LEADING THE WAY INTO A BRIGHT FUTURE

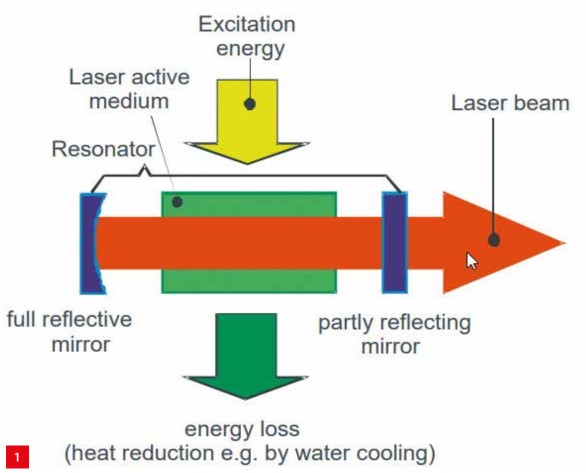
Sixty years after its inception, laser technology is still steadily evolving and a large number of industrial applications have been developed over this period. In recent years, institutes and manufacturers have presented a tsunami of innovations around this powerful source of light, regarding knowhow, technology and practices. For laser-based materials processing, the continuous evolution towards shorter wavelengths stands out, as opening up a wide 'supply' of dedicated wavelengths fitting major contemporary practical purposes. Furthermore, laser quality has increased, efficiency has surpassed 50% and performance has improved spectacularly even with a decreasing laser footprint, while functionality expanded considerably in micro- as well as macro-applications.

JAN WIJERS

A bit of history

After World War II, quite a number of researchers worldwide invested their energy in inventing a laser technology – building on Einstein's discovery of the phenomenon of stimulated emission in 1917 – and they actually made a lot of progress. Nevertheless, it was 1960 before Theodore Maiman of the then famous Hughes Aircraft Corporation Labs made the very first active laser a reality and lit it for mankind. It was classified as a glass-type laser with a ruby crystal as the lasing medium.

In its early days, this unique invention (Figure 1) was qualified as sort of a 'solution to a non-existent problem'. At first, research into medical applications boomed. Five to ten years later, high-powered specimens of the new laser light source hit the market in professional configurations, with sheet metal cutting being the first industrial task for this new, advanced tool.



1

General laser principle showing the main components. (Source: SLT)

AUTHOR'S NOTE

Jan Wijers is a freelance technical writer from Eindhoven (NL), operating formerly, amongst other positions, as a manufacturing technologist within the main Philips Research Lab. He still specialises in traditional and non-conventional production technologies and machine tools.

Machining drive

At that time, conventional machining or chipping was already at a respectable level, while worldwide R&D was running for further improvement. New non-traditional technologies, such as EDM (electrical discharge machining), ECM (electro-chemical machining), WJM (water jet machining) and USM (ultrasonic machining), also came out in the open. They were applied, for example, to master in particular those jobs where intrinsic blank hardness and miniaturised dimensions became a critical problem – concerning tool wear, process forces and quality – with materials such as tungsten carbide and hardened and cold-drawn steel.

However, the long, slender, 'sharp' and in itself weightless laser beam proved to be able to execute all these demanding tasks, while also reaching further down – with a larger aspect ratio – without being bent or displaced, as compared to a solid cutting tool that produces chips. A typical example is the profiling and drilling of diamond, which could be done using spark erosion preceded by the graphitisation of a thin layer. It is extraordinary that a 'soft tool' such as the intense radiation of a Nd:YAG or an excimer laser could also execute the job, without pre-treatment and leaving no traces of converted graphite.

In the machining industry, new base materials were introduced over the years, including titanium, tungsten carbide and hybrid materials such as fibre-reinforced aluminium composites. Many of these materials are brittle and hard to machine; they require specials tools and cause considerable tool wear, thereby reducing flexibility while increasing processing time and costs. As a flexible, no-wear technology, laser machining became the preferred option for these materials.

It is striking that currently an increasing selection of conventional high-end machine tool producers – e.g. Kern or KLM, Makino, Elb, Mazak, GF and Vollmer – are (on the way to) integrating some kind of advanced laser technology into or onto their 3- and 5-axis machining centres, for processes such as engraving, welding, deburring, hardening, structuring and additive manufacturing (AM).

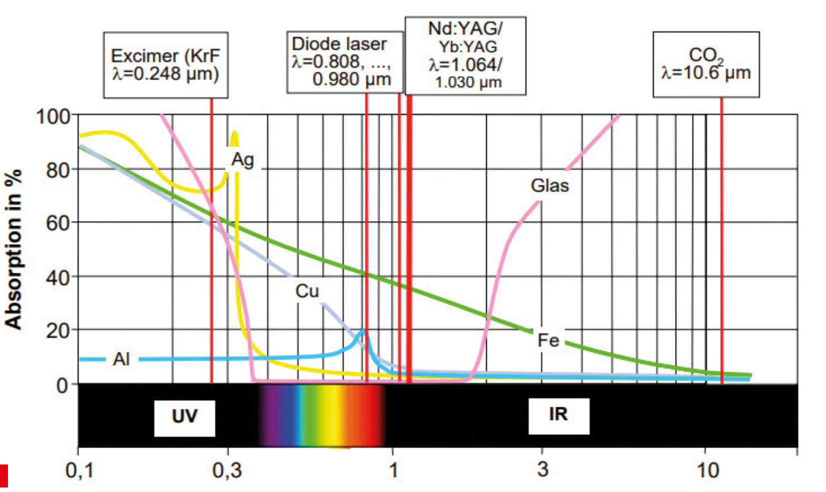
Exploiting the full availability of different laser implementations over time initiated an increasing number of applications in machining, (tele)communication and Internet-of-Things data technology, medical technology and metrology. The laser proved to be a perfect tool – both technically and economically – for delivering energy in the demanded format to exactly the one or more spots where it is needed. Light as a ground-breaking, powerful energy source will continue to push frontiers in many key enabling technologies during the 21st century.

Conventional versus laser light

LASER is an acronym for 'Light Amplification by Stimulated Emission of Radiation', covering part of the electromagnetic spectrum. The main difference between a laser and a conventional light source is that a laser intrinsically emits highly directional, monochromatic light (i.e. at one wavelength only). A laser beam has a very small divergence, its light is coherent in time and space – regarding direction, phase and wavelength – and the beam has a high intensity, whether it is produced in continuous wave (CW) or in pulsed mode. Its good focusability onto a small focal spot is another highly valued merit.

Design for laser manufacturing

By comparison, energy density (W/m^2) is 10^3 for sun rays, 10^{10} for EDM pulses and 10^{12} for an electron beam, while a laser beam is able to deliver 10^{12} up to 10^{20} W/m^2, representing an incredible amount of power. Wavelengths used by the various lasers cover the visible light range – approximately between 380 and 750 nm – as well as the infrared (IR) and ultraviolet (UV) range of the electromagnetic spectrum (Figure 2).



2

The relevant part of the electromagnetic spectrum, showing emission lines of lasers and absorption curves of various materials.

In the end, it is the – mainly thermally based – application that dictates the particular choice of laser, in terms of sufficient quality at an acceptable price. Making the selection for a particular laser beam to fit an application is certainly not easy. The benefits of laser applications, such as the larger range of materials available for machining and the increased flexibility, have a strong positive influence on engineering and designing new goals with fewer constraints for both actual as well as new products, apparatus and machines. To exploit these advantages, a dedicated design-for-laser-manufacturing approach and matching mindset is required.

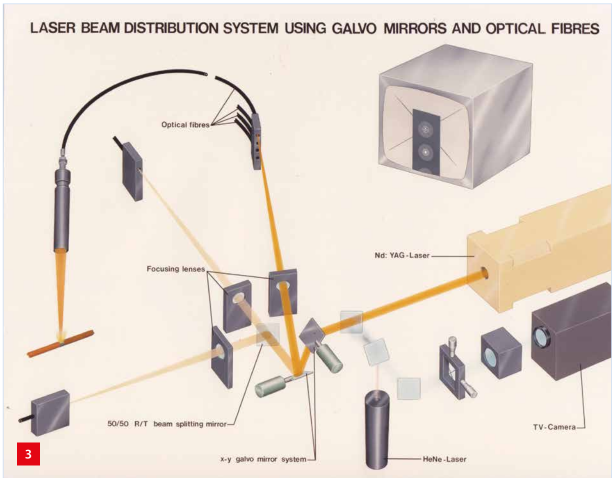
Basic physics

The LASER acronym explains that a laser produces light through stimulated emission of radiation, by means of an active gas or a solid-state medium confined inside a so-called resonator (Figure 1). This consists of two in-line mirrors, one fully reflecting (the rear mirror) and opposite it one partly transparent (the output mirror), which determines the amount of laser power that becomes available. By way of transmitting or 'feeding' energy from the outside into the medium – 'pumping' in jargon – a (stimulated) emission of light at one specific wavelength is brought about. The photons thus produced are reflected back and forth between the two mirrors, while each time part of them passes the output mirror and exits the laser.

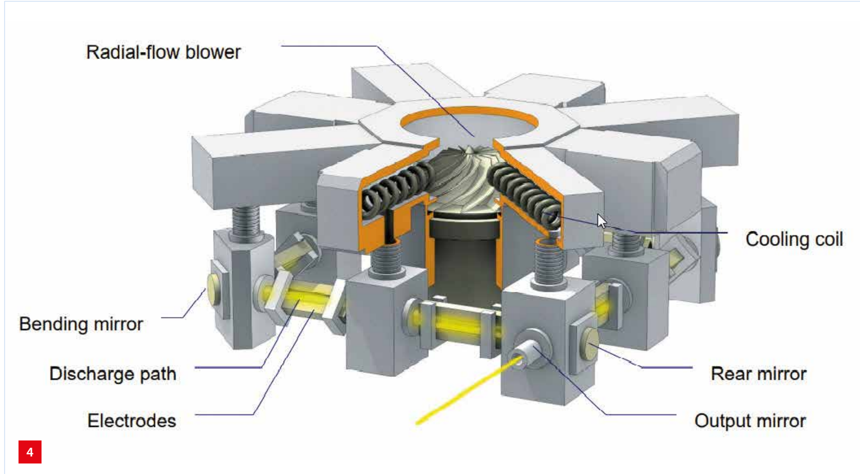
In practice, the majority of applications in material removal (machining) are based on efficiently converting as much as possible of the energy projected onto the workpiece into just sufficient heat to do the required job properly, while preventing any possible harm; quite a delicate balance. Even more so because of the effect that the incident beam at the surface is spent – to a material-specific degree – on reflection, absorption and transmission, respectively. All imaginable physical effects do occur during the interaction of the laser with the workpiece surface, ranging from heating (the main aspect in hardening) and melting (in drilling) to evaporation through ionisation (in ablation), sublimation and immediate dissociation (in structuring).

Advantages

Advantages of laser technology include:
- Universality in practical use.
- Short switch-over.
- Contactlessness, independent of mechanical properties.
- 'Cold' as well as 'hot' applicability.
- No-wear 'tool'.
- High reproducibility.



Optical beam splitting, with one single power source feeding several 'output stations'. (Source: WISE 2000)



Cross-section of a fast-flow CO_2 gas laser; fast-flow refers to the internal fan-induced gas flow for optimal mixing and cooling. (Source: Trumpf)

- Low weight, making accurate, ultrafast and dynamic 3D manipulation feasible.
- Direct deployability, without (time- and energy-consuming) warm-up.
- High flexibility (regarding power, position, spot, geometry and speed).
- Easy optical beam splitting, with one single power source feeding several 'output stations' (Figure 3).
- Digital fit for Industry 4.0 (integration in the digitalisation and big data trend).

Gas lasers

As the different types of laser configurations are rather numerous – CO_2, HeNe, Nd:glass, Argon-ion, ruby, etc. – only those that are dominant in industry and research are worked out briefly below; see Table 1 for an overview. A standard high-power CO_2 gas laser with 2-20 kilowatt power, DC- or RF-excited, like the one in Figure 4, with the robust and folded resonator (folded for minimising length and footprint) and an integrated and shielding beam guide, is a top-quality, high-tech machine, operating reliably with good beam quality in the IR spectrum at a wavelength of 10,640 nm (see Figure 2). Its efficiency η varies in line with its specific configuration from 10-15%, whether operating in continuous wave (CW) or pulsed mode.

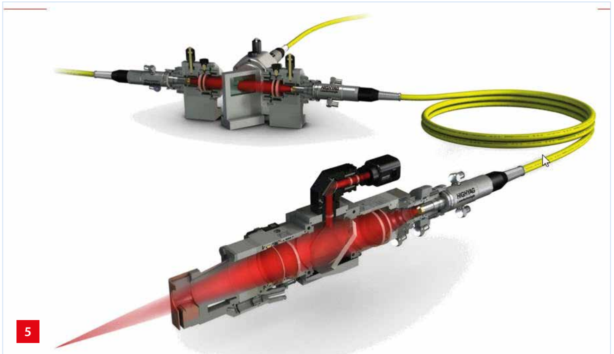
It is still without doubt the go-to, relatively low-priced flat-bed workhorse in the sheet metal industry, producing products of an excellent cutting quality in a wide diversity of materials and thicknesses. Guiding the IR beam to the work spot and compensating for the varying beam length for obtaining a stable spot can only be effectuated by means of a not-so-flexible, bulky combination of flying optics and protection measures. In the infrared, guidance with a far more flexible fibre cable comes with too much intensity loss and, therefore, is unsuitable. Another drawback is that the laser gas – being a mixture of helium, nitrogen and CO_2 – requires frequent handling; this includes sampling the composition and refilling, and is a quite cumbersome necessity. Currently, the CO_2 types are gradually being overtaken by younger alternatives, except in specific (high-power, pulsed) applications such as ASML's EUV generator.

The excimer laser (excited dimer) also belongs to the gas-laser division, operating with an efficiency that runs around 1-3%. They operate at various UV wavelengths – solely in

Table 1
Overview of high-power laser configurations with their main industrial applications.

Medium*	Efficiency (%)	Power (kW)	Wavelength (nm)	Applications
Gas / CO_2	10-15	0.05-100	IR: 10,640	Micro/macro 2D/3D cutting, welding, surface treatment, EUV-generation (lithography)
Gas / excimer	≤ 2	1	UV: 157 (F_2), 193 (ArF), 248 (KrF), 308 (XeCl), 351 (XeF)	Micro/precision fabrication, drilling (inkjet nozzles), perforation/ablation
Solid-state / crystal/glass, Nd:YAG**	1-20	< 10	Near IR: 1,064	Micro-welding, -cutting and -drilling
Solid-state / active fibre (diode-pumped)	~30	1-20	Near IR: 1,030-1,070	Cutting, drilling, welding and marking
Semiconductor / diode	30-50	≤ 20	Near IR: 800-980	Precision machining
		1.5-3	Visible (blue): 450	Welding of copper and dissimilar metal combinations
		> 1.5***	Visible (green): 515	AM of copper

* *All laser types can be used in CW as well as pulsed mode (ultrashort pulsed mode with fibre and diode lasers); excimers are mainly operated in pulsed mode.*
** *Three versions: rod, slab, disk.*
Pulsating mode: Q-switched (1,064 nm), frequency-doubled (532 nm) or -tripled (355 nm).
*** *Disk version.*



5

Elaborated complete fibre beam delivery system. (Source: HIGHYAG)

pulsed mode in microlithography as an application field, amongst others – with a high-pressure gas mixture inside, consisting of a halogen gas and a rare gas (i.e., the dimer), for example XeF (xenon fluoride) at 351 nm, KrF (krypton fluoride) at 248 nm and ArF (argon fluoride) at 193 nm.

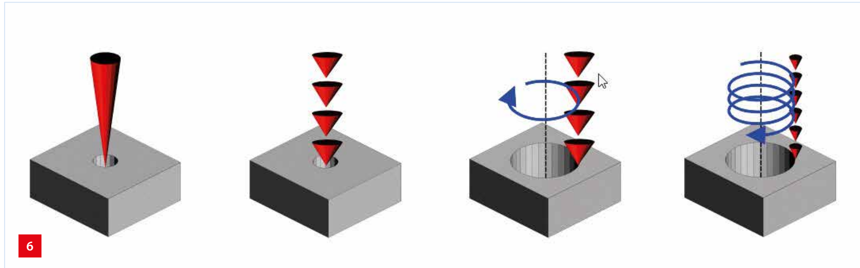
Solid-state, fibre or diode

The more costly Nd:YAG solid-state laser uses a flash lamp or diode to pump a neodymium-doped transparent substance (yttrium aluminium garnet) as its medium. At lower operational costs, as compared to the aforementioned gas lasers, in general it uses a rod as a resonator and will transmit at the 1,064 μm wavelength at a mean 4-5 kW power, with η = 3-15 %. Being in a so-called frequency-doubled or -tripled state, this laser transmits at 532 or 355 nm, respectively – aside from the originally often-used Q-switching mode. Two alternative versions of this solid-state laser, both offering good beam quality, are identified by the names 'slab' and 'disk', reflecting the polished outline of the specific resonator: a rectangular bar and a thin disc, respectively. Use of a flexible, totally internally reflective glass-core fibre for beam delivery to the actual work spot over a considerable distance is normal practice with this kind of industrial light source (Figure 5).

Recently, two mainly electronics-based, easily controllable, high-efficient power sources with high potential and low service costs came out of the labs. These are the far more compact, robust and efficient cladding-pumped fibre lasers (η = 30%; natural cooling, reduced spot size) and the upcoming diode (or semiconductor) types (η up to 50%; fluid cooling through integrated microchannels). They can be assembled from existing, easy-to-handle and easy-to-scale-up electronic modules. These newcomers leave behind the initial barriers of laser technology, such as large dimensions, inflexible and massive free-standing components, separate cooling units, semi-mechanical-electrical controls and service sensitivity.

Applications

State-of-the-art and next-generation industrial fabrication



6

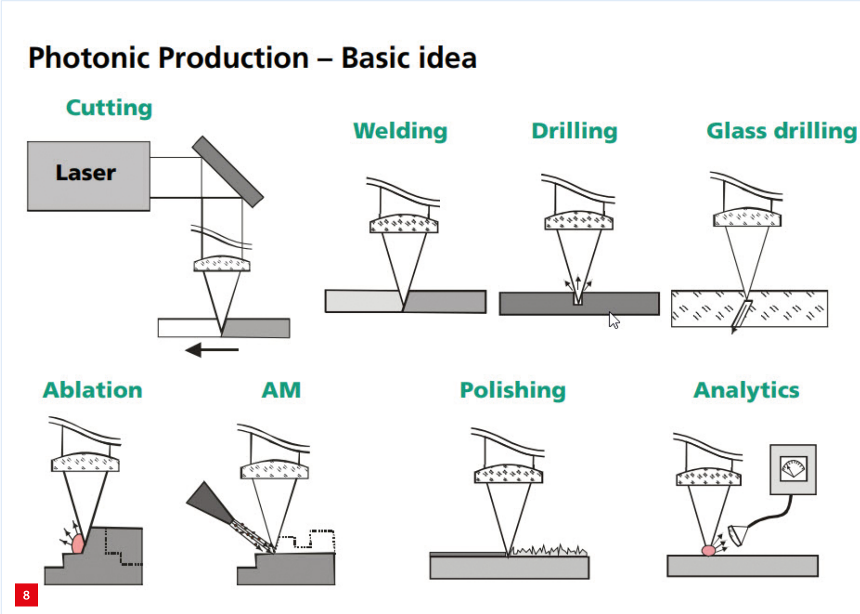
Four laser drilling modes: single-pulse, percussion, trepanning and helical. (Source: SLT)

applications of laser technology, from the macro- and micro- down to the nanoscale, include:

- 2D and 3D cutting.
- Drilling (Figure 6) and perforating.
- (Laser-assisted) turning.
- Joining: welding (including micro- and hybrid), soldering and high-temperature brazing.
- Deburring.
- Ablating (surface micromachining, Figure 7).
- Marking, by means of masks.
- Engraving (free-moving laser beam using mirrors or galvo-scanner motion).
- Etching, by way of a reactive gas or fluid.
- Polishing.
- Surface microfunctionalisation (e.g. texturing and graining: visually, haptically and in a tribological sense [1]).
- Balancing.
- Dressing (profiling and re-sharpening grinding wheels).
- Scribing (wafers).
- Wire stripping.
- Cleaning (even under water).
- Cladding (applying wear-resistant, hardness-enhanced or tribologically improved layers, or re-engineering).
- Heat treatment (hardening, annealing, ...) and other material transformations.
- Substrate surface modification (alloying, diffusion, ...).
- Glazing (rapid self-quenching of a laser-molten layer).

7

Ablated revolution counter in 'day-night' design.



Some of the major industrial fabrication applications of laser technology. (Source: ILT/AKL)

- 3D printing (AM) of metals, plastics, amorphous matter and so on, in various formats:
  - PBF: powder bed fusion;
  - SLS: selective laser sintering;
  - LMD: laser metal depositioning.

From these, major applications are visualised in Figure 8.

Developments

A number of major advances in the field of laser technology are certainly worth highlighting here. It can be noted that the operational pulse-to-pulse stability has increased significantly, in combination with improved laser beam quality – as every user knows, reproducibility is an absolute requirement in most production chains.

These days, quite a line-up of high-energy, (ultra)short-pulsed laser types are at hand, with pulse duration ranging from milli- (ms: 10^{-3} s), micro- (μs: 10^{-6} s) and nano- (ns: 10^{-9} s) down to pico- (ps: 10^{-12} s) and femtoseconds (fs: 10^{-15} s). The latter (ps and fs pulses) are bringing 'cold' machining within reach, even when using a principally 'thermal tool', for example in micromachining application such as ablation and surface microstructuring. The interaction time is so short that the energy beamed in does not get time to penetrate deeper than into a thin top layer of the material.

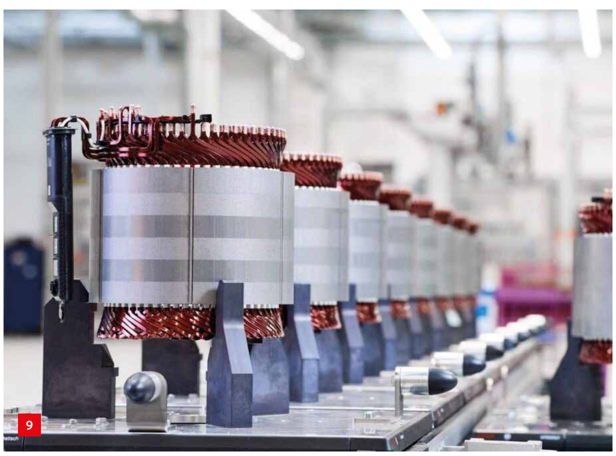
Copper

As a base material in the periodic system, the chemical element 29 (copper, Cu) stands out for its optimal, low-loss conductivity of both electricity and heat. For example, new types of high-efficiency heat exchangers made from copper are on the road to mass production, in some cases using laser welding, while the more complex configurations can at last be 3D printed, also using a laser.

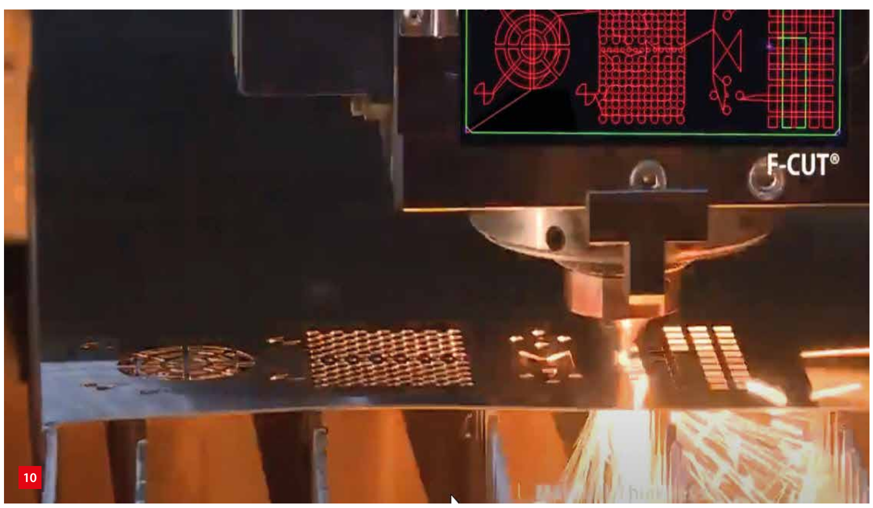
Also relevant is the e-mobility trend away from fossil fuels. This boosts especially the manufacturing of automotive e-drives – which use a very different type of coil windings requiring an advanced joining technique involving the 'shooting' of copper wires with a square cross-section into the iron packet and laser welding the so-called 'hairpins' (Figure 9) [2] – and brake systems, as well as potentially more powerful solid-state battery packs and charging and energy-storage stations. Their production features a lot of laser welding of copper, for example of cyclic loading-resistant copper microjoints (5 to 15 μm thick) for battery cells, modules and packs both on the anode and cathode side, and in the necessary power electronics. The specification of the required quality of all those welds in sheet, strip and foil material has also boosted laser engineering in the blue and green wavelength range.

Cutting needs welding

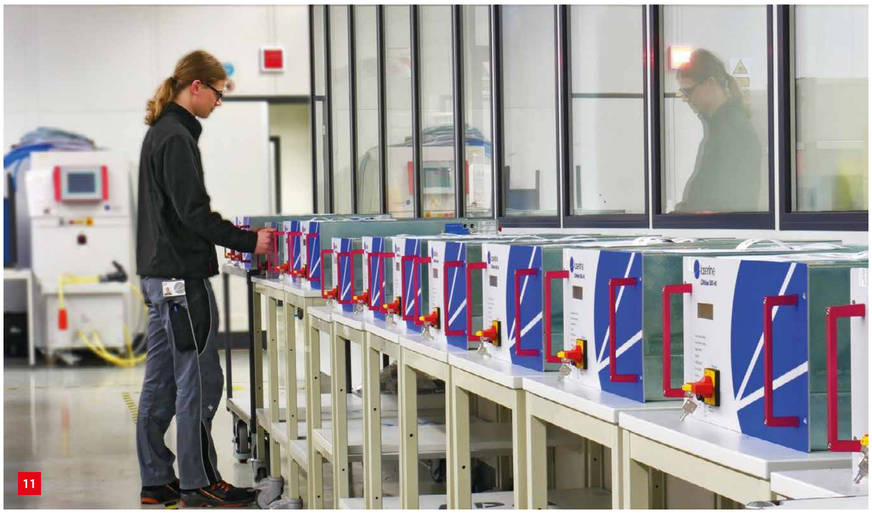
This has brought welding as well as sheet metal cutting (Figure 10) back into the spotlight for lightweight car body



BMW e-motor manufacturing line recently opened in Dingolfing (Germany), at the top of each motor showing the protruding ends of hairpin-like windings that are laser-welded together.



Laser cutting using a modern flat-bed laser cutter. (Source: Mitsubishi).



Production of newest 19"-generation 2 kW fibre-coupled blue diode LDM 2000 lasers. (Source: Laserline)

and platform solutions, with strict specifications regarding speed and quality. Normally, each of these techniques requires a different laser configuration. However, in this case what is cut must generally be joined afterwards as the next operation in the product chain to obtain a ready-to-use part. Therefore, one-of-a-kind combination heads for welding and cutting have been introduced that increase productivity and quality. There is even work currently being undertaken to add 3D-printing functionality.

Shorter wavelengths

So, copper has boosted laser innovation, while simultaneously constituting a processing horror: laser-matter interaction is hampered by copper's exceptionally high specific reflection – up to 90% at wavelengths of 1 μm and higher, as proven, for example, in the CO_2-laser optical guidance systems fitted with copper mirrors – and correspondingly low absorption (and transmission). When using infrared radiation, it is therefore necessary to start with a high-energy setting, to get some energy into the material. In the very split second after melting occurs, the absorption exhibits a peak, so it is an absolute must to switch back the energy within an extremely short time lap and settle at a considerably lower level, to prevent large-scale melting.

One (marginal) solution to increase absorption for an improved processing effect is to roughen the copper surface slightly or provide it with a special coating. A more fundamental solution is to go to shorter wavelengths, where copper's specific absorption is higher (Figure 2). For this, laser solutions have become available, in pulsed mode in a robust power pack size. Especially, blue (450 nm, Figure 11) and green (515 nm) lasers, both in the visible spectrum, have been launched as very promising precision tools that are perfectly tuned to copper and other high-reflective materials. In addition, ultrashort pulsing brings more stability in conduction welding, even under highly varying conditions for a variety of materials.

'Cold' precision alternative

The shorter the laser pulse, the less energy is inserted into the material with each pulse. Hence, short-pulsed fs-laser machining is called 'cold' machining. A remarkable example is the possibility – developed by Trumpf – of cutting and welding hard and brittle stock, such as glass, using lasers with adjustable beam quality, instead of sawing or grinding and gluing with all their disadvantages. Lasers are also called upon for delicate cleaning jobs, as well as – at the other extreme – for removing, in a coarser marine style, biological fouling from ships.

Another remarkable achievement comes from companies such as Avonisys, Sitec and Synova [3], who produce advanced, automated CNC laser systems based on a fine-tuned, small-diameter pressurised waterjet as an innovative

Waterjet-guided laser technology.
(a) Straight diamond cut.
(b) Synova's Laser MicroJet in action.

High-speed copper AM production.
(a) Intricate heat-exchanger design.
(b) Induction coils.

means to guide a laser beam in a controlled way.
This extraordinary laser technology (Figure 12) adds unprecedented material processing capabilities – away from local heating, up to the 'cold' machining of almost any material – without any negative effects such as heat-affected zones, micro-cracks and burrs. Aside from a clear, sharp cut and the large aspect-ratio precision bores that can be achieved in drilling, proven advantages include an increased working distance and range, as well as controlled surface cooling and flushing (Figure 12).

3D printing copper

Until recently, it was inconceivable that AM could master copper in 3D printing. However, several companies have now demonstrated the possibility of producing complex AM parts (Figure 13), such as Trumpf with its high-performance 515-nm green disk lasers, while Nuburu, Shimadzu and Laserline used their proprietary blue 450-nm diode versions.
In the quest for more speed in AM, multi-beam configurations have been introduced in modern printers fit for small batch or small-scale series production of AM metal monoparts, which have no vulnerable weld seams.

Perspective

The latest innovation, by GLOphotonics (Fr), is the so-called hollow-core fibre concept, following up on the traditional glass core build-up of fibres. This provides a simpler interface using a new micro-structured cladding, for completely confining the laser beam, and has proven to deliver high-power ultrashort pulses in a reliable way, opening up future application potential in dedicated laser communication networks.
Still missing – if ever conceivable in future – is one single universal type of laser that will handle all imaginable tasks in materials processing and manufacturing.

REFERENCES

[1] "High precision, low energy, no heat – Ultrashort-pulsed laser machining of hard materials", *Mikroniek*, Vol. 60 (5), pp. 37-38, 2020.
[2] F. Zuurveen, "Lasering e-cars – Facilitating mass production of electric vehicles", *Mikroniek*, Vol. 58 (5), pp. 36-37, 2018.
[3] J. Wijers, "The hybrid Laser MicroJet is cool and precise – 'Wet' laser machining technology picking up speed", *Mikroniek*, Vol 55 (4), pp. 29-35, 2015.