Laser beam machining (LBM), state of the art and new opportunities

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Abstract

An overview is given of the state of the art of laser beam machining in general with special emphasis on applications of short and ultrashort lasers. In laser welding the trend is to apply optical sensors for process control. Laser surface treatment is mostly used to apply corrosion and wear resistant layers, but also for repair of engine and machine parts. In micro-machining, shorter pulses reduce heat-affected damage of the material and opens new ways for nanometer accuracy. Even 40 years after the development of the laser there is a lot of effort in developing new and better performing lasers. The driving force is higher accuracy at reasonable cost, which is realised by compact systems delivering short laser pulses of high beam quality. Another trend is the shift towards shorter wavelengths, which are better absorbed by the material and which allows smaller feature sizes to be produced. Examples of new products, which became possible by this technique, are given. The trends in miniaturisation as predicted by Moore and Taniguchi are expected to continue over the next decade too thanks to short and ultrashort laser machining techniques.
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1. Introduction

Photons are in this century. They are replacing electrons as the favourite tool in modern industry. Light is used for everything from eye surgery to telephone technology and materials processing. Photons are applied in an increasing number of topics addressed by this ISEM 14. An important property of light is that it has no volume, photons have no charge, so when concentrated into a very small space, they do not repulse each other like negative charged electrons do. This is an important property especial for ultrashort machining. Light moves through space as a wave, but when it encounters matter it behaves like a particle of energy, a photon. Not all photons have the same amount of energy. The visible part of the spectrum contains wavelengths from 400 to 750 nm. Radiation below 400 nm includes the harmful frequencies of UV and X-rays, while above 750 nm the invisible infrared, microwave and radio frequencies are included.

The energy of photons is $E = h\nu$. For the visible 500 nm wavelength this is 4×10^{-19} J or 2.5 eV per photon, which is not enough to break the chemical bonds in the material, which requires 3–10 eV. In the laser materials processing this can be overcome in different ways. The first solution is simply heating the material by absorption of laser energy, which is a thermal or pyrolytic process. Secondly higher energy photons (UV) can be used with photon energies of 3–7 eV, which is used to break the chemical bonds directly (especially plastics). This is a photolytic process. For metals even more energy is required (up to five times the sublimation energy of about 4 eV for most metals). The third option is using lasers that deliver so many photons on a time that electrons are hit by several photons simultaneously. Absorption of multi-photons has the same result as single high energetic photons. In this case the photon energy, thus the wavelength, is less important because energy is transferred by multi-photons simultaneously. This is a reason that such lasers are preferable operated in the visible part of the spectrum with relatively simple optics. In this paper, some comments are made about developments in welding and surface treatment and deals in more detail with the challenges of applications using short and ultrashort pulsed lasers.

2. Laser welding

After the maturation of laser cutting also welding is becoming everyday technology. For 10 years people said 'we can weld any material, as long as it is stainless steel'. Now indeed almost all materials can be laser welded. Challenges
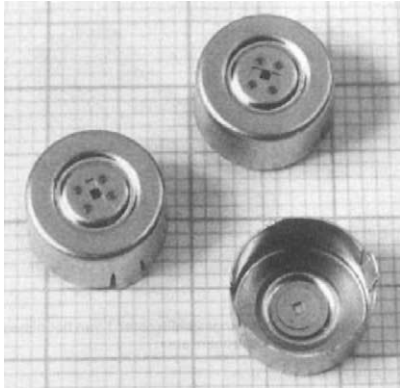
Fig. 1. Laser welded parts for a TV electron gun (Philips CFT).

Fig. 3. Laser welding of steel (top) on aluminium.

Fig. 4. Sensors can be fully integrated in a laser-robot welding system.

are found in the area of beam and product handling. In the high volume market, e.g. in the electronics industry special machines are built around one product for just a few welds (Fig. 1). In such applications, the required accuracy for laser welding is built-in in the machine.

The same is seen in welding of tailor made blanks, which become more and more popular in car manufacturing. It is the production of blanks of steel used to press sheet metal parts like doors, hoods, suspensions, etc. The sheet elements are chosen of different thickness or different strength to meet the requirements of the composed part. Here the welds are mostly linear while the accuracy is obtained by the design of the machine and the clamping tools. In this area there is trend to inspect each weld by CCD cameras directly after welding and even to observe the seam before in order to correct for instance for uneven cutting edges. In automotive applications, in special in bodywork, it is hard to meet the tolerances. This problem is often solved by the construction, using overlap seams, which are more faults tolerant. The effects of some errors in are shown in Fig. 2. Gaps should be restricted to 10–20% of the sheet thickness. The process is more tolerant for displacement tolerances. Aluminium is less sensitive for adjustment errors, probably due to the better heat conductivity.

A new area is welding of dissimilar materials like steel and aluminium, which is known to be impossible in conventional welding. Fig. 3 shows an overlap weld of a 1 mm thick steel plate to aluminium. For a good wettability the material

should be free from oxides before welding and the speed and temperature should be balanced to reduce the intermetallic layer (less than 5 μm). It is shown that the aluminium flows nicely over the steel. This type of welds are of growing interest in shipbuilding and automotive applications.

The high welding speeds in laser welding, e.g. 100 mm/s and the small tolerances require a high degree of automation. In particular robots are applied more and more. Developments are ongoing on real time process sensing and control as well as on-line quality inspection. Postma et al. [1] have developed a system for measuring and control the welding process by sensing the plume radiation optimising the welding speed. Such a systems can be fully integrated in laser-robot welding systems with the sensor measuring through the same optical fibre as used for beam delivery (Fig. 4).

3. Laser cladding and alloying

Lasercladden is used to improve the surface quality by applying a hard or a corrosion resistant layer on a product of cheap or better to machine material. The common technique is to create a shallow melt pool by a defocussed laserbeam and supply metal powder in that pool using an inert gas flow. Examples are shown in Fig. 5, left the cladding of a roller wheel for sheet metal forming, centre cross section of the wheel and right a diesel engine crankshaft.

The last application restoring (costly) products by applying fresh material on worn out or corroded products is applied on diesel engine parts like cylinder heads, valves,
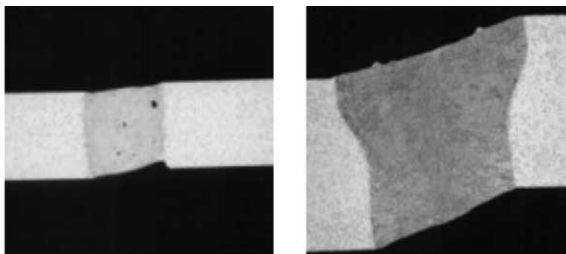
Thick 1mm, gap 0.2 mm   Thick 2mm, displacement 0.6

Fig. 2. Effect of tolerances in laser welding of aluminium.

Fig. 5. Examples of laser cladding.

shafts, etc. Further applications are for the chemical industry, mining, marine and military applications.

This technique can be applied also to form new products (prototypes) directly from a CAD file [2]. By varying the powder composition material properties can be changed continuously during the build-up. In this way products made from graded materials are obtained.

As well in laser welding as in laser cladding CO_2-lasers are used because of their high power better efficiency and good beam quality. Nowadays more and more Nd:YAG lasers are used because they are easily combined with robots. Further also YAG lasers become available at higher power levels. The reason for a poor beam quality of high power Nd:YAG lasers is the thermal load of the laser rod resulting in thermal expansion of the rod, in the centre more than at the peripheral which causes optical aberrations in the laser cavity. The laser industry is solving that by different ways. The first solution was using diode lasers to pump the laser, as a next step the laser rod is shortened to just a thin disk which can be effectively cooled over the whole diameter. This has resulted in the Nd:YAG disk laser which in power ranges up to 4 kW is coming on the market. Another promising solution is the opposite way by stretching the rod into a long thin fibre. Techniques as multimode fibre coupling of diode pump light into the active (single mode) fibre, which originates from the telecom industry, enables multi-kilowatt input by thousands of (few Watts) diode lasers. Now industrial fibre lasers up to 10 kW output and 25% efficiency are coming on the market. It is expected that such systems which require less floor space ($\approx 0.5\,m^2$ for a 4 kW system) will cause a breakthrough in high power applications like laser welding and laser cladding.

4. Laser–material interactions, short and ultrashort

Since the invention of the laser there has been a constant development to shorter pulse times. Only a few years ago 10 ns pulses were the shortest obtainable but now femtosecond lasers are applied and even shorter pulses can be obtained in the lab. Therefore, we will discuss first what is short from the viewpoint of the laser.

Like very long distances can be expressed in light-years we can express very short times in light-distances, that is the distance a light wave or a photon travels during that short time. This distance is for 100 fs pulse only 30 μm. In Fig. 6, these light-distances are shown in relation to the laser machining processes. For very short femtosecond pulses this distance is in the order of the wavelength of the light!
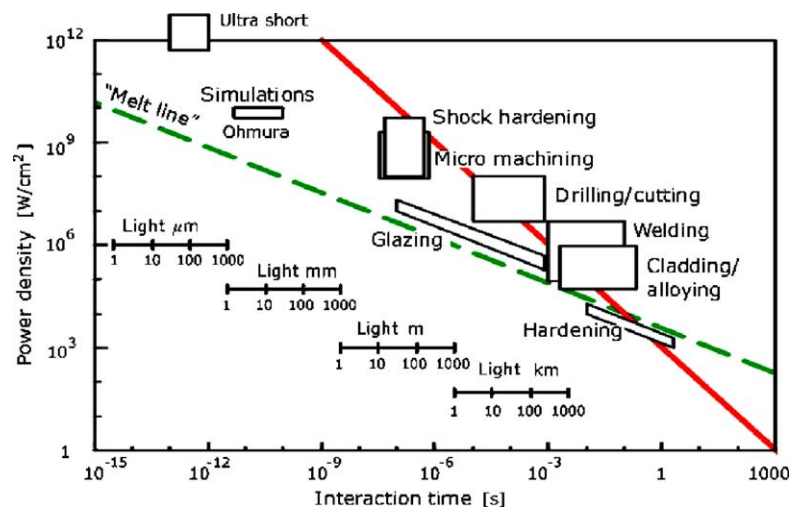

Fig. 6. Overview of laser machining processes. The 'conventional' laser processes are found around the line of $1\,kJ/cm^2$. The dotted line indicates the melt boundary of metal. Ultrashort processes require less energy per square centimetre in general.

The question how short is short enough can also be approached from the viewpoint of the applications. Chen and Liu [3] compared different pulse widths and concluded that shorter pulses produce better quality but at higher cost. The question what is short and what is ultrashort can be discussed also from the viewpoint of the material. The material is subjected to a beam of photons coming from outside which is absorbed in a *skin layer*. The photons are absorbed in that skin layer by the free electrons, in about 1 fs (10^{-15} s). The relaxation time of the electrons is about 1 ps (10^{-12} s). During that time the energy is stored in the electrons, after the relaxation time it is converted into heat.

The intensity of the incoming beam is expressed by I_0. The decrease of the laser intensity in the depth is given by $I_x = I_0 e^{-\alpha x}$ where α the optical absorptivity of the material and x the depth into the material. An important quantity is the penetration depth δ ($\delta = 2/\alpha$) in which almost all laser energy is absorbed. This optical penetration depth is for metals in the order of 10 nm. It means that the laser energy heats a 10 nm thick layer of metal in 1 ps. This heat will diffuse from that skin layer to the bulk. The diffusion depth is expressed by $d = \sqrt{4at}$ with a as the thermal diffusivity and t the diffusion time. In case of steel we obtain in 10 fs a diffusion depth of 1 nm while during a 1 ps pulse the heat diffuses over 10 nm. Taking the results together than we see that:

- it takes 1 ps to convert laser energy into heat,
- this takes place in a 10 nm thick skin layer,
- the diffusion depth for 1 ps is also 10 nm.

From these results we consider a pulse as ultrashort when the (thermal) diffusion depth during the pulse is in the same order or less than the skin layer depth (optical penetration depth). The optical penetration depth depends on the material and the laser wavelength. The diffusion depth depends on the material properties. Table 1 gives some numbers for different materials. Since especially for glass and plastics the material can be more or less transparent for certain wavelengths this is just a rough indication. Detailed information is given by Bosman [4]. In general we will consider pulses shorter than 1 ps as ultrashort.

Based on physical considerations a removal rate of 10 nm/pulse at $F = 1$ J/cm² is expected on steel, while an excess of laser fluence is spilled. Experiments at Lawrence Livermore however, show higher yields of 50 nm/pulse at $F = 4$ J/cm² up to 350 nm/pulse at $F = 14$ J/cm² which is the saturation limit according to Semak [5]. These results are explained by the interaction with the hot solid plasma that is
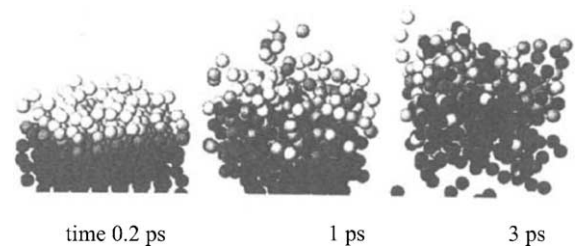
Table 1
Ultrashort pulses times for some materials

Material	Pulse length
Metals	1 ps
Ceramics	10 ps
Plastics	1 ns

Fig. 7. Ablation of silicon by a 200 fs, 5×10^{10} W/cm² laser pulse. The 5 nm thick layer is released from the surface within 3 ps [7].

formed during the pulse and which is expected to evaporate metal even after the pulse has been finished. According to Semak, there is no detailed knowledge about the real interaction processes during femtosecond laser pulses up to now. Computer simulations however, based on three-dimensional molecular dynamics, will give some insight in the interaction phenomena. Ohmura et al. [6–9] have simulated the interaction and ablation behaviour of aluminium, copper and silicon at 266 nm wavelength (Fig. 7). The optical penetration depth was 7, 12 and 5 nm, respectively.

The applied power density was in the range of $(5–50) \times 10^9$ W/cm². It was found that the material evaporates as small particles (0.3–10 nm), most of them smaller than 1 nm. The average velocity of the particles is several kilometres per second or more, but there are also particles whose velocities are in opposite direction. They return to the substrate causing some deposition of debris. Another effect found by simulation was the generation of dislocation slip planes and vacancies due to shock waves acting until 50 nm below the surface.

4.1. Generation of short laser pulses

The mechanism for generating laser pulses lies in the nature of the active laser medium and the corresponding lifetimes of the atomic energy levels. By using different pulse generation techniques [10] the pulse duration, pulse energy and reproducibility can be modified over wide ranges.

- *Gain switching*. It can be regarded as the most direct method to generate laser pulses. After the pumping process has been started, the population inversion builds up. The laser starts to oscillate when the critical inversion is reached, i.e. the gain becomes larger than losses. This continues until the pumping process is switched off, or until the losses become higher than the amplification. The reproducibility and stability are stochastic. Pulse duration available from flash lamp-pumped solid-state lasers by gain switching can vary from 10 µs to 10 ms.
- *Q-switching*. The output of a gain switched, pulsed solid-state laser is generally a train of irregular pulses. It is possible to remove these irregularities and at the same time increase the peak power by *Q*-switching. Such lasers emit one giant pulse per operational cycle. The pulse length is less than a microsecond down to several nanoseconds
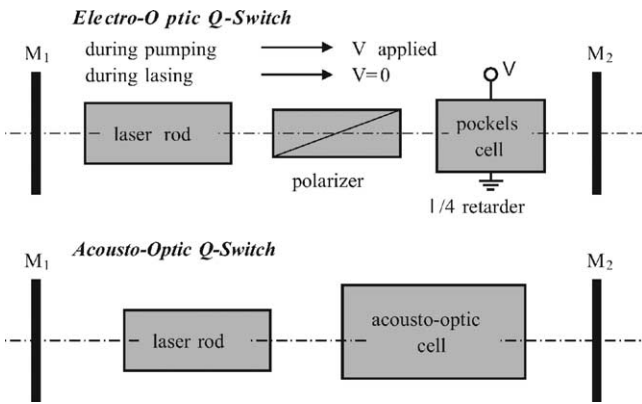
Fig. 8. *Q*-switching techniques.

with peak powers between 10^6 and 10^9 W. This technique can also be applied to continuously pumped lasers in order to produce a train of *Q*-switched pulses with regular duration, peak power, and repetition rate. The energy is stored in the laser material during pumping in the form of excited atoms and then released in a single, short burst. This is done by changing the optical quality of the laser cavity. The quality factor *Q* is defined as the ratio of the energy stored in the cavity to the energy loss per cycle. During pumping the high reflectivity (HR) mirror is effectively removed from the system preventing laser emission and a large amount of energy is stored in the active medium. When the HR mirror is returned to proper alignment most of the stored energy emerges in a single short pulse [11]. A *Q*-switch is essentially a shutter placed between the active medium and the HR mirror. With this shutter closed, the HR mirror is blocked preventing oscillation. When the amplifier gain reaches a predetermined value, the shutter is opened to increase the cavity quality. Several techniques can be used for *Q*-switching lasers (Fig. 8).

○ *Spinning reflectors* are used quite frequently in *Q*-switched systems where it is not necessary to closely synchronise the output to some other event. Usually the high reflecting mirror is rotated so that the mirror is tilted out of alignment. The system is *Q*-switched when the mirror rotates back into alignment (it is in alignment once each revolution). Switching time is typically a few nanoseconds.

○ *Electro-optic Q-switching* uses a polarisation filter and rotator placed into the reflecting cavity between the laser rod and the reflecting mirror. Rotating the polarisation vector of the laser beam inside the cavity results in low cavity feedback so that it cannot pass through the polarisation filter. When this polarisation rotation is terminated, the cavity reflectivity is high and the system will produce a giant pulse. Two of the electro-optic devices used in this application are Kerr cells and Pockels cells. The Pockels effect is a linear electro-optical effect, i.e. the refraction index change in the parallel

and orthogonal direction is proportional to the applied voltage. The Kerr effect is a non-linear electro-optical effect dependent on a square function of the applied voltage. Switching time is fast, less than a nanosecond.

○ *Acousto-optic Q-switches* have a transparent element placed in the cavity. This element, when excited with intense standing acoustic waves by a piezoelectric crystal, exhibits a diffraction effect on the intracavity laser beam and diffracts part of the beam out of the cavity alignment. This results in a low feedback. When the acoustic wave is over, the diffraction disappears and the system emits a giant pulse. Switching time is slow at 100 ns or greater.

○ *Saturable absorbers* are available as thin films on glass substrates or as liquids in glass cells. For *Q*-switching, a dye cell is placed in the laser cavity. The dye absorbs the laser wavelength presenting a very high cavity loss to the laser, and preventing lasing until the amplifier has been pumped to a high gain state. When the irradiance from the active medium becomes intense enough, the energy that is absorbed by the dye optically pumps the dye material, causing it to be transparent at the laser wavelength. The dye cell is bleached and causes no longer high cavity losses, i.e. the quality of the resonator increases. The absorption change of the dye is the equivalent of *Q*-switching in the laser, and it can occur in less than a nanosecond. The switching time is fast.

• *Mode-locking*. While *Q*-switching can be used to generate pulses with high intensities in the ns-range, mode-locking is used to generate ultrashort laser pulses with pulse duration in the ps- to fs-range. Pulses in the ps-range were generated for the first time by passive mode-locking of a ruby laser shortly after its discovery by Mocker in the mid-1960s [12]. Mode-locking can be used very effectively for lasers with a relatively broad laser transition bandwidth, and thus for lasers with a broad amplification profile, in which numerous longitudinal modes can oscillate simultaneously. For achieving the mode-locking condition, active and passive mode-locking techniques can be used.

Active mode-locking implies that the resonator is equipped with a modulator, which is triggered by an external signal in such a way that a sinusoidal modulation of the losses in the optical resonator takes place. The frequency is equal to the frequency distance of the longitudinal modes. Initially, this loss modulation represents an amplitude modulation with the frequency of the mode, which starts to oscillate first at a maximum amplification at the frequency. This modulation then induces the neighbouring modes with the frequencies, which experience an amplitude modulation as well. This process continues until all longitudinal modes within the amplification bandwidth of the laser are coupled and synchronised. Flash lamp-pumped solid-state lasers typically produce pulse durations of 100 ps, with

Table 2
Short pulsed lasers

Laser	Wavelength (nm)	Pulse length	Frequency (kHz)
TEA CO_2	10600	200 μs	5
Nd:YAG	1060, 532, 355, 266	100 ns 10 ns	50
Excimer	193–351	20 ns	0.1–1
Copper vapor	611–578	30 ns	4–20
Ti Sapphire	775	100 fs	1–250

Nd:YAG and 30 ps with Nd:YLF using active mode-locking. Diode-pumped Nd:YLF lasers with active mode-locking are even able to provide laser pulses below 10 ps.

Passive mode-locking is based on the same principle as active mode-locking, which is a temporal modulation of the resonator losses. In contrast to active mode-locking, the laser system itself determines the point in time at which the losses are at their minimum [13].
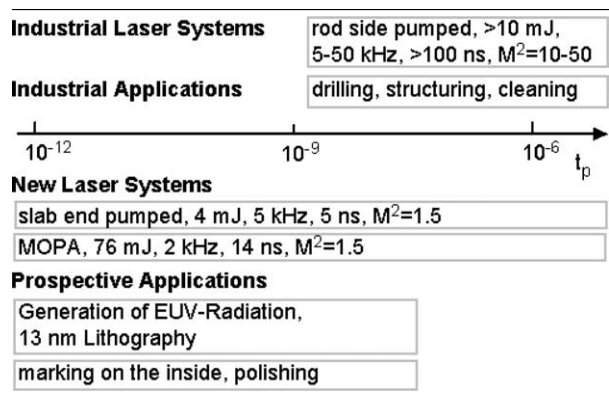
5. Overview of lasers and application fields

The passively Q-switched micro-lasers [14,15] open new ways for micro-machining. A continuous wave diode laser of about 1 W is used to pump a laser material with a saturable absorber on the output window. When this solid-state Q-switch reaches the threshold it becomes transparent within a nanosecond and a short pulse (0.3–1.5 ns) is delivered. Repetition rates are between 2 and 50 kHz. An overview of lasers and micro-machining applications is given in Tables 2 and 3.

Table 4
Roadmap for solid-state laser systems for industrial applications

6. Solid-state pulsed lasers

The most important parameters for the laser performance are shown in Table 4: pulse energy E_p (mJ), repetition rate v_{rep}, pulse duration t_p, and beam quality M^2. For the highest beam quality ($M^2 = 1$) beam is diffraction limited. The key properties are beam quality and output power as well as compact design. The combination of enhanced capabilities for tailoring the optical energy density with new laser systems and improved processing strategies using the advanced picosecond and femtosecond lasers [17] leads to further improvement.

Actual developments enable new applications like marking inside transparent materials as well as polishing of metal parts (Fig. 10), micro-machining of transparent material with

Table 3
Laser micro-machining applications [16]

Laser	Applications	Material
Micro-electronics packaging		
Excimer	Via drilling and interconnect drilling	Plastics, ceramics, silicon
Lamp-pumped solid-state	Via drilling and interconnect drilling	Plastics, metal, ceramics, silicon
Diode-pumped solid-state	High volume via drilling, tuning quartz oscillators	Plastics, metal, inorganic
CO_2 sealed or TEA	Excising and scribing of circuit devices, large panel via drilling	Ceramics, plastics
Semiconductor manufacturing		
Excimer	UV-lithography IC repair, thin films, wafer cleaning	Resist, plastics, metals, oxides silicon
Solid-state	IC repair, thin films, bulk machining resistor and capacitor trimming	Plastics, silicon, metals, oxides silicon, thick film
CO_2 or TEA	Excising, trimming	Silicon
Data-storage devices		
Excimer	Wire stripping air bearings, heads micro via drilling	Plastics, glass silicon ceramics plastics
Diode-pumped solid-state	Disk texturing servo etching micro via drilling	Metal, ceramics metals, plastic
CO_2 or TEA	Wire stripping	Plastics
Medical devices		
Excimer	Drilling catheters balloons, angioplasty devices. Micro-orifice drilling	Plastics, metals ceramics, inorganics
Solid-state	Stents, diagnostic tools	Metals
CO_2 or TEA	Orifice drilling	Plastics
Communication and computer peripherals		
Excimer	Cellular phone, fiber gratings, flat panel annealing, ink jet heads	Plastics, silicon, glass, metals, inorganics
Solid-state	Via interconnect coating removal tape devices	Plastics, metals, oxides, ceramics
CO_2 or TEA	Optical circuits	Glass, silicon

high form accuracy and also generation of EUV radiation at 13 nm wavelength for next generation lithography. Beyond metals and ceramics also materials like diamond and semiconductors as well as very weak materials like silicon and rubber can be processed.

Tailoring the laser performance is balancing the fundamental phenomena involved in the laser action and taking full advantage of the diode laser as excitation source for the laser crystal. The mechanisms of excitation, amplification and saturation in the crystal, depending on spectral and spatial matching of diode pump volume to the volume of the desired laser mode, influence efficiency and beam quality. In conventional side pumped laser designs for example thermo-optical effects introduce thermal lensing and birefringence which reduce beam quality and stable laser operation. As consequence of thermal induced birefringence the polarisation is changed and optical losses are introduced. Successful resonator design depends on knowledge about the physical phenomena. Currently applied designs are

- *Rod end pumped*. The output power is limited by thermo mechanical damage of the crystal even for high strength YAG-material. The beam quality and scalability of output power is limited by thermal lensing.
- *Rod side pumped*. The beam quality is limited by birefringence, since the thermal lens becomes polarisation dependent. In spite of these limitations actual development of industrial solutions for robust and economical power amplifier for next generation EUV-Lithography are based on rod side pumped modules.
- *Slab side pumped* (*conventional, almost the whole slab volume is excited*). The amplifier gain is limited by parasitic modes. The laser emission is not gain guided and therefore additional, parasitic modes are amplified outside the fundamental mode volume. The output power is limited by thermo mechanical damage of the crystal. In particular excitation and heating at the corners and edges of the crystal are critical.
- *Innoslab end pumped*. The scalability of the laser power at high beam quality is limited by the spatial homogeneity of the pump radiation in the scaling direction. Shaping of the diode laser beam by optical integrators is the challenge.
- *Disc end pumped*. The thin (100 μm) disc concept [18] relies on multi-pass excitation and high regenerative amplification in order to compensate the small crystal volume. The optical arrangement of multi-pass excitation is crucial for the beam quality. In comparison to the end pumped slab laser the heat exchange and reflection of the laser light is at the mounted surface of the disc.

New laser sources like diode-pumped solid-state lasers and diode lasers lead to improved beam quality, efficiency and compactness compared to conventional CO_2 and lamp-pumped lasers. In the past 4 years the first generation of diode laser-based new laser sources have been introduced into industrial production. First prototypes of the second
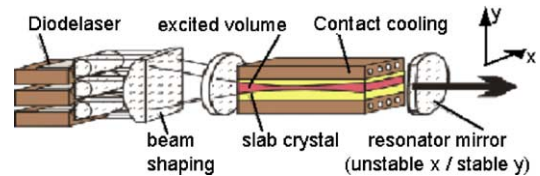
Fig. 9. The Innoslab concept takes advantage of gain-guided generation of laser radiation. Homogeneous excitation by beam shaping of the diode laser is a key feature.

generation of diode-pumped solid-state lasers are ready for use. Beside improvements in efficiency and beam quality these laser sources provide short (ns) and ultrashort (ps and fs) pulses with very high pulse powers, leading to improved process efficiencies and new fields of laser application.

Disc lasers and end pumped slab lasers allow average powers up to the kilowatt regime and beam qualities comparable to a CO_2-laser. While disk lasers have been proven to provide good CW performance, pulse performance is limited by comparable low pulse energy and low gain, leading to 100 ns pulses in *Q*-switched operation. Mode-locked oscillators generating ps pulses at more than 100 W average output power have been demonstrated.

Slab lasers provide highest beam quality at kilowatt output level and the ability of short pulse generation (5–10 ns) in *Q*-switch mode. High gain lead to efficient single pass amplification for example amplification of a 4 W signal at 7 ps pulse duration and 100 MHz repetition rate to about 50 W average power with a single amplifier stage are available already.

Based on the end pumped slab laser concept (Fig. 9) the Fraunhofer Institute ILT and the Company EdgeWave have developed an electro-optically *Q*-switched laser delivering 50 W output power at 45 kHz. The pulse length is about 5 ns. The pulse energy reaches 5 mJ at 5 kHz. The pulse peak power is 800 kW at almost diffraction limited beam quality. This high peak power and beam quality is used for engraving inside transparent materials (Fig. 10) generating three-dimensional pictures. A new application is laser polishing; remelting with CW-lasers and finishing by short pulse lasers.

Processing of dielectric materials generally requires ultraviolet radiation because of the low absorption of the infrared. Therefore, excimer lasers and frequency-tripled Nd:YAG lasers are used because of their good optical absorption and high ablation efficiency. Short pulse lasers, especially frequency-tripled, diode-pumped Nd:YAG lasers with a high beam quality offer the possibility to ablate these materials with high quality. With a spot size of about 10 μm, high fluence ($>100 J/cm^2$) is achieved, so that the materials are vapourised with small amounts of molten material. This technique is applicable for drilling small holes with diameters ≥ 5 μm (aspect ratio up to 60) and cutting of thin ceramic substrates (thickness 0.5 mm). The edges are sharp and the surface roughness can be reduced to $R_a \leq 0.1$ μm. Low ablation rates (0.05 μg per pulse) are in favour of controlled
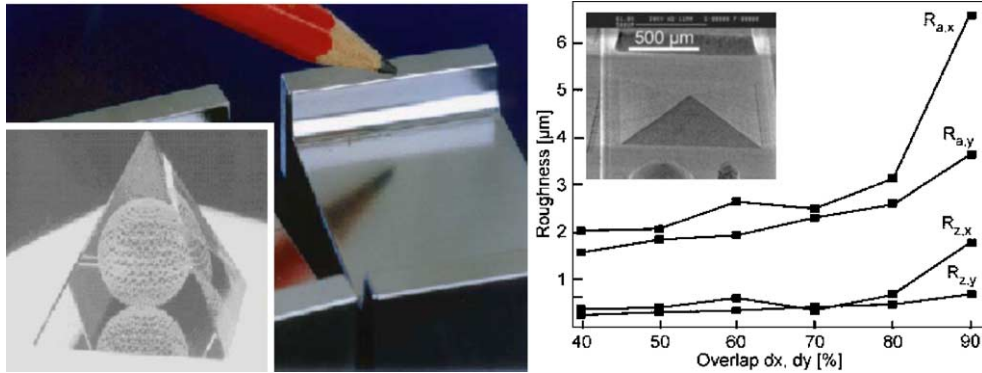
Fig. 10. Left: engraving inside transparent material at $400\,GW/cm^2$ generates optical breakdown causing visible micro deformations and laser polishing by remelting with CW-lasers and finishing by short pulse lasers. Right: surface roughness of WC-embossing tool after laser micro-structuring ($\lambda = 355$ nm, $f_p = 5$ kHz, $E_p = 0.26$ mJ).

micro-machining and high precision. The achieved removal depth per pulse has a maximum at a material specific energy density and decreases for higher values. The thickness of the recast layer can be reduced to $<5\,\mu m$ depending on energy per pulse and pulse length.

Precise products are produced by 30–50% overlap. Out of this range the roughness increases steeply [19,20]. As an example, the pyramid made of WC as part of an embossing tool has a surface roughness, comparable to EDM (Fig. 10). The ablation removes around $1\,\mu m$ per step without thermal damage. The adhesion of the removed debris is very weak, the structures are cleaned easily in an ultrasonic bath.

6.1. Examples of applications

6.1.1. Laser cleaning

Pulsed Nd:YAG lasers are also used in the cleaning and recycling area. Spur [21] has developed a process for de-coating compact disks, made of $\varnothing 120$ mm $\times$ 1.2 mm polycarbonate discs coated with 50 nm aluminium and $10\,\mu m$ varnish. The industry is seeking solutions for an economical and efficient recycling process due to the EU waste law for information technology. It is estimated that of the 10 billion disks annually 3 billion pieces will be collected for recycling. The applied laser is a 50 W, 8 ns Q-switched Nd:YAG laser delivering 2 J pulses, which chip the aluminium and varnish, and does not influence the transparent polycarbonate. The removal rate at 50 Hz is $22\,cm^2/s$ which results in a de-coating time of 5 s and cost (including handling and labour) of \$ 0.04 per disk. This is in the same order as the production costs of a new disk! [22].

Another cleaning application is surface cleaning of silicon wafer by 'laser sparking' which is a gas breakdown caused by an intense laser pulse focussed in the air above the wafer surface. It was shown by Lee et al. [23] that an airborne plasma shock wave above the surface successfully removes small particles ($\sim 1\,\mu m$ diameter) such as tungsten, copper and gold from the silicon surface. This contactless cleaning technique is an efficient, fast and damage-free pro-

cess. It has superior characteristics compared with conventional laser cleaning employing direct interactions between the laser pulse and the particles. In conventional laser cleaning a fourth harmonic Q-switched Nd:YAG laser (266 nm, 10 ns) is directed on the Si substrate. The small tungsten particles are removed by a rapid thermal expansion of the particle resulting from the laser absorption. This requires fluencies above $0.65\,J/cm^2$ to overcome the strong adhesion force for smaller particles. The short wavelength is necessary because of the better absorptivity of W, Cu and Au for this wavelength. The fluency, however, must be kept below the threshold fluency of Si damage ($0.3\,J/cm^2$). This is not enough for efficient particle removal in the conventional way. In the new contactless method the striking incoming beam is focussed 2 mm above the surface at around $10^{11}\,W/cm^2$ causing an optical breakdown of the air resulting in a shock wave of several hundreds of megapascals [24,25] depending on the distance to the origin. This is well above the adhesion forces of 1 MPa for $1\,\mu m$ or 3 MPa for $0.1\,\mu m$ tungsten particles. Once the bond between the particle and the substrate surface is broken, the detached particles are accelerated to high velocity and blown away by the expansion following the shock wave (Fig. 11). In this application, the fundamental 1064 nm wavelength of the 10 ns Q-switched Nd:YAG laser can be applied because there is no direct interaction with the particles. The cleaned area per shock is around $2\,cm^2$, which is one order above the conventional technique.

Fig. 11. Optical micrographs of the silicon surface, (left) before and (right) after the laser shock treatment for the removal of a mixture of submicron W, Cu and Au particles adhered on the surface, Lee et al. [23].
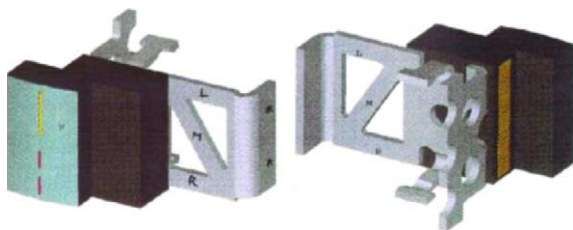
Fig. 12. Laser fine adjustment of an audio head. Laser heating at L rotates the head clockwise at R counter-clockwise. A pulse at M, moves the head downwards and at L + R upwards [27].
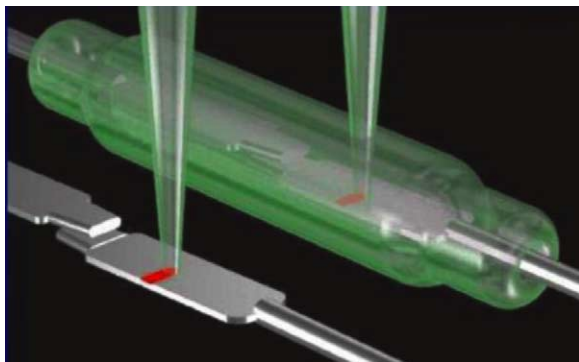

Fig. 13. Laser adjustment of reed contacts. The distance between the metal reeds determines the strength of the magnetic field where the switch closes.

6.1.2. Adjustment

Pulsed lasers are applied successfully to adjust micro-electro mechanical assemblies. This opens new ways to optimise the design of actuators according to Geiger et al. [26]. Pulsed Nd:YAG as well as excimer lasers are applied to adjust (and bend) various materials as stainless steel, copper alloys or lead frame materials like FeNi42. Hoving [27] describes the adjustment of audio heads mounted on a dedicated adjustment frame (Fig. 12). Laser pulses on the indicated positions result in a micrometer accuracy fine adjustment. Another application is the adjustment of reed contacts. The intensity of the adjustment pulse is based on the measured magnetic field to open/close the contacts (Fig. 13). A special requirement for this application is that the laserbeam has to pass the green glass enclosure of the reed contacts. Laser adjustment is a flexible alternative for micro-bending by sparks. Otsu et al. [28] found the latter more advantageous for highly reflecting materials like copper.

7. Excimer lasers

Excimer lasers are a family of pulsed lasers operating in the ultraviolet by a fast electrical discharge in a high-pressure mixture of rare gas (krypton, argon or xenon) and a halogen gas (fluorine or hydrogen chloride). The combination of rare gas and halogen determines the output wavelength. Typical pulse energies are a few hundred millijoules to one joule.

Table 5
Photon energies obtained from different laser sources [29]

Laser	Wavelength (nm)	Photon energy (eV)
XeF	351	3.53
XeCl	308	4.03
KrF	248	5.00
KrCl	222	5.50
ArF	193	6.42
F_2	157	7.43

The average power is in the range of 10 W to 1 kW. The pulse length is typical in the 10–20 ns range resulting in peak powers of tens of megawatts. These lasers offer a variety of photon energies (Table 5). Application areas are: ablation, lithography, micro-fabrication.

7.1. Ablation

Two ablation mechanisms are distinguished: photolytic and pyrolytic processes. In photolytic processes the photon energy is directly applied to overcome the chemical bonding energy of (macro) molecules. In case of polymers they are broken into smaller often gaseous monomers. The photon energy of the KrF laser is sufficient for most cases (Tables 5 and 6).

When all laser energy is used to overcome the chemical binding energy, the ideal case, it is known as "cold ablation". In case of metals, however, the laser energy is first absorbed by electrons, then transferred to heat, which melts and evaporates the metal, just like other lasers do. Fig. 14 shows how in photolytic processes the molecules are taken away, while pyrolytic processes melt the material first and evaporates from the melt surface.

The material removal of organic polymers consists of three steps. First the UV photons are absorbed in the top layer of typical 0.2 μm thickness, then the long chain molecules in this layer are broken into parts and finally they are removed from the processing area in the form of vapour and small particles. Photons with more than 5.1 eV will break oxygen molecules in its path. This is demonstrated by the characteristic ozone smell of a 193 nm ArF beam passing through air. The threshold fluence for a wide variety of plastics is about 120 mJ/cm^2. At low fluence the walls become tapered from about 2° at 500 mJ/cm^2 to 20° at 150 mJ/cm^2. Useful fluences are given in Table 7.

Table 6
Chemical bonding energies

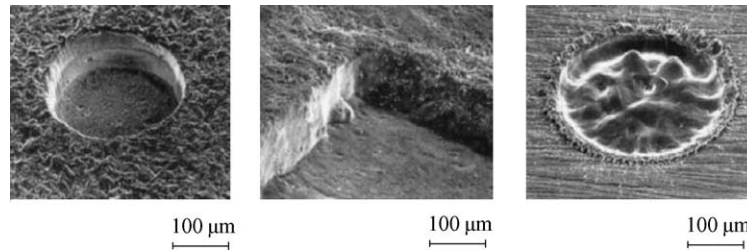| Chemical bond	Bond energy (eV)
Si–Si, Cl–Cl	1.8–3
C–N, C–C	3–3.5
C–H, O–H	4.5–4.9
C=C	7

Fig. 14. Interaction of excimer laser radiation with solids. Right: PVC, photolytic ablation. Left: metal, melt. Middle: Al_2O_3 ceramic, combined photolytic and pyrolytic process. Lambda Physik [30].

7.2. Lithography

Lithography is a vital step in micro-electronics. The cost of lithography is typical 35–40% of the wafer costs. Currently mostly the 248 nm KrF laser is applied in step and repeat cameras. Based upon trends over the last 20 years [31] it is likely that 64 Gb DRAMS with 70 nm features will be in production in 2010. This requires shorter wavelengths of 193 nm and further 157 nm which requires high performance deep-UV optical components from materials like BaF_2 or CaF_2 which have to be developed under an tight time schedule for the introduction of 157 nm that the industry is committed to achieve [32].

7.3. Laser LIGA

Excimer laser ablation is also used for the fabrication of micro-electro mechanical systems (MEMS) by the LIGA process. As an alternative for the expensive X-ray LIGA the laser LIGA process has been developed for the realisation of three-dimensional micro-structures [33]. This process produces nickel structures of several hundred-micrometer thicknesses. By alternating deposition of metal and resin layers complex multiplayer structures can be obtained by excimer mask projection ablation [34].

7.4. Micro-fabrication

Micro-parts of almost any geometry can be produced by mask projection. Drilling holes, however, is the key application in micro-fabrication. Excimer lasers offer three significant advantages for drilling applications over lasers that emit in the visible and infrared. First, the short ultraviolet light can be imaged to a smaller spot size than the longer wavelengths. This is because the minimum feature size is limited by diffraction, which depends linearly with the wavelength. The second advantage is that due to the mechanism of "photoablation" there is less thermal influence or melting of the surrounding material. Finally, most materials show a strong absorption in the ultraviolet region. This means that the penetration depth is small and each pulse removes only a thin layer of material, allowing precise control of the drilling depth [35].

In printed circuit board (PCB) fabrication many bridging holes (via's) are produced to make electrical connections in multi-layer PCBs. The holes are drilled in dielectric polyimide layer until the underlying copper layer is uncovered. The drilling then stops automatically because of the higher threshold (one order of magnitude) of copper. The conducting connection is made by a following chemical deposition of copper on the via walls. The process has been developed in 1990 by Bachmann [36] and is used for drilling small $\approx 10\,\mu m$ holes. For bigger holes of $100\,\mu m$ and above the cheaper and faster CO_2-lasers are currently used.

7.5. Ink jet nozzles

Ink jet printers are widely used because they offer good quality at low cost, based on a simple design. It consist of an array of small orifices with precisely defined diameter and taper, each located on top of a channel with resister heater. Small bubbles are formed when the ink is heated; ejecting small (3–80 pl) drops out of the nozzle. Riccardi et al. [37] describes the fabrication of high-resolution bubble ink jet nozzles, Fig. 15. Depending on the design up to 300 holes have to be drilled simultaneously in a $0.5\,mm \times 15\,mm$ area. This is obtained by $5\times$ demagnification of a 400 mJ pulse

Table 7
Ablation thresholds for various materials

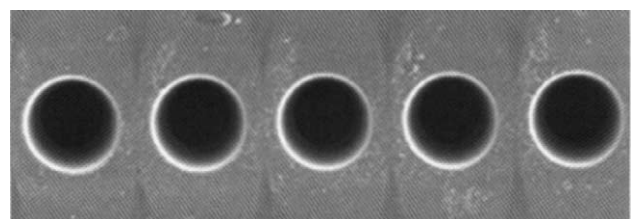| Material	Fluency (mJ/cm^2)
Photo resist	30
Polycarbonate	40
Polyimide	45
Silicon nitride	195
SiO_2	350
Glass, metal oxide	700–1200
Metals	4000–8000

Fig. 15. Array of ink jet nozzles drilled in $50\,\mu m$ thick polyimide.

to 0.6–0.8 J/cm^2 fluency. About 300 pulses are applied to obtain 55 μm holes with 27° taper. The total drilling time is about 1 s, using a 300 Hz KrF laser. Recent developments will require smaller holes below 25 μm diameter.

7.6. Others

There are a lot of other applications of short pulsed excimer lasers like marking of eye glasses, medical devices, aircraft cables and electronic devices, writing of fiber Bragg gratings for telecom applications, medical applications in surgery, etc. Two of them will be described in more detail, ablation of diamond and laser cleaning.

7.7. Laser ablation of diamond

Diamond is difficult to machine [38] because it is transparent in a wide wavelength range. At high power densities, however, the diamond is transited into graphite, which absorbs the laser power and is removed by ablation subsequently. Diamond machining is currently done by microsecond pulse Nd:YAG and nanosecond pulse excimer lasers [39].

Examples of applications are drilling holes in wire drawing dies (Fig. 16) and cutting of knife blades for eye surgery. Thin layers of graphite or amorphous carbon are found on the surface after laser machining which requires an extra polishing operation to remove the graphite. An alternative (new) technique is the use of ultrashort femtosecond lasers. No evidence of graphite was found [40] because the thermal diffusion depth is only 50 nm. Some processing data is given in Table 8.

7.8. Excimer laser cleaning

Excimer lasers but also *Q*-switched Nd:YAG lasers are applied for surface cleaning, particularly in the electronic industry. Examples are cleaning of silicon stencils (masks

Table 8
Laser ablation of diamond

Laser	*Q*-switched Nd:YAG	Excimer laser	Femtosecond laser
Wavelength	1.06 μm	248 nm	248 nm
Pulse length	150 ns	20 ns	500 fs
Diffusion depth	30 μm	10 μm	50 nm
Fluence (J/cm^2)	Removal rates per pulse		
0.8		5 nm	5 nm
2		10 nm	15 nm
4		20 nm	35 nm
6		30 nm	50 nm
10	0.5 μm	45 nm	
20	1.0 μm	60 nm	
50	2.5 μm		
150	4.0 μm		

for e-beam lithography), magnetic head sliders and optical components. Particles are preferably removed using a thin liquid film of water or ethanol allowing low energy densities for an explosive evaporation of the liquid, which blows away all particles. Differences in ablation threshold are used to remove printing residues from chromium plated rotogravure cylinders. By scanning the whole surface at a fluency below the ablation threshold for the chromium ($\approx$5 J/cm^2) all contamination is removed in an environmental friendly way [41].

7.9. Surface cleaning of art

Impressing results were achieved in the restoration of paintings by 20 ns KrF excimer laser pulses (Fig. 17). The ablation depth per pulse is about 1 μm. Process monitoring of the laser induced plasma by real time spectroscopy [42] allows for precise control of the ablation depth and identification of the different layers.

Fig. 16. Diamond wire drawing die. Wire opening 50 μm (Diamond Tools Group).

Fig. 17. Partial (left) and fully cleaned fine arts, Art-Innovation, NL [43].

The market forecast for excimer lasers is more or less stable. At the low power segment there is a shift from excimer lasers toward higher harmonic Nd:YAG lasers (green 532 nm and UV 355 or 266 nm), which become available for low power micro-machining and for semiconductor materials processing. The UV Nd:YAG lasers operate in the same wavelength and pulse length domain as the excimer laser. The average output is one to two orders less, but nevertheless the peak power intensity is high (10^7 to 10^8 W/cm^2) because of the short pulse length and superior beam quality.

Another development are the very high power kilowatt excimer lasers, which are developed for simultaneous drilling for huge amounts of small holes for instance for the aerospace industry (holes for cooling of engine parts and for boundary layer suction). One of the research efforts in this area is the generation of longer pulses [44]. The driving force is an increased overall system efficiency, lower stresses on the electrical components and better beam quality. Longer pulses could also be more efficiently transmitted in fiber delivery systems [45].

7.10. Three-dimensional micro-machining

With normal mask projection techniques the homogeneous power density distribution will result in an equal ablation over the whole area of the mask. For three-dimensional structures different sets of mask are used. This generally results in a stepwise structure. Masuzawa et al. [46] has developed the Hole Area Modulation method using a semitransparent mask, consisting of series of small holes enabling a continuous variable depth just by oscillating the mask in pre-programmed patterns.

8. Copper vapour lasers

Copper vapour lasers (CVL) belong to the family of metal vapour lasers, which use mixtures of metal vapour and rare gases to produce laser light. There are copper vapour, helium–cadmium and gold vapour lasers. They operate at temperatures of 200–1200 °C to keep the metal in vapour state. The excitation is by electrical discharges in the gas mixture. Copper vapour lasers produce green and yellow light from a mixture of copper vapour and helium

or neon. They are excellent sources of short, high intensity laser pulses at high repetition rate. The active medium, copper, is contained in a ceramic tube 1 m length, 25 mm diameter for 20 W output and up to 3 m × 60 mm for 300 W and more. The tube is contained in vacuum and heated by a pulsed discharge to 1450 °C where the copper vaporises. Laser action results from high-energy electrons and neutral copper atoms. The neon at a pressure of 20–60 mbar starts the discharge current when the tube is cold.

Copper vapour lasers are mainly applied to drill, cut and micro-mill materials with a thickness up to 1.5 mm in metals, silicon, diamond, ceramics and polymers. Typical applications are: inkjet nozzle drilling, diesel injector drilling, spinneret drilling and cutting, precision machining and writing Fiber Bragg Gratings. Drilling, cutting and micro-milling are the common applications for the green light [47]. Among them simple "holes" are the most popular structures. These are found in medical flow controllers, micro-electronic contacts and medical filters (Fig. 18). Holes are also used to make plastics "breathable", to calibrate leak testers and to perforate foils.

The light of copper vapour lasers is more strongly absorbed in metals than that of IR lasers. This leads to deep holes with a small heat-affected zone. Aspect ratios of greater than 40 and surface roughness in the order of 1–2 μm are reported by Allen et al. [48].

In the automotive sector engineers are under considerably regulatory pressure to reduce the emission level of combustion engines. A major contributor to high emissions is the fuel injector. The current technique of EDM produces excellent holes but at low processing speed. Hole diameters less than 150 μm become increasingly difficult. Micro-machining by CVL has demonstrated the ability to produce nozzles with diameters of 50–200 μm without dross on the exit side. The entry side has minimum dross, which can be removed by light abrasion. Fig. 19 (left) shows some 50 μm holes.

Progress in drug discovery and analysis of the human genome sequence require the development of micro-tools and techniques to acquire and process vast amounts of data looking at the behaviour of many thousands of genes together. This corresponds with increased speed and automation in biomedical instrumentation like a pin-based picolitre dispenser to take thousands of genetic samples for massive
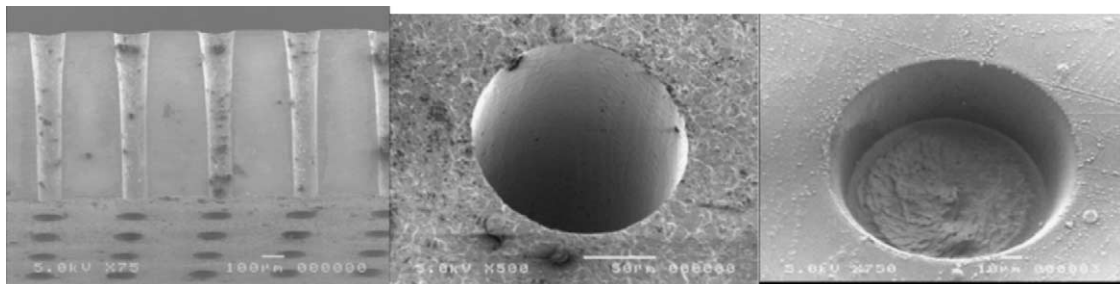

Fig. 18. Hundred-micrometer holes for medical filters, middle close up of one hole, right blind hole.
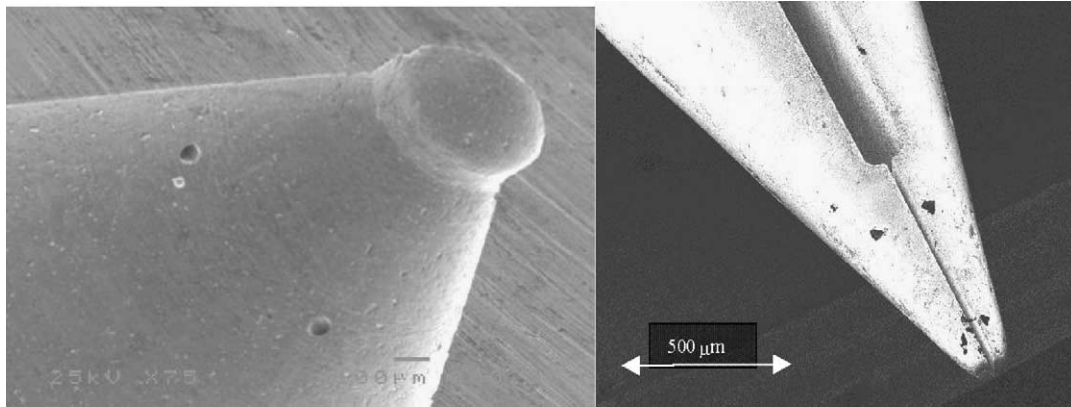
Fig. 19. Left: section of diesel injection nozzle. Right: a micro-reservoir pin with a 15 μm wide by 600 μm long capillary and a reservoir 100 μm wide and 1000 μm long [49].

parallel testing. The critical component is a tapered pin with a capillary slot [49] produced by CVL (Fig. 19, right).

Ink jet nozzles require accurate dimensions and smooth surface finish to obtain laminar flow of ink and prevent turbulence. Allen et al. [50] has fabricated ink jet nozzles of metal sheet by three different fabrication techniques (micro-electrodischarge machining, micro-drilling and CVL machining). He evaluated the characteristics of each technique while assessing the differences between them.

Micro-EDM is one of the few techniques that can be used for micro-hole fabrication following Almond et al. [51] and Masuzawa [52]. A single hole of 50 μm diameter through 100 μm thick stainless steel takes typical 3 min. With CVL a single pulse will remove the material to a depth of 10 μm, which means that micro-holes are machined within seconds by 30 ns pulses at 10 kHz. The short pulsewidth in CVL reduces the heat-affected zone. Aspect ratios greater than 40 are reported for stainless steel, the surface roughness is of the order of 1–2 μm. Trepanning was used to improve the quality of the holes. Results are given in Table 9.

Although micro-EDM is an established process with excellent hole quality, its relative slowness is its main drawback. CVL is much faster but the improvement of surface profile requires further investigation for direct writing of complex micro-structures as applied in creating channels in glass plates to control micro-fluid flow, engraving hard materials, micro-marking for security purposes etc. High precision micro-machining will be the key application that finally will cause the industrial breakthrough.

Table 9
Comparison of micro-hole fabrication methods

Process	Advantages	Disadvantages
Micro-EDM	Surface finish, edge profile	Slow
CVL	Edge profile, fast	Flaked recast gives rougher appearance
Micro-drilling	Fast	Burring of edges, tool breakage

9. Femtosecond lasers

The latest generation pulsed lasers delivering the shortest pulses are the femtosecond lasers. In these systems, pulsing is mostly achieved by mode coupling of a broadband laser source. Typically, the bandwidth exceeds several tens of nanometer bandwidth, which allows pulse duration well below 100 fs. Due to the short pulse duration, peak powers of more than 15 GW can be reached, which gives access to further ablation mechanisms, like multi-photon ionisation.

Due to the short interaction time, only the electrons within the material are heated during the pulse duration. Once the laser pulse has stopped, the lattice of the material experiences the influence of the overheated electrons. This results in two different ablation regimes, dependent on the penetration depth of the overheated electrons, which at fluencies over 500 mJ/cm^2 can exceed the optical penetration depth of about 10 nm [53]. This enables ablation rates up to 250 nm at 10 J/cm^2. Especially for low fluences, where the thermal diffusion length is smaller than the optical penetration depth, heat diffusion is be strongly suppressed, which allows highest precision and minimal heat influence within the material. The intensity during such laser pulses initiates multi-photon effects, which allows machining of literally any solid material. Applications are limited to micro-machining processes, where the total volume of ablated material is rather small due to the limited average power output.

Most femtosecond lasers are based on titanium:sapphire, due to its broad bandwidth. The short pulses are generated within the oscillator, typically providing a pulse train of short pulses at low pulse energy of some nanojoules per pulse. As this energy is not sufficient for most micro-machining applications, further amplification has to be provided. A direct amplification is not viable, as the intensity would destruct beam profiles and the internal optics. Therefore, the intensity has to be reduced to sufficient values, which is being done using the *Chirped Pulse Amplification* (CPA) technique [54]. Typical commercial available systems show average output powers of 1.5 W and up to 250 kHz repetition
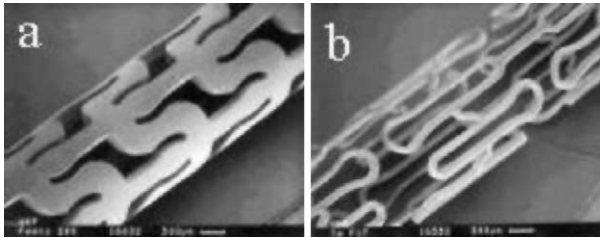
Fig. 20. Prototypes of stents made of: (a) bio-resorbable polymer and (b) tantalum.

Fig. 21. Examples of silicon cutting.

rate. This power output allows micro-machining processes, but limits the amount of removed material per time. Nevertheless, promising applications are found in the precise machining of thermal sensitive materials.

Apart from direct use of fs-lasers in medicine for surgery, for example the correction of myopia like laser assisted in situ keratomileusis (LASIK), the structuring of medical implants, e.g. coronary stents, is a promising application with growing industrial interest [55]. Coronary stents are used as a minimally invasive treatment of arteriosclerosis, an alternative for bypass operations. The requirements of medical implants (e.g. burr-freeness, X-ray opacity) are very strict so just a few materials are commonly used. Typical materials used for stents are stainless steel or shape memory alloys. Chemical post-processing techniques have been developed to achieve the required properties. However, these materials are not optimal in several medical aspects (e.g. risk of restenosis, limited bio-compatibility, etc.). New approaches favour stents for temporary use, which necessitate bioresorbable materials like special bio-polymers (Fig. 20a).

Other materials, like tantalum, show improved X-ray visibility (Fig. 20b). For these materials, no established post-processing technique is available. Most of them show strong reactions to thermal load. It is essential to avoid influences on the remaining material in order to keep the specific material properties. Femtosecond pulse laser material processing meets these requirements.

9.1. Cutting of silicon

Silicon is the most important material in the micro- and semiconductor industry for the fabrication of micro-chips, sensors, and actuators. Conventional lasers have not be applied for high precision structuring of semiconductors as they cause thermal melting, cracks, and deposits but femtosecond laser systems overcome these limitations, since thermal and mechanical influences are minimised. Cutting of silicon using fs-laser pulses shows high quality (Fig. 21) well suited for cutting thin wafers. In contrast to the conventional dicing method, non-linear narrow cuts are performed with a wear-free tool. The process quality is enhanced because there is no interaction between the expanding plasma and the laser pulse (plasma shielding effect) as light absorption and ablation are separated in time.
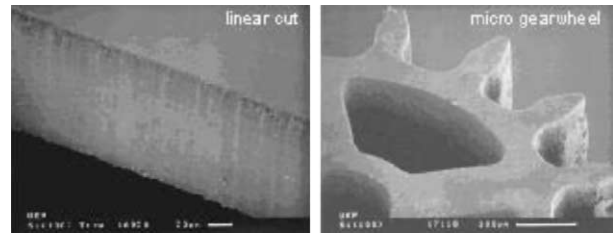
Although femtosecond lasers offer new and very promising ways of micro-machining almost any solid material, they are not yet introduced into industrial service due to some drawbacks. As the CPA-technique is fairly complex, the system contains much more optical components than conventional lasers. This might influence the stability of operation by environmental conditions like temperature, vibrations, etc. Up to today, those systems are mainly applied for scientific purposes, which necessitates operating the laser by highly trained staff. For industrial operation, such operators are not available. Therefore, industrial service requires much easier operations and less maintenance. The laser manufacturers have identified these problems, so the fs-lasers are presently designed to match the requirements of industrial service. fs-Lasers will be used for high quality applications, which are not achievable by other means. Due to high investments, low-cost applications seem not to be economically by this kind of lasers. Future laser development will increase the process speed by increasing repetition rate as well as average output power. By reducing the costs for the laser system as well, economical machining of several applications will be realised.

10. Accuracy

Improvement of accuracy has been a central topic along 50 years of CIRP history as described by Peters et al. [56], Merchant [57], McKeown [58] and many others. Short pulses have great potential to obtain higher accuracies in dimensional control because of the very small amounts of material that can be removed per pulse, as well because the very small damaged (heat-affected) zone at the surface. Another merit of using 'image tools' compared with solid tools (e.g. EDM) is the wide space, available for release of debris. Applications are found in the semiconductor industry where the demand for accuracy follows from the continuing miniaturisation in accordance with Moore's law developed in 1965 [59–61] and in the ultra precision machining following the trend given by Taniguchi in 1983 [62].

In 1965, Gordon Moore, the founder of Fairchild Semiconductor and Intel, observed only 6 years after the introduction of the commercial planar transistor in 1959 an astounding trend; the number of transistors per chip was doubling every year. In 1975 Moore updated his law

distinguishing three contributing components: (1) increasing chip area (15% each year), (2) decreasing feature size (11% per year, or 27% less area). Both factors resulted in 60% increase of the number transistors per chip; (3) the rest of the improvement was because of better design. In the first 15 years the chip complexity doubled each year and since 1975 when the design has reached its optimum, the increase was still 60% per year. When we extrapolate current trends to the year 2010, the minimum feature size will be 70 nm.

This sets the requirements for the future lasers. The feature size depends on four factors; the beam quality should be excellent ($M^2 \approx 1$), the wavelength as short as possible in the UV, the f number small ($f\# \approx 1$) and the power density just above the threshold intensity so that only the central part of the beam is used. Currently, feature sizes of 30 nm have been experimentally demonstrated [63], but it is far from production. Companies are assessing nano photolithography with excimer wavelengths of 193 and 152 nm.

In the machine industry, Taniguchi published his famous paper in 1983 [62]. From his graphs an increasing accuracy of 10% per year is found, which is remarkable in balance with the 11% predicted by Moore. Taniguchi expected in 2010 an ultimate accuracy of 1 nm by atom, molecule or ion beam machining. He did not consider laserbeam processing although photons are a much finer tool than atoms or ions. Even electron beams are not considered because he says:

> "it became clear that direct thermal machining using high energy electron beams is not suitable for ultra precision machining because the high energy electrons penetrate the surface layers to depths of many microns or tens of microns (at 50 kV typically 10 μm in aluminium). The energy is transferred to the atoms in the form of heat over a relatively large zone of several microns".

The reason that photons can perform better is because:

- photons are much smaller than electrons,
- they are electrical neutral so there are no repulsive forces,
- the optical penetration depth is only 10 nm for metals,
- the thermal penetration depth is of the same order.

Taniguchi could not consider this because there was no idea of femtosecond machining at that time. Nevertheless, some problems have to be solved before laser micro-machining will be applied on industrial scale. Not only the lasers should be more compact and robust but also the reliability in process- and dimensional control is most challenging.

Acknowledgements

References

[1] S. Postma, J. Meijer, R.G.K.M. Aarts, Method and device for measuring and controlling a laser welding process, International Patent WO 03/022508 A1 (2003).

[2] G.N. Levy, R. Schindell, J.P. Kruth, Rapid manufacturing and rapid tooling with layer manufacturing technologies, state of the art and future perspectives, Ann. CIRP 52 (2) (2003) 589–610.

[3] X. Chen, X. Liu, Short pulsed laser machining: how short is short enough? J. Laser Appl. 11 (6) (1999) 268–272.

[4] J. Bosman, Laser engraving processes, Ph.D. Thesis, University of Twente, in preparation.

[5] V. Semak, Laser drilling: from milli to femto, Laser solutions course, in: Proceedings of the ICALEO 2001, Jacksonville, October 18, 2001, pp. 1–9.

[6] E. Ohmura, I. Miyamoto, Molecular dynamics simulation on laser ablation of metals and silicon, Int. J. Jpn. Soc. Precis. Eng. 34 (4) (1998) 248–253.

[7] Y. Ishizaka, K. Watanabe, I. Fukumoto, E. Ohmura, I. Miyamoto, Three-dimensional molecular dynamics simulation on laser materials processing of silicon, in: Proceedings of the ICALEO98, 1998, pp. A55–A63.

[8] E. Ohmura, I. Fukumoto, I. Miyamoto, Molecular dynamics simulation on laser ablation and thermal shock phenomena, in: Proceedings of the ICALEO 1998, pp. A45–A54.

[9] E. Ohmura, I. Fukumoto, Study on fusing- and evaporating process of fcc metal due to laser irradiation using molecular dynamics, Int. J. Jpn. Soc. Precis. Eng. 30 (1) (1996) 47–48.

[10] J. Meijer, K. Du, A. Gillner, D. Hoffmann, V.S. Kovalenko, T. Matsunawa, A. Ostendorf, R. Poprawe, W. Schulz, Laser machining by short and ultrashort pulses, state of the art and new opportunities in the age of the photons, Ann. CIRP 51 (2) (2002) 531–550.

[11] F.J. McClung, R.W. Hellwarth, Characteristics of giant optical pulsations from ruby, Proc. IEEE 51 (1963) 46.

[12] H.W. Mocker, R.J. Collins, Mode competition and self-locking effects in a Q-switched ruby laser, Appl. Phys. Lett. (7) (1965) 270.

[13] F. Krausz, T. Brabec, C. Spielmann, Self-starting passive mode locking, Opt. Lett. 16 (1991) 235.

[14] D. Guillot, Microlasers, Photonics Spectra 32 (1998) 143–146.

[15] V.S. Kovalenko, Laser Technology, Vyscha Schola, Kiev, 1989, 280 pp.

[16] G. Ogura, J. Angell, D. Wall, Applications test potential of laser micromachining, Laser Focus World 34 (1998) 117–123.

[17] S.M. Klimentov, S.V. Garnov, T.V. Kononenko, V.I. Konov, P.A. Pivovarov, F. Dausinger, High rate deep channel ablative formation by picosecond–nanosecond combined laser pulses, Appl. Phys. A 69 (1999) 633–636.

[18] C. Stewen, K. Contag, M. Larionov, A. Giesen, H. Hügel, A 1 kW thin disc laser, IEEE JSTQE 6 (4) (2000) 650–658.

[19] H.K. Tönshoff, J. Mommsen, Process of generating three-dimensional microstructures with excimer lasers, in: Proceedings of the ECLAT92, Göttingen, 1992.

[20] D. Hellrung, A. Gillner, R. Poprawe, Laser beam removal of micro-structures with Nd:YAG lasers, in: Proceedings of the Lasers in Material Processing Laser'97, Munich, SPIE 3097 (1997) 267–273.

[21] G. Spur, Industrial cleaning technologies for hard surfaces: dry ice blasting and laser, in: Proceedings of the 40th International detergency Conference IDC'01, 2001, pp. 156–165.

[22] W. Hoving, Philips, CFT, Private communication.

[23] J.M. Lee, K.G. Watkins, W.M. Steen, Surface cleaning of silicon wafer by laser sparking, J. Laser Appl. 13 (4) (2001) 154–158.

[24] J.F. Ready, Effects of High Power Laser Radiation, Academic Press, New York, 1971, p. 213.

[25] R.E. Kidder, Nucl. Fusion 8 (1968) 3.

[26] M. Geiger, M. Kleiner, R. Eckstein, N. Tiesler, U. Engel, Microforming, Ann. CIRP 50 (2) (2001) 445–462.

[27] W. Hoving, Laser fine adjustment, in: Proceedings of the ICALEO, 2001.

[28] M. Otsu, T. Wada, K. Osakada, Micro bending of thin spring by laser forming and spark forming, Ann. CIRP 50 (1) (2001) 141–144.

[29] J. Meijer, in: J.A. McGeough (Ed.), Micromachining Materials, Marcel Dekker, 2002, pp. 203–237.

[30] D. Basting, Excimer Laser Technology: Laser Sources, Optics, Systems and Applications, Lambda Physik AG, Göttingen (D), 2001.

[31] A. Hind, Spectrophotometry takes measure of deep UV lithography, Photonics Spectra 35 (2001) 82–86.

[32] J.H. Burnett, Z.H. Levine, E.L. Shirley, Hidden in plain sight: can lithographers design out the intrinsic birefringence of calcium fluoride, or must they find a new material solution for 157 nm lithography, Photonics Spectra 35 (2001) 88–92.

[33] http://www.cee.hw.ac.uk/microengineering/microsystems/uv-liga/.

[34] J.A. MacGeough, M.C. Leu, K.P. Rajurkar, A.K.M. De Silva, Q. Liu, Electroforming process and application to micro/macro manufacturing, CIRP Ann. 50 (2) (2001) 499–514.

[35] J.F. Ready, LIA Handbook of Laser Materials Processing, Magnolia Publ. Inc., 2001, p. 491.

[36] F.G. Bachmann, Industrial laser applications, Appl. Surf. Sci. 46 (1990) 254–263.

[37] G. Riccardi, M. Cantello, F. Mariotti, P. Giacosa, Micromachining with excimer laser, Ann. CIRP 47 (1) (1998) 145–148.

[38] Lasers are diamond's best friend, Photonics Spectra 26 (1992) 40.

[39] R. Windholz, P. Molian, Nanosecond pulsed excimer laser machining of CVD diamond and HOPG graphite, J. Mater. Sci. 32 (1997) 4295–4301.

[40] M.D. Shirk, P.A. Molian, Ultrashort laser ablation of diamond, J. Laser Appl. 10 (2) (1998) 64–70.

[41] R. Lotze, J. Birkel, K. Wissenbach, Entlacken mit Laserstrahlung, Neue industrielle Anwendungen, JOT Journal für Oberflächentechnik, 1999/8.

[42] S. Klein, T. Stratoudaki, V. Zafiropoulos, J. Hildenhagen, K. Dickmann, Th. Lehmkuhl, Laser induced breakdown spectroscopy for on line laser cleaning of sandstone and stained glasses, Appl. Phys. A 69 (1999) 441–444.

[43] http://www.art-innovation.nl.

[44] A. Schoonderbeek, C.A. Biesheuvel, R.M. Hofstra, K.-J. Boller, J. Meijer, High speed drilling of metals with a long pulse XeCl excimer laser, Proc. SPIE 4760 (2002).

[45] C. Fotakis, in: Handbook of the EuroLaser Academy, vol. 1, Chapman & Hall, London, 1998, pp. 227–265.

[46] T. Masuzawa, J. Olde Benneker, J.J.C. Eindhoven, A new method for three dimensional excimer laser micromachining by hole area modulation (HAM), Ann. CIRP 49 (2000) 139–142.

[47] V. Kovalenko, M. Anyakin, Y. Uno, Modeling and optimization of laser semi conductor cutting, in: Proceedings of the ICALEO, Laser Microfabrication, vol. 90, 2000, pp. 82–92.

[48] D. Allen, H. Almond, P. Logan, A technical comparison of micro-electrodischarge machining, micro drilling and copper vapour laser machining for the fabrication of ink jet nozzles, Proc. SPIE 4019 (2000) 531–540.

[49] S. Elmes, et al., Laser machining of micro reservoir pins for gene analysis and high throughput screening, in: Proceedings of the ICALEO Laser Micro Fabrication Conference M303, 2001. ISBN0912035-73-0.

[50] D.M. Allen, H.J.A. Almond, J.S. Bhogal, A.A. Green, P. Logan, X.X. Huang, Typical metrology of micro hole arrays made in stainless steel foils by two stage EDM, Ann. CIRP 48 (1) (1999) 127–130.

[51] H. Almond, J. Bhogal, D.M. Allen, A positional accuracy study of a micro EDM machine, Proc. SPIE 3680 (1999) 1113–1124.

[52] T. Masuzawa, State of the art of micromachining, Ann. CIRP 49 (2) (2000) 473–488.

[53] S. Nolte, et al., Ablation of metals by ultrashort laser pulses, J. Opt. Soc. Am. B 14 (10) (1997) 2716–2722.

[54] D. Strickland, G. Mourou, Compression of amplified chirped optical pulses, Opt. Commun. 56 (1985) 219.

[55] C. Momma, U. Knoop, S. Nolte, Laser cutting of slotted tube coronary stents, State of the art and future developments, Biomed. Res. (1999) 39–44.

[56] J. Peters, et al., Contribution of CIRP to the metrology and surface quality evaluation during the last fifty years, Ann. CIRP 50 (2) (2001) 471–489.

[57] M.E. Merchant, Delphi forecast of future production engineering, Ann. CIRP 20 (2) (1971) 205–213.

[58] P.A. McKeown, The role of precision engineering in manufacturing of the future, Ann. CIRP 36 (2) (1987) 495–502.

[59] G.E. Moore, Cramming more components onto integrated circuits, Electronics 38 (1965) 114–117.

[60] G.E. Moore, Progress digital integrated electronics, IEDM Techn. Digest, Washington (1975) 11–13.

[61] The national Technology Roadmap for Semiconductors, 1994, Semiconductor Industry Association, San Jose, California.

[62] N. Taniguchi, Current status in, and future trends of, ultra precision machining and ultra fine materials processing, Ann. CIRP 32 (2) (1983) 573–580.

[63] J. Corbett, P.A. McKeown, G.N. Peggs, R. Whatmore, Nanotechnology: international developments and emerging products, Ann. CIRP 49 (2) (2000) 523–545.