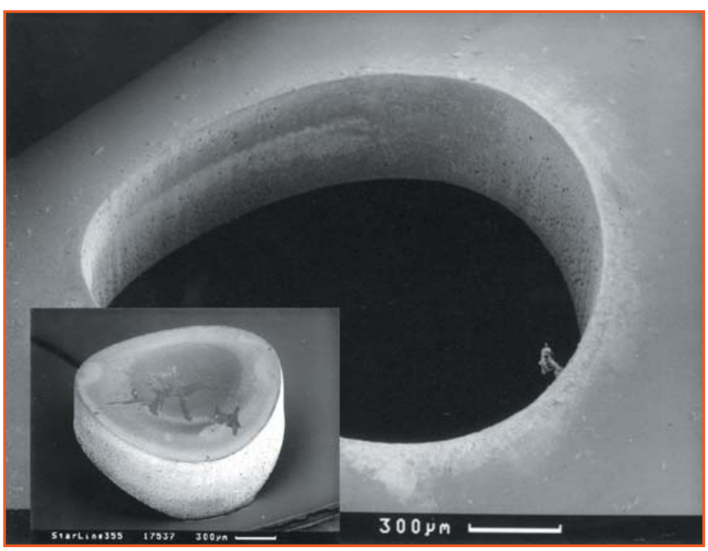

Figure 4: Drilled catheter.

High Accuracy Microdrilling of Steel with Solid-State UV Laser at 10 mm/sec Rate

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Introduction

Multi-kilo Hertz lasers with high brightness and pulse length of 10 to 30 nanoseconds allow high accuracy, high throughput micromachining of steel and ceramics [1 – 3]. This is primarily because most of the material is removed in a vapor state, as opposed to melt ejection dominating long-pulse drilling. In order to maintain high accuracy and minimize the heat affected zone, the laser fluence has to be limited to few 10 J/cm², so as to reduce plasma shielding and post-pulse plasma heating effects [1]. This level of intensity produces a material removal rate of about 1 µm per pulse. Thus, high repetition rate is essential in increasing micromachining speed.

Metal vapor and plasma shielding becomes a major limiting factor in drilling of high aspect ratio holes in thicker, on the order of 1 mm thick, steel. In order to reach the bottom of the deep and narrow hole, the laser beam has to penetrate a 1 mm-thick layer of dense vapor and plasma, whereas the thickness of the plasma layer at the surface is limited to roughly 100 µm during the length of the pulse. Thus, it is desirable to employ all possible means, such as using a shorter wavelength, in order to reduce plasma formation.

In this paper, we investigated wavelength and intensity-dependence of ablation rate achievable with a diode-pumped Q-switched Nd:YAG laser with frequency doubling and tripling. The results indicate that for drilling thick metal samples, using UV output of the laser gives significant advantage due to higher average drilling speed and accuracy, and minimal recast layer.

Experimental

The laser source consisted of side-pumped, q-switched Nd:YAG oscillator (Lambda Physik's Gator) followed by a diode-pumped amplifier. The oscillator produced 15 ns pulses in TEM_{00} beam with an average power of 10 W at 1064 nm and a nominal repetition rate of 10 kHz. The amplifier output was 28 W at the fundamental wavelength, and 15 W and 10 W at the second and third harmonic wavelength correspondingly. Divergence of the amplified beam was within 1.2 times of diffraction limit. All experiments were completed in ambient air. For removing recast layer in some samples, electro-chemical etching was used.

Results and Discussion

Intensity dependence of ablation rate in stainless steel

For 15 ns-long laser pulses, the laser fluence threshold for fast material removal is on the order of 10 J/cm² [1 – 3]. As opposed to photo-chemical reaction in UV laser ablation of organic materials, the material removal mechanism in metals is basically thermal, via fast melting and evaporation. However, the term "ablation" is commonly used to distinguish from the melt ejection mechanism in long pulse drilling. **Fig.1 a – c** shows laser fluence dependence of average ablation rate for three different thicknesses of stainless steel samples. In 50 µm-thick foil, ablation can be considered a surface ablation, since the beam diameter at the surface (20 to 30 µm) is comparable to the sample thickness. Fast material removal begins at approximately 10 J/cm², with the ablation rate reaching roughly 1 µm per pulse. Consistently with the previous works [2, 3], ablation rate increases only slightly as the laser fluence is increased by more than an order of magnitude above this threshold. Similar tendency is clear in case of 370 µm-thick sample (Fig.1 b). Several mechanisms that limit ablation rates at higher fluences, involving laser beam absorption and scattering in plasma, and metal vapor and droplets have been discussed extensively in the past [4]. Notably, vapor expansion rates reach several km/s, thus approaching the thermodynamic limit of gas expansion [4]. Therefore, increasing laser fluence causes increase in plasma density due to photoionization and inverse bremsstrahlung effect, instead of faster vapor removal. In effect, an increased portion of laser energy is transferred to the plasma, rather than to the sample.

As the thickness t of the sample increases (Fig.1 b,c), the minimum laser fluence required to penetrate the entire sample increases from 10 J/cm² to 30 J/cm² for t = 370 µm, and 100 J/cm² for t = 870 µm. Apparently, at a lower laser fluence, ablation terminates at a certain depth, due to attenuation of the beam in the column of vapor and plasma that fill the hole. Since the

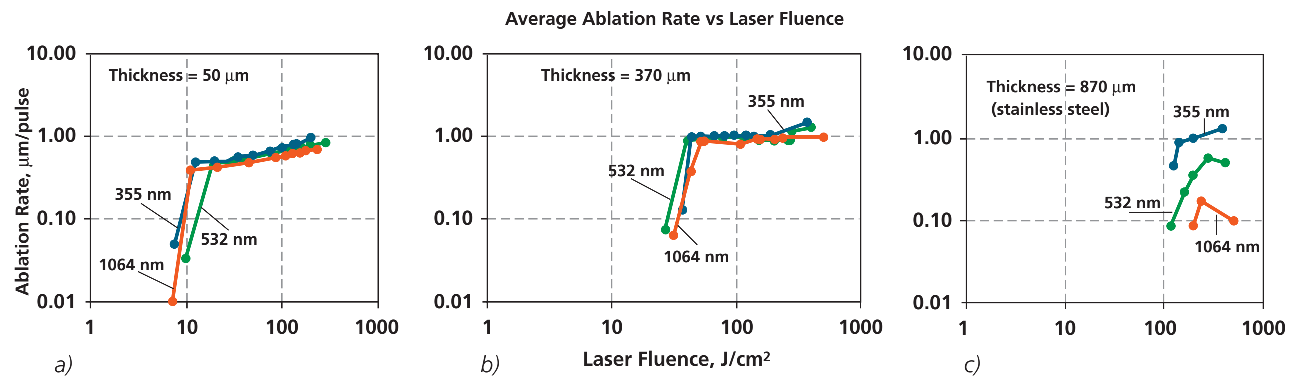

Fig.1. Ablation rate per pulse in stainless steel as a function of laser fluence at different wavelengths and thickness of the sample a) 50 µm, b) 370 µm and c) 870 µm.

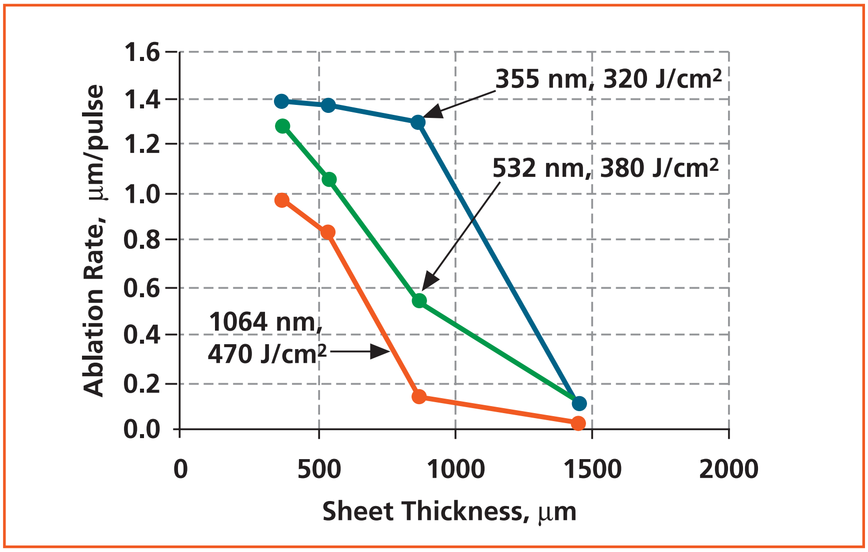

Fig.2. Ablation rate as a function of sample thickness at three different wavelengths.

vapor expansion rate at the surface was measured [4] to be less than 10 km/s, the characteristic depth at which the beam path length in plasma at least doubles compared to surface condition is roughly 100 to 200 µm. Another factor leading to increased attenuation inside the hole is that the vapor flows in a single dimension, as opposed to three-dimensional expansion at the surface. This creates higher density of vapor and plasma, thus leading to stronger attenuation.

Effect of the wavelength on drilling speed of thicker samples

As the sample thickness approaches 1 mm, the ablation rate becomes strongly wavelength-dependent (see Fig.1 c). At similar laser fluence, a UV laser beam provides almost an order of magnitude faster drilling than an IR beam. This trend is summarized in **Fig. 2**.

The characteristic sample thickness at which average ablation rate starts decreasing, is greater for shorter wavelength. Apparently, in the thicker samples, beams of different wavelength are attenuated to different degree inside the hole. Although ablation rates at the surface are similar for all three wavelengths (Fig.1 a), attenuation of the beam towards the exit of the hole and subsequent reduction in material removal in thick samples lead to reduction of average ablation rate, as plotted in Fig. 2.

One possible mechanism responsible for such drastic wavelength dependence is inverse bremsstrahlung effect. Simple estimate of the plasma absorption using formula taken from [4]:

$$\alpha(\mathrm{cm}^{-1}) = 1.37\,\lambda^3\, n_e^2\, T_e^{-1/2} \qquad (1)$$

and assuming plasma density $n_e = 1.4 \cdot 10^{19}$ cm^{-3}, plasma temperature T_e = 20,000K, leads to extinction length L (1064) = 0.5 mm at 1064 nm, L (532) = 4 mm at 532 nm and L (355) = 13 mm at 355 nm. Additionally, one has to account for an avalanche-like increase of n_e,T_e for longer wavelength due to radiation heating of plasma.

High aspect ratio drilling

Due to the nearly diffraction-limited beam quality of the solid-state laser, it is possible to achieve intensity levels above ablation threshold even with relatively low pulse energies. However, the high aspect ratio of the hole for the thicker samples becomes the limiting factor. In **Fig. 3**, we illustrate this trend by comparing the average ablation rate in 1.46 mm-thick stainless steel sheet at different wavelengths and laser spot diameters. We tried to maintain roughly constant laser fluence at the surface. Obviously, this required increasing the average power of the beam proportionally to its cross-sectional area, as the aspect ratio decreased. As was expected, for each given wavelength, higher aspect ratios led to significantly lower ablation rates, even though the laser fluence remained nearly constant. Besides factors associated with the flow of melt and vapor in high aspect ratio holes, there may be an influence from local temperature build-up from pulse to pulse. Assuming simple cylindrical symmetry, the heat transfer rate dQ/dt from the hole walls into the bulk of the sample is independent of the hole diameter d:

$$dQ/dt = \mathrm{const}(d). \qquad (2)$$

At the same time, heat input rate scales as a cross-sectional area of the beam:

$$dQ/dt \sim d^2. \qquad (3)$$

Therefore, for larger diameter and lower aspect ratio holes, each subsequent pulse is incident onto material with a higher temperature and thus, a smaller portion of its energy is required to bring the material temperature to the melting and boiling point.

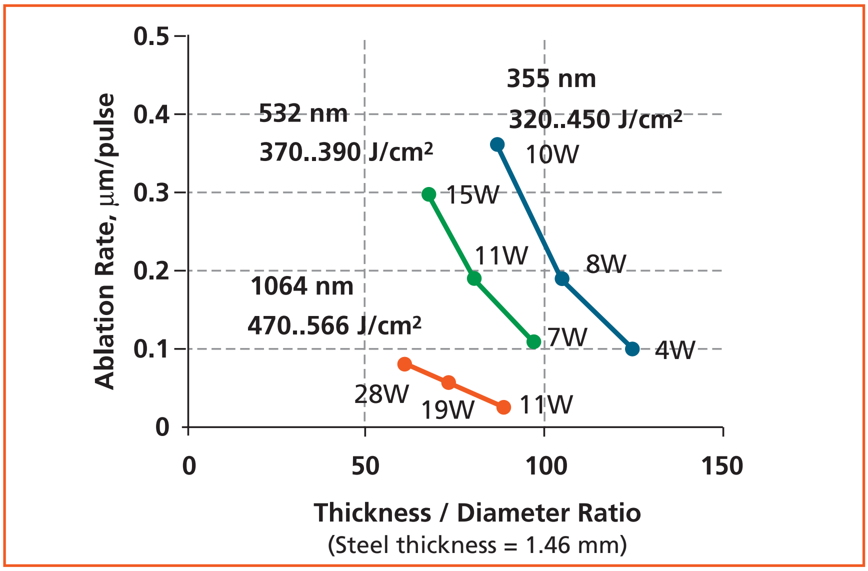

Fig.3. Average ablation rate in 1.46 mm-thick stainless steel sample as a function of aspect ratio. Laser fluence was maintained at roughly constant level as the beam diameter was varied. This required adjusting laser average power proportionally to the beam cross-section area, as labeled next to each experimental point.

Besides aspect-ratio dependence, even more pronounced is the dependence of ablation rate on wavelength. Basically, our finding is that a shorter wavelength allows the drilling of higher aspect ratio holes at a higher speed for the sample thickness exceeding 1 mm. Again, this dependence is so strong because the beam has to penetrate a thick layer of dense plasma and vapor, which is not present in drilling thin foils.

Practical drilling examples

In practical applications, one is concerned not only with drilling speed but also with quality of holes. For thick metal sheets, it is generally difficult to minimize taper of the holes and maintain smooth and round exits. The reason for this is that as the beam is attenuated towards the exit, intensity in peripheral areas of the hole fall below ablation threshold, thus leading to reduced exit diameter and irregular, rough edges. Therefore, using a shorter wavelength is beneficial for improving the quality of the holes drilled in thick metal samples.

We were able to drill holes with aspect ratios as high as 50 in 1.46 mm-thick stainless steel using the percussion method with a 10 W UV beam. Taper did not exceed 15% and total drilling time was less than 0.4 seconds. Using trepanning with a relatively low UV power of 4 W, we produced low taper holes with good roundness in 0.55 mm-thick stainless steel and 0.75 mm-thick carbon steel. **Fig. 4, 5** show SEM images of these trepanned holes.

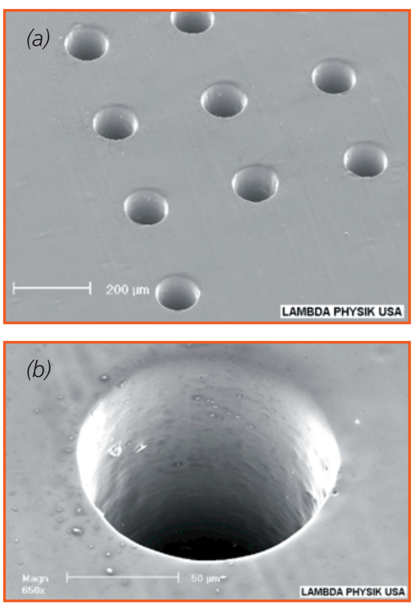

Fig.4. Holes trepanned in 0.55 mm-thick stainless steel with 4W UV beam: a) overview; b) close-up of entrance side. Hole diameter is 110 µm.

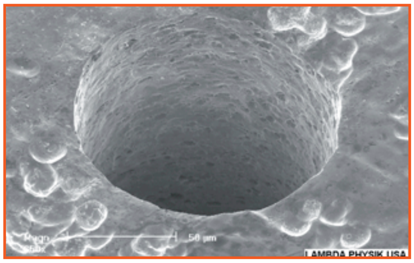

Fig.5. Close-up view of hole trepanned in 0.75 mm-thick carbon steel with 4W UV beam.

Conclusion

In conclusion, we showed that using UV output from high repetition rate diode-pumped, q-switched solid state lasers is beneficial in high speed, high accuracy micromachining of steel. The main difference from IR output arises from significantly reduced plasma formation which tends to be a limiting factor for drilling speed and quality in thicker, on the order of 1 mm, steel samples.

We presented practical examples of trepanning of 100 µm-diameter holes in steel sheets with roundness and taper errors within a few micrometers, as well as percussion drilling of 30 µm-diameter holes in 1.5 mm steel with an aspect ratio of 50.

Acknowledgments

We would like to thank Dr. M. Lynn from the University of Miami for producing SEM images of micro-machined samples.

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High Precision Machining with Solid-State Lasers

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Laser micro-machining is emerging as a viable manufacturing solution due to the development of industrial grade diode pumped, short pulsed, frequency-multiplied solid-state lasers. Using the new helical drilling method, an outstanding level of accuracy at high aspect ratios can be achieved (**Figure 1**).

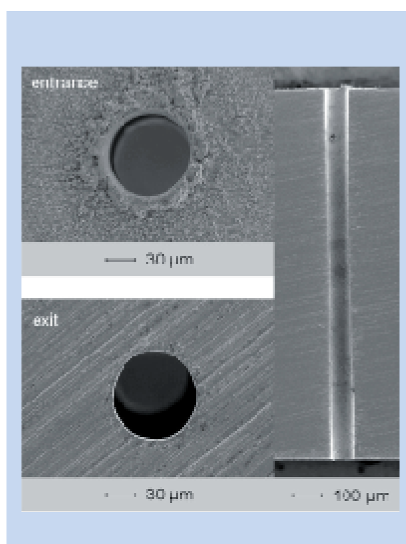

Figure 1: Micro-hole (ø 70 µm) in 1 mm thick steel plate (helical drilling, λ = 1.06 µm).

Introduction

Lamp-pumped Nd:YAG-lasers with pulse lengths of several tenths of milliseconds are well established tools for drilling of metal alloys and composites. A well-known example is the airfoil cooling holes in components of aircraft engines. These holes can tolerate moderate diameter and shape inaccuracies as well as a thin recast layer. In cases when high accuracy is required, laser drilling with millisecond pulses could not

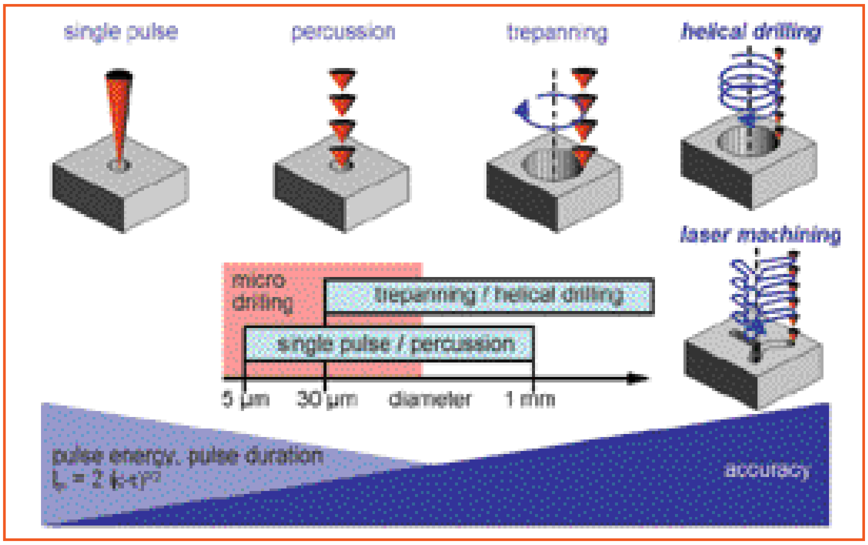

Figure 2: Process strategies to achieve high accuracy in laser drilling.

fulfill the requirements, up until now.

The major problem is the melt produced when using long pulsed lasers. Irregular and incomplete melt expulsion affects the shape of the hole, produces recast layers and may even completely close a hole which was open initially.

The depth which can be heated to melting temperature during a laser pulse of length τ is determined by the optical penetration depth l_α and the thermal one l_{th}. In metals for example l_α is small compared to l_{th} which is given by: $l_{th} = 2 \cdot (\kappa \cdot t)^{1/2}$ (κ = thermal diffusivity). This leads to the expectation, that shortening of pulse duration reduces the negative influence of melt.

A further reduction of unwanted thermal effects was achieved by applying green laser light (frequency doubled Nd:YAG) instead of IR [2]. The advantage of green light was confirmed by Chang et al. [3] who used a copper vapor laser with 30 – 40 ns pulse length. However, an explanation for the influence of the wavelength was not given.

In metals the thermal penetration depth is predominant in laser ablation. Whereas with ceramics the optical penetration depth is expected to be much longer. This is due to the lower heat conductivity, but mainly caused by the low absorption coefficient a which leads to fairly high values of optical penetration depth in the so-called transmission window which includes visible and near IR wavelengths. As a result, to date, CO_2 lasers (10.6 µm) and excimer lasers (UV) are preferred for the machining of ceramic materials. Ceramic materials can be machined with Nd:YAG-lasers quite efficiently. An explanation for this surprising observation was found by investigating the high temperature optical behavior of various ceramics. Although the penetration depth decreases for ceramics, the reflectivity increases at certain temperatures, based on material composition. This effect could be connected with the high temperature chemistry of these materials, causing a decomposition in gaseous and liquid metallic components. We can conclude that at energy density values high enough to heat the surface within the pulse duration to decomposition temperature, ceramic materials begin showing metal-like optical behavior.

In recent years, diode-pumped solid-state lasers appeared on the market with attractive features such as:

- easy operation
- low maintenance
- small footprint
- high beam quality
- short ns-pulses
- high enough pulse energy for drilling, micromachining and cutting
- selection of wavelength from IR to UV

This new class of lasers are powerful tools for high accuracy drilling of steel and ceramics.

Processing Technique

Traditional industrial laser drilling has used three techniques (see **Fig. 2**):

- single pulse drilling
- percussion drilling
- trepanning

Higher dimensional and surface accuracies can be achieved by using a shorter pulse duration (removing less material per pulse), as opposed to removing larger volumes of material with longer pulse durations.

Helical drilling uses a multitude of ablation steps to enhance drilling accuracy. In contrast to trepanning, which is essentially a percussion drilling followed by a cutting procedure, the helical drilling reaches the breakthrough after many turns of a spiral, describing the path of the ablation front. While penetrating the sample, the focal position, the pulse energy and to some extent the helix radius energy can be varied. In addition to rotationally symmetrical holes, it is also possible to generate geometrically complex holes using an appropriate processing strategy.

The following **Fig. 3** and **Fig. 4** show some examples of successful applications of the helical drilling and the laser machining method [4, 5].

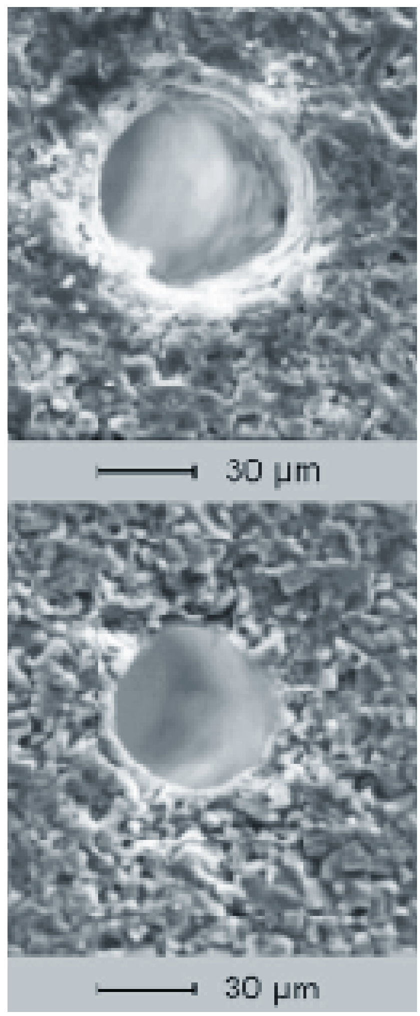

Figure 3: Micro-hole in 800 µm thick Al_2O_3 (helical drilling, λ = 532 nm, τ = 10 ns). Above: entrance (ø 49 µm), below: exit (ø 43 µm).

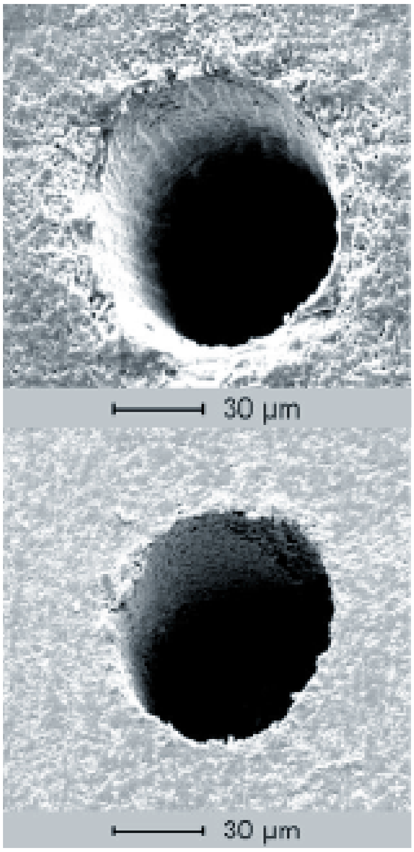

Figure 4: Micro-hole in 1 mm thick Si_3N_4 (helical drilling, λ = 532 nm, τ = 10 ns). Above: entrance (ø 70 µm), below: exit (ø 69 µm).

Hirschegg Model for Drilling with Short-Pulsed Lasers

The observations of several drilling experiments led to a physical model developed during a German-Russian Workshop in Hirschegg, Austria [6]. The interaction of two effects occur during drilling. The primary effect is the laser beam which is responsible for hole deepening in the propagation direction. The second effect is a laser induced plasma which acts primarily in radial directions, to widen the hole and smooth the wall surface. During the laser pulse the plasma absorbs a part of the laser power which can be observed by reduction of transmission and drilling velocity. The amount of plasma absorption depends strongly on wavelength because underlying interaction mechanisms like inverse bremsstrahlung react proportionally to the square of the wavelength.

With this model the transient behavior of the drilling process can be explained as follows:

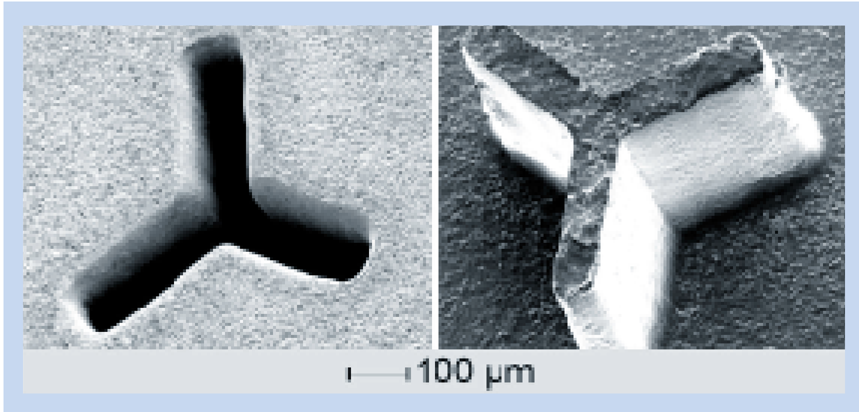

Figure 5: Trilobal geometry for spinnerets in 400 µm thick Al_2O_3 (laser machining, λ = 1064 nm, τ = 10 ns). Leg length: 300 µm, leg width: 100 µm.

1. At the beginning of the penetration the influence of plasma on the laser beam is relatively weak, therefore the highest drilling velocity is observed.
2. Drilling velocity then decreases due to plasma absorption increasing to a value determined by power density, wavelength and pulse duration.
3. In the following period of constant drilling velocity, plasma acts as a control of the drilling velocity keeping it constant. In the range of low energy density, transmission increases linearly with decreasing incident energy density. As the hole deepens, losses due to wall absorption increase, and the energy density at the plasma cloud decreases. The drilling velocity remains constant, because the energy density transmitted to the bottom of the hole remains constant.
4. When the energy density arriving at the bottom of the keyhole falls below the ablation threshold, the drilling process stops.

From the described model assumption, which certainly needs further experimental and theoretical confirmation, conclusions can be drawn for choosing adequate process parameters. Wavelength selection is key to determining the influence of plasma and to optimizing its positive (widening, cleaning) and negative (reduction of drilling velocity, heat load) effects.

Conclusion

Newly developed diode-pumped solid-state lasers offering pulse energy values beyond several mJ at pulse durations near 10 ns allow micro-hole drilling of high aspect ratios and unprecedented accuracy in steel and ceramics. In addition, higher repetition rates (for higher productivity) and shorter pulse lengths (for even higher accuracy) are preferred for yielding higher productivity and accuracy.

Acknowledgement

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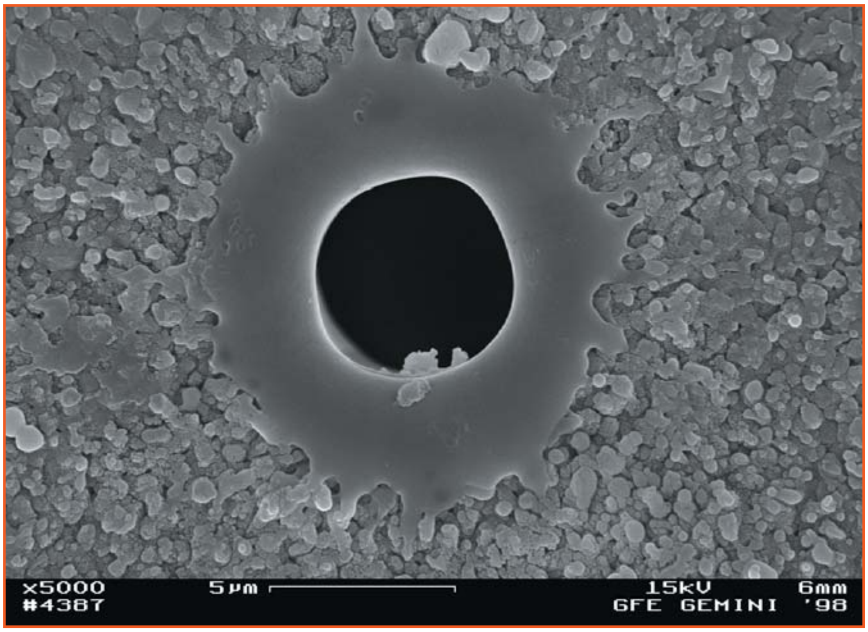


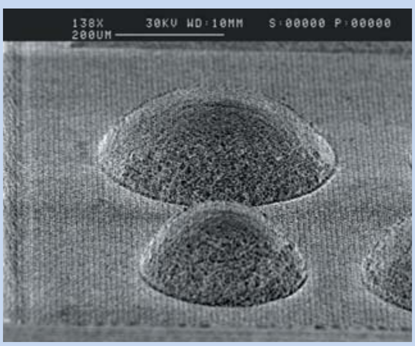
Figure 1: Hole in Al_2O_3.

High pulse energy and short pulse duration enable lasers like the StarLine® and Gator™ (Lambda Physik) to achieve drilling and cutting results, not previously possible. This new generation of diode pumped solid state lasers will replace pulsed flashlamp pumped Nd:YAG-lasers and longer pulse duration DPSS lasers in some material processing applications, due to higher surface quality and better dimensional results. With the option of frequency conversion, to UV wavelengths, DPSS lasers are an interesting alternative to even some applications dominated by excimer lasers. Several investigations with different materials, such as hard metals, ceramic, steel, glass and diamond, at various wavelengths from the first to the third harmonic (1064 nm, 532 nm and 355 nm) were performed using the StarLine at the Institute for Laser Technology (ILT).

High aspect ratios were reached in drilling of small holes with diameters from 5 µm up to 100 µm and a material thickness up to 1 mm. Thin materials (5 – 50 µm) can be drilled without any deformation of the sheet. **Figure 1** shows a 5 µm hole in a 250 µm thick Al_2O_3-substrate, with an aspect ratio of 50. The entrance diameter is slightly larger (10 µm), so that the taper of the hole is less than 0.6°. The reproducibility of the roundness and the diameter is very high (± 0.5 µm). Wafers with several thousand holes have been produced for biomedical applications. Other industrial application areas are calibration, tool manufacturing, automotive and aerospace components.

A new technique is the material ablation or laser milling process for manufacturing 3D microstructures in very hard materials. With each laser pulse a small element of the material (diameter ~ 5 µm) is vaporized. Under specific conditions, complex 3D microstructures can be produced by ablating several thousands of these elements. In combination with conventional CAD/CAM-software the process becomes very flexible. In comparison to Electrical Discharge Machining (EDM) and Ultrasonic methods no tool is necessary. The result is a drastic reduction in the total machining time from the design to the final microstructure. **Figure 2** and **Figure 3** show typical results of such microstructures. The minimal surface roughness depends on the material and can be reduced to Ra < 0.1 µm. The accuracy is < 2 µm.

The microstructures can be used as tools for the mass production of microparts by metal forming (stamping, embossing) or injection molding. The rapid prototyping or rapid tooling profits from the material flexibility and prototypes can be produced under real conditions.



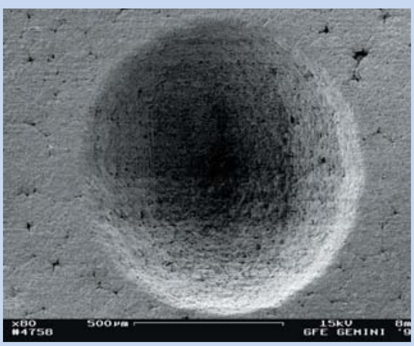


Figure 2 and Figure 3: Spheroid structures in hard metal (in co-operation with Heidelberg Instruments) and Al_2O_3.

Impressum

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