

10.

Laser Beam Welding

The term laser is the abbreviation for „Light Amplification by Stimulated Emission of Radiation“. The laser is the further development of the maser (m=microwave), Figure 10.1. Al-

though the principle of the stimulated emission and the quantum-mechanical fundamentals have already been postulated by Einstein in the beginning of the 20<sup>th</sup> century, the first laser - a ruby laser - was not implemented until 1960 in the Hughes Research Laboratories. Until then numerous tests on materials had to be carried out in order to gain a more precise knowledge about the atomic structure. The following years had been characterised by a fast development of the laser technology. Already since the beginning of the Seventies and, increasingly since the Eighties when the first high-performance lasers were available, **CO<sub>2</sub> and solid state lasers** have been used for **production metal working**.

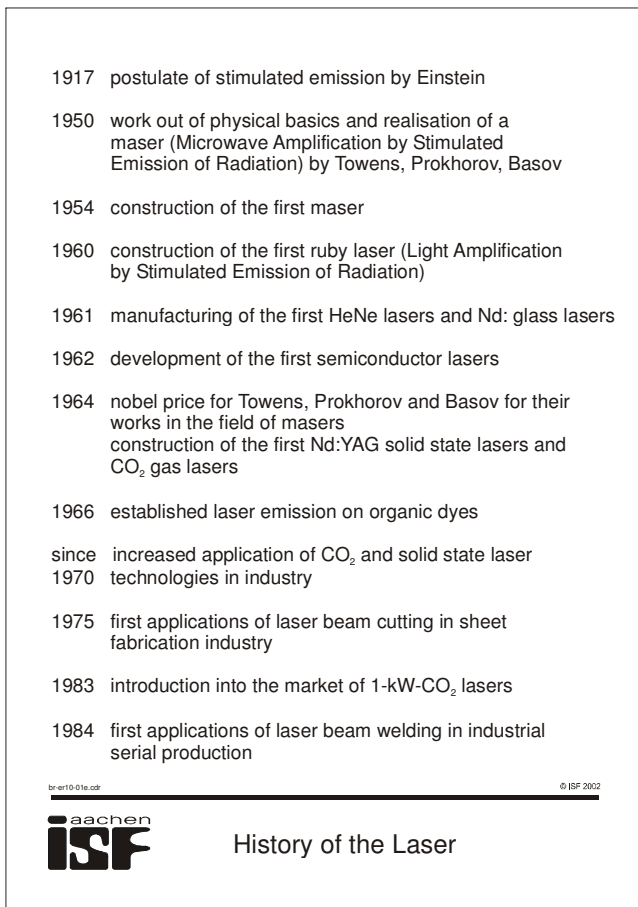


Figure 10.1

The number of the annual sales of laser beam sources has constantly increased in the course of the last few years, Figure 10.2.

The application areas for the laser beam sources sold in 1994 are shown in Figure 10.3. The main application areas of the laser in the field of production metal working are joining and cutting jobs.

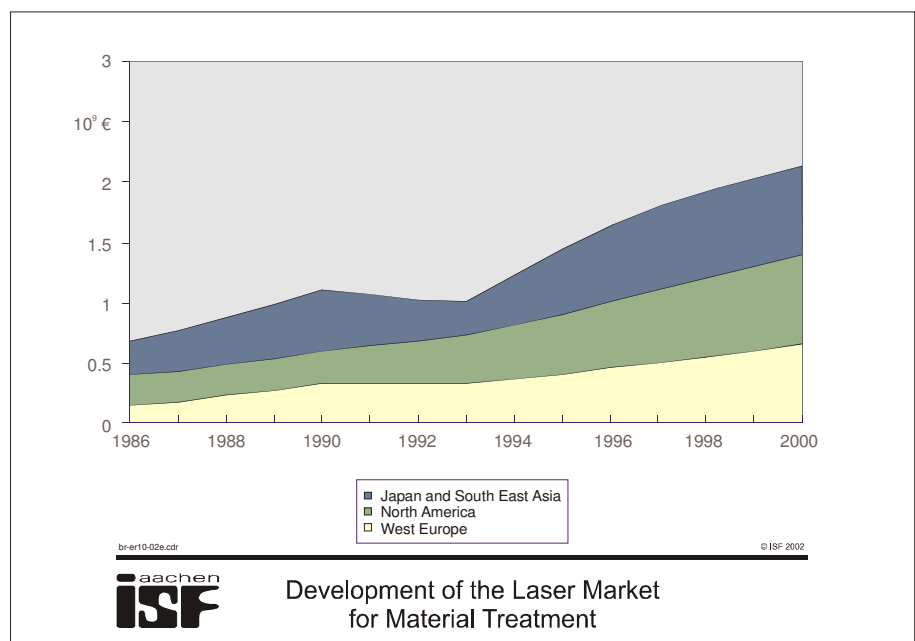


Figure 10.2

The availability of more efficient laser beam sources opens up new application possibilities and - guided by financial considerations - makes the use of the laser also more attractive, Figure 10.4.

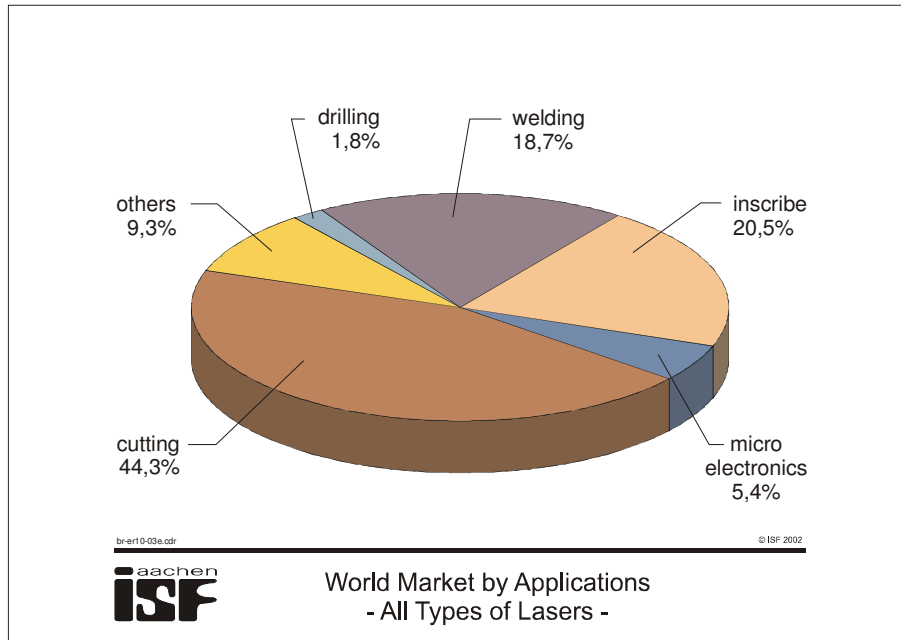


Figure 10.3

Figure 10.5 shows the **characteristic properties** of the laser beam. By reason of the induced or stimulated emission the radiation is coherent and monochromatic. As the divergence is only 1/10 mrad, long transmission paths without significant beam divergences are possible.

Inside the resonator, Figure 10.6, the **laser-active medium** (gas molecules, ions) is excited to a **higher energy level** (“**pumping**”) by energy input (electrical gas discharge, flash lamps).

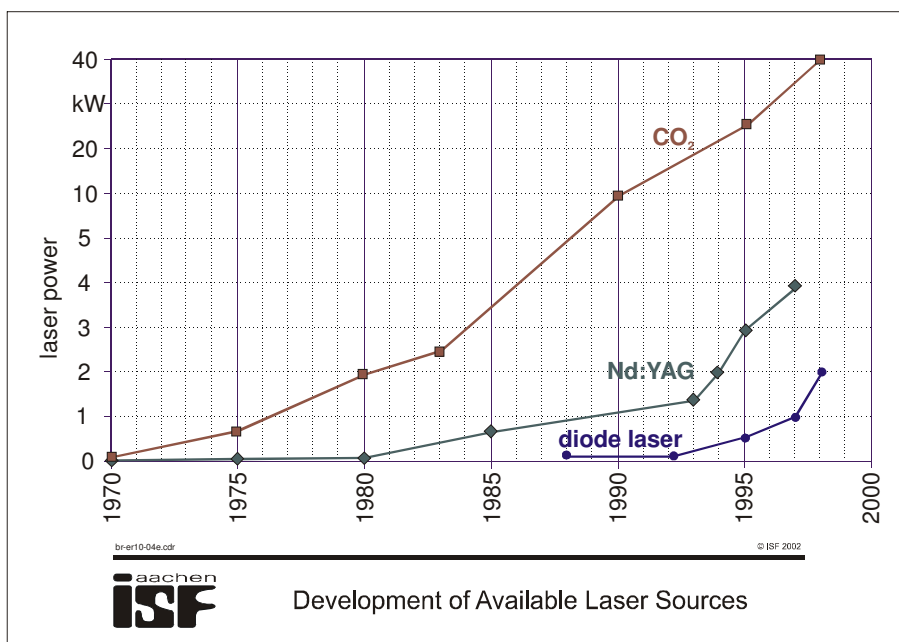


Figure 10.4

During **retreat to a lower level**, the energy is released in the form of a light quantum (photon). The **wave length** depends on the energy difference between both excited states and is thus a **characteristic for the respective laser-active medium**.

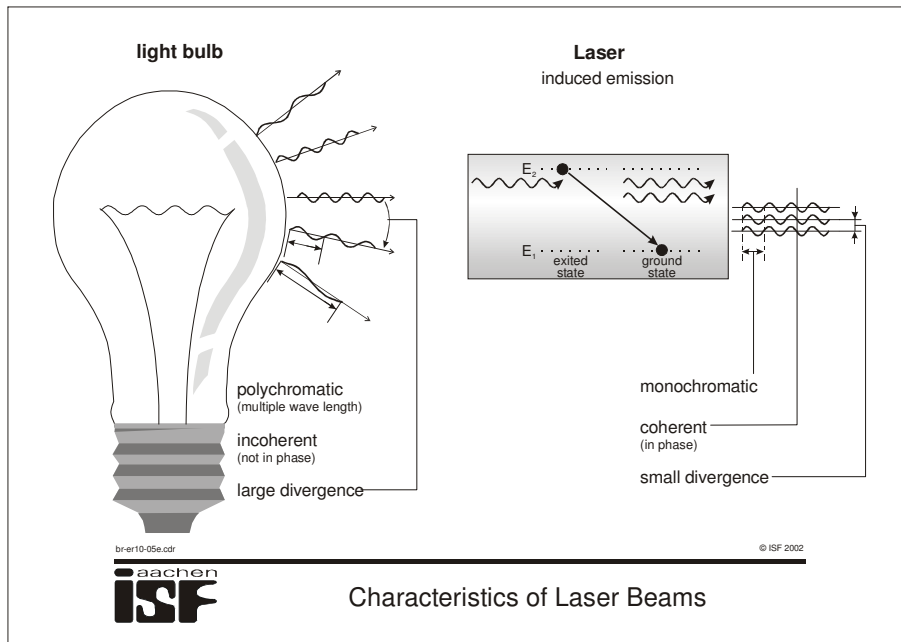


Figure 10.5

A distinction is made between spontaneous and induced transition. While the spontaneous emission is non-directional and incoherent (e.g. in fluorescent tubes) is a laser beam generated by induced emission when a particle with a higher energy level is hit by a photon. The resulting photon has the same properties (frequency, direction, phase)

as the exciting photon ("coherence"). In order to maintain the ratio of the desired induced emission / spontaneous emission as high as possible, the upper energy level must be constantly overcrowded, in comparison with the lower one, the so-called "laser-inversion". As result, a stationary light wave is formed between the mirrors of the resonator (one of which is semi-reflecting) causing parts of the excited laser-active medium to emit light.

In the field of production metal working, and particularly in welding, especially CO<sub>2</sub> and Nd:YAG lasers are applied for their high power outputs. At present, the development of diode lasers is so far advanced that their sporadic use in the field of material processing is also possible. The industrial standard powers for CO<sub>2</sub> lasers are, nowadays, approximately 5 - 20 kW, lasers with powers of up to 40 kW are available. In the field of solid state lasers average output powers of up to 4 kW are nowadays obtainable.

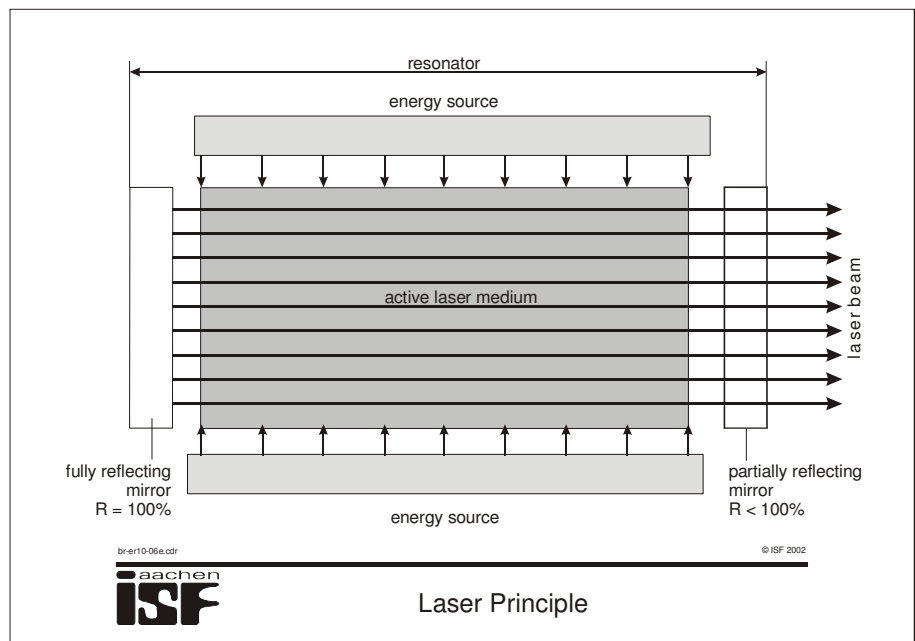
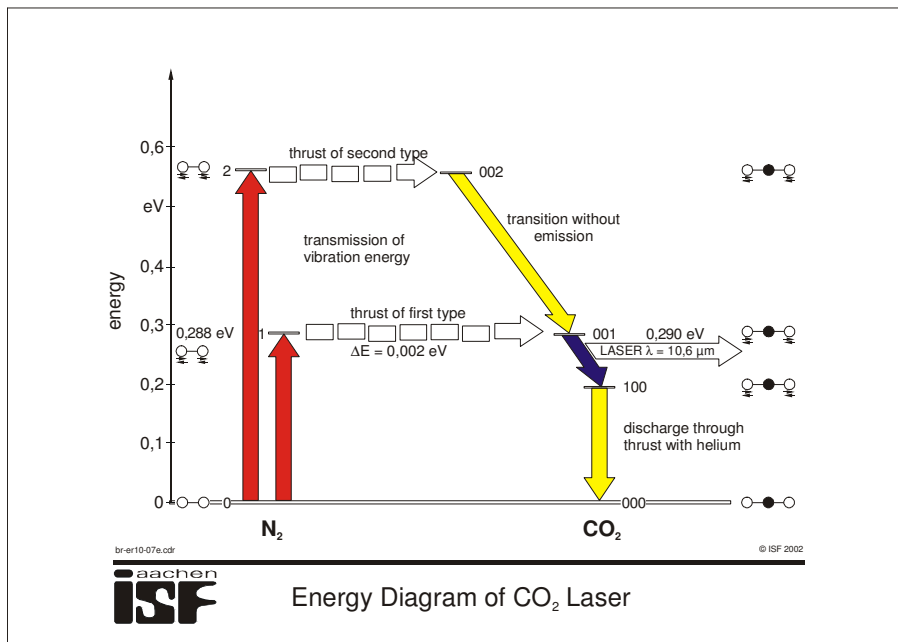


Figure 10.6

In the case of the CO<sub>2</sub> laser, Figure 10.7, where the resonator is filled with a N<sub>2</sub>-CO<sub>2</sub>-He gas mixture, pumping is carried out over the vibrational excitation of nitrogen molecules which



again, with thrusts of the second type, transfer their vibrational energy to the carbon dioxide. During the transition to the lower energy level, CO<sub>2</sub> molecules emit a radiation with a wavelength of 10.6 μm. The helium atoms, finally, lead the CO<sub>2</sub> molecules back to their energy level.

Figure 10.7

The efficiency of up to 15%, which is achievable with CO<sub>2</sub> high performance lasers, is, in comparison with other laser systems, relatively high. The high dissipation component is the heat which must be discharged from the resonator. This is achieved by means of the constant gas mixture circulation and cooling by heat exchangers. In

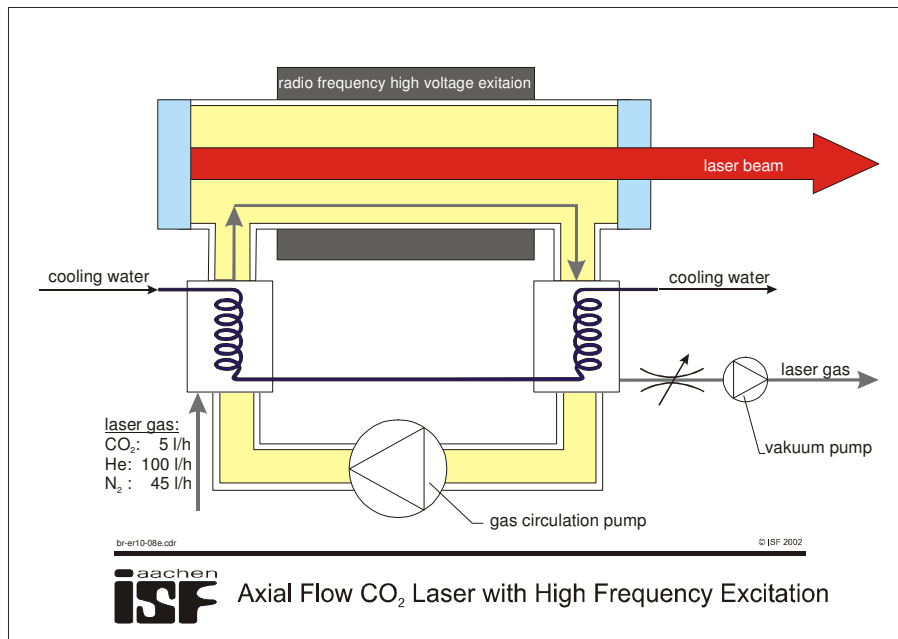


Figure 10.8

dependence of the type of gas transport, laser systems are classified into longitudinal-flow and transverse-flow laser systems, Figures 10.8 and 10.9.

With **transverse-flow laser systems** of a compact design can the multiple folding ability of the beam reach higher output powers than those achievable with **longitudinal-flow systems**, the beam quality, however, is worse. In **d.c.-excited** systems (high voltage), the electrodes are positioned inside the resonator. The interaction between the electrode material and the gas molecules causes electrode burn-off.

In addition to the wear of the electrodes, the burn-off also entails a contamination of the laser gas. Parts of the gas mixture must be therefore exchanged permanently. In high-frequency **a.c.-excited systems** the electrodes are positioned outside the gas discharge tube where the electrical energy is capacitively coupled. High electrode lives and high achievable pulse frequencies characterise this kind of excitation principle. In **diffusion-cooled CO<sub>2</sub> systems** beams of a high quality are generated in a minimum of space. Moreover, gas exchange is hardly ever necessary.

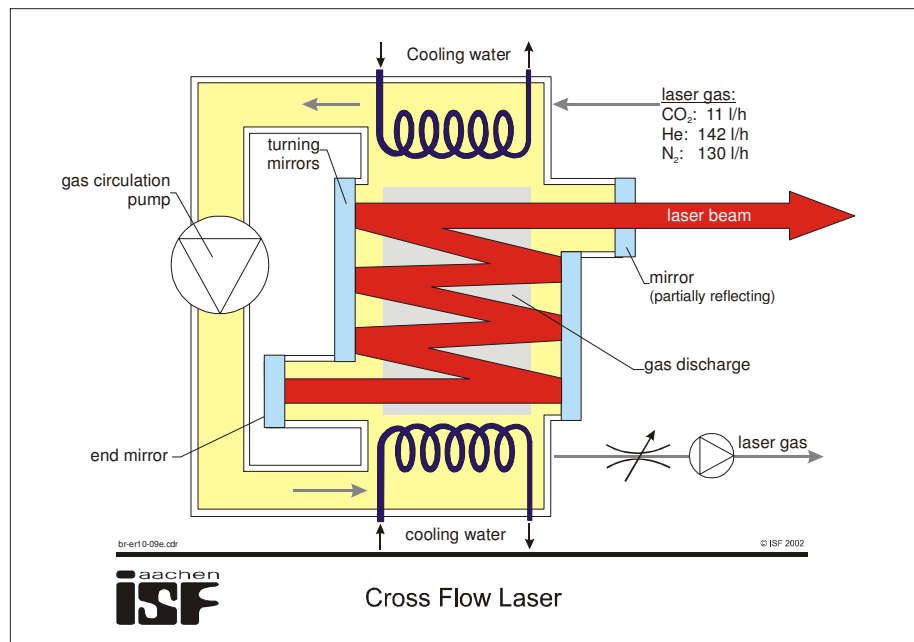


Figure 10.9

The intensity distribution is not constant across the laser beam. The intensity distribution in the case of the ideal beam is described by **TEM modes** (transversal electronic-magnetic). In the Gaussian or basic mode TEM<sub>00</sub> is the peak energy in the centre of the beam weakening towards its periphery, similar to the Gaussian normal distribution. In

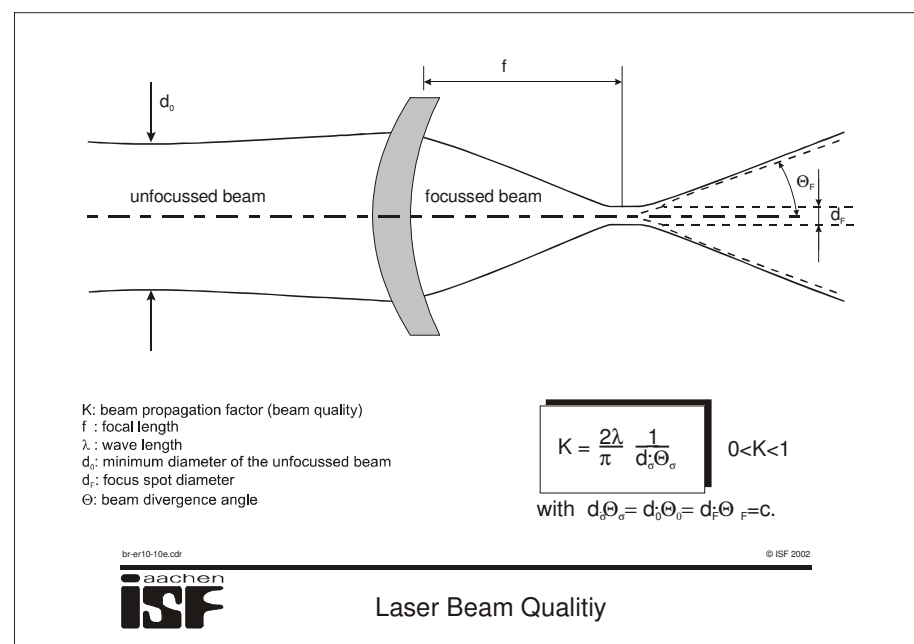


Figure 10.10

practice, the quality of a laser beam is, in accordance with DIN EN 11146, distinguished by the non-dimensional **beam quality factor** (or **propagation factor**)  $K$  (0...1), Figure 10.10. The factor describes the ratio of the distance field divergence of a beam in the basic mode to that of a real beam and is therefore a measure of a beam focus strength. By means of the beam quality factor, different beam sources may be compared objectively and quantitatively.

The CO<sub>2</sub> laser beam is guided from the resonator over a beam reflection mirror system to one or several processing stations, Figures 10.11 and 10.12. The low divergence allows long transmission paths. At the processing station is the beam, with the help of the focussing optics, formed according to the working task. The relative motion between beam and workpiece may be realised in different ways:

- moving workpiece, fixed optics
- moving ("flying") optics
- moving workpiece and moving optics (two handling facilities).

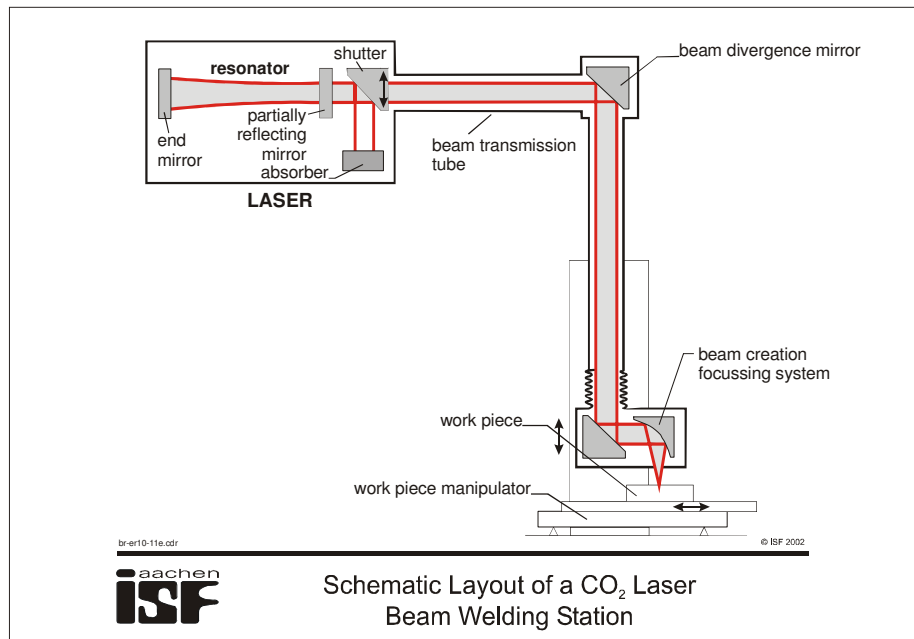


Figure 10.11

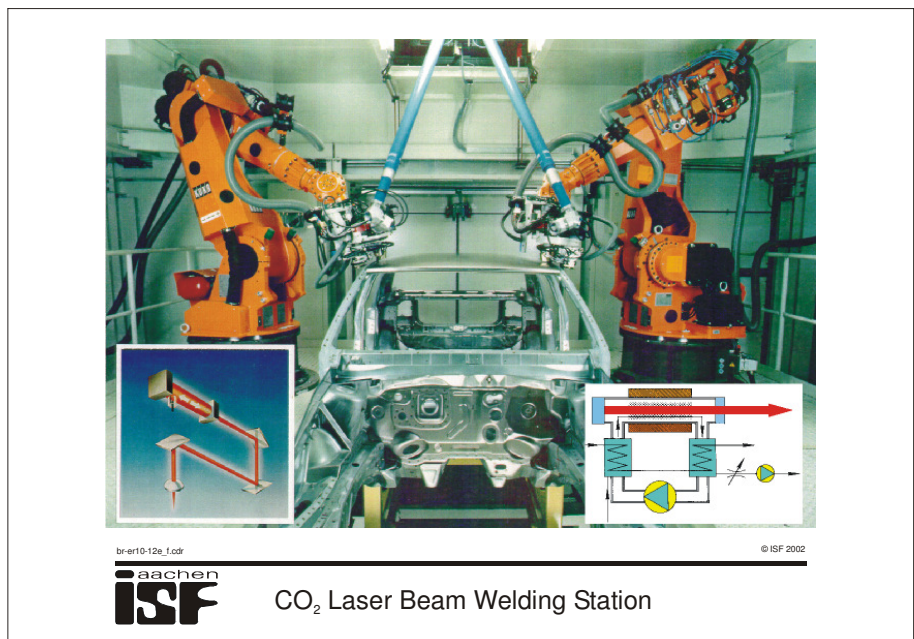


Figure 10.12

In the case of the CO<sub>2</sub> laser, beam focussing is normally carried out with **mirror optics**, Figure 10.13. **Lenses** may heat up, due to absorption, especially with high powers or contaminations. As the heat may be dissipated only over the holders, there is a risk of deformation (alteration of the focal length) or destruction through thermal overloading.

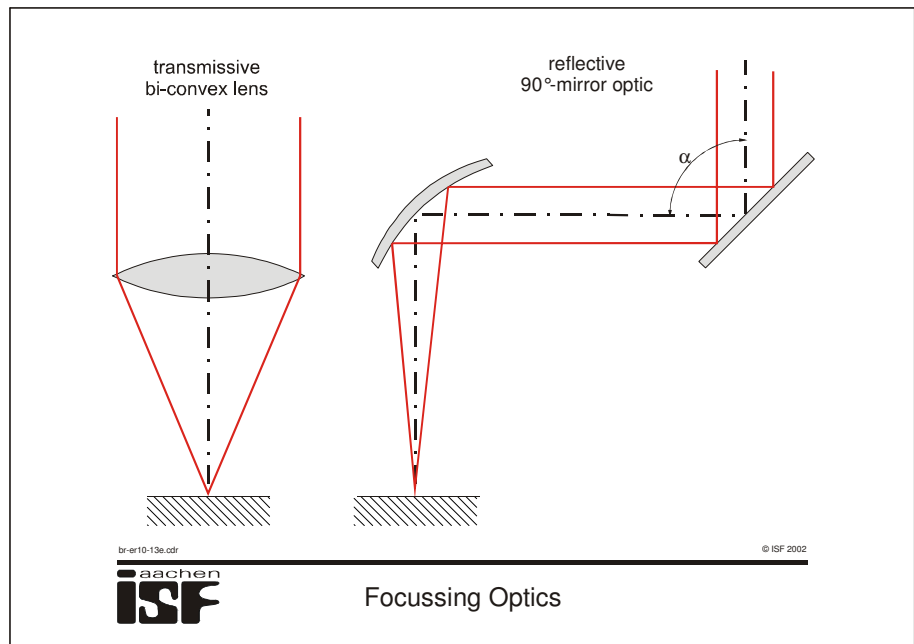


Figure 10.13

In the case of **solid state laser**, the normally cylindrical **rod** serves only the purpose to pick up the **laser-active ions** (in the case of the Nd:YAG laser with yttrium-aluminium-garnet crystals dosed with Nd<sup>3+</sup> ions), Figure 10.14. The excitation is, for the most part, carried out using flash or arc lamps, which for the optimal utilisation of the excitation energy are arranged as a double ellipsoid; the rod is positioned in their common focal point. The achieved efficiency is below 4%. In the meantime, also diode-pumped solid state lasers have been in-

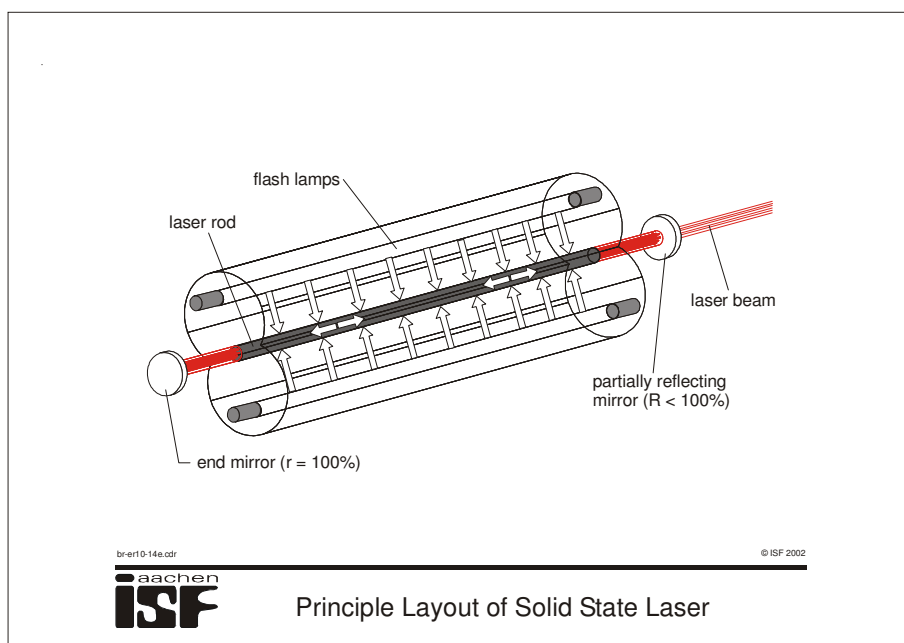


Figure 10.14

troduced to the market. The possibility to guide the solid-state laser beam over flexible fibre optics makes these systems destined for the robot application, whereas the CO<sub>2</sub> laser application is restricted, as its necessary complex mirror systems may cause radiation losses, Figure 10.15.



Some types of optical fibres allow, with fibre diameters of  $\leq 1$  mm bending radii of up to 100 mm. With optical switches a multiple utilisation of the solid state laser source is possible; with beam splitters (mostly with a fixed splitting proportion) simultaneous welding at several processing stations is possible. The disadvantage of this type of beam projection is the impaired beam quality on account of multiple reflection.

The **semiconductor** or **diode lasers** are characterised by their mechanical robustness, high efficiency and compact design, Figure 10.16. High performance diode lasers allow the welding of metals, although no deep penetration effect is achieved. In material processing they are therefore particularly suitable for welding thin sheets.



Figure 10.15

Energy input into the workpiece is carried out over the **absorption of the laser beam**. The absorption coefficient is, apart from the surface quality, also dependent on the wave length and the material. The problem is that a large part of the radiation is reflected and that, for example, steel which is exposed to wave lengths of  $10.6 \mu\text{m}$  reflects only 10% of the impinging radiation, Figure 10.17. As copper is a highly reflective metal

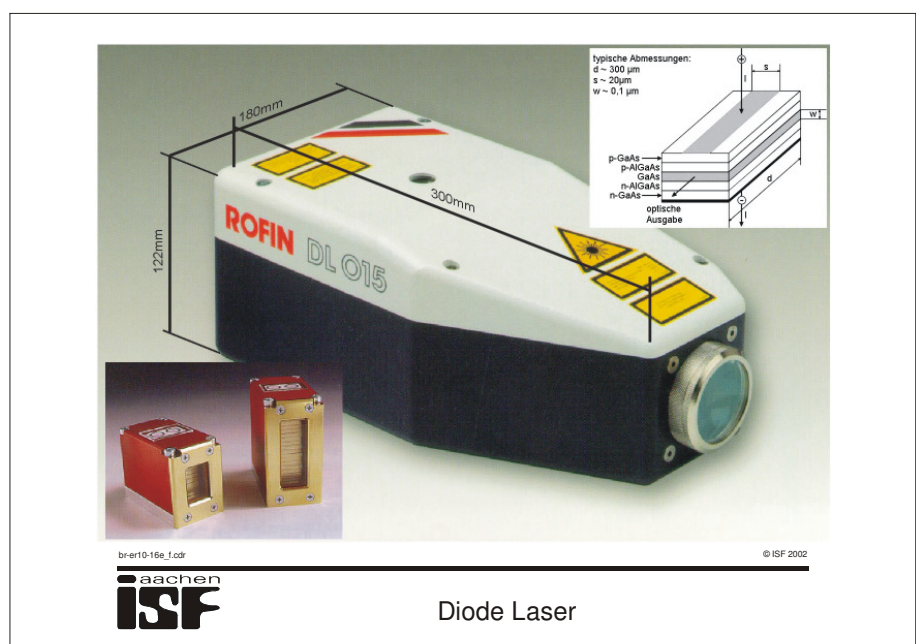


Figure 10.16

with also a good heat conductivity, it is frequently used as mirror material.

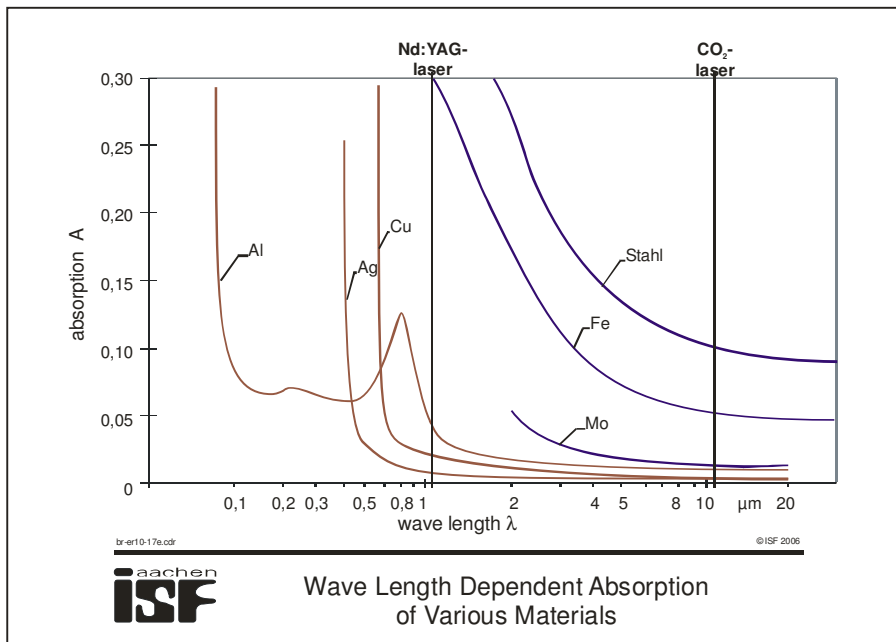


Figure 10.17

and workpiece surface must be maintained within close tolerances. At the same time, highest accuracy and quality demands are set on all machine components (handling, optics, resonator, beam manipulation, etc.).

Steel materials with treated surfaces reflect the laser beam to a degree of up to 95%, Figures 10.19 - 10.22.

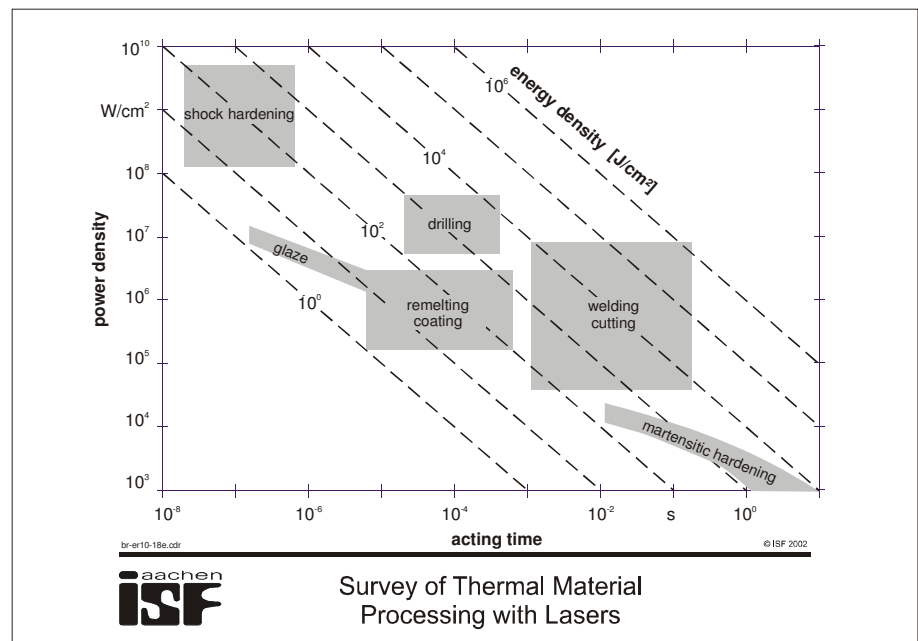
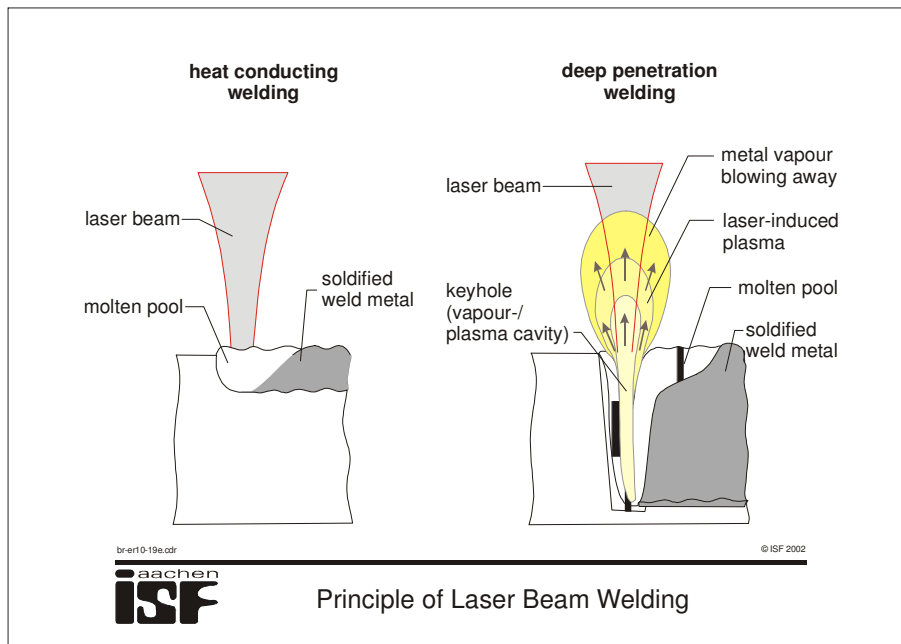


Figure 10.18

When metals are welded with a low-intensity laser beam ( $I \leq 10^5 \text{ W/cm}^2$ ), just the **workpiece surfaces** and/or edges are **melted** and thus **thermal-conduction welding** with a low deep-penetration effect is possible. Above the **threshold intensity value** ( $I \leq 10^6 \text{ W/cm}^2$ ) a phase transition occurs and **laser-induced plasma** develops. The plasma, whose absorption characteristics depend on the beam intensity and the vapour density, absorbs an increased quantity of radiation.



A **vapour cavity** forms and allows the laser beam to penetrate deep into the material (energy input deep beyond the work-piece surface); this effect is called the “**deep penetration effect**”. The cavity which is moved through the joining zone and is prevented to close due to the vapour pressure is surrounded by the largest part

of the molten metal. The residual material vaporises and condenses either on the cavity side walls or flows off in an ionised form. With suitable parameter selection, an almost complete energy input into the workpiece can be obtained.

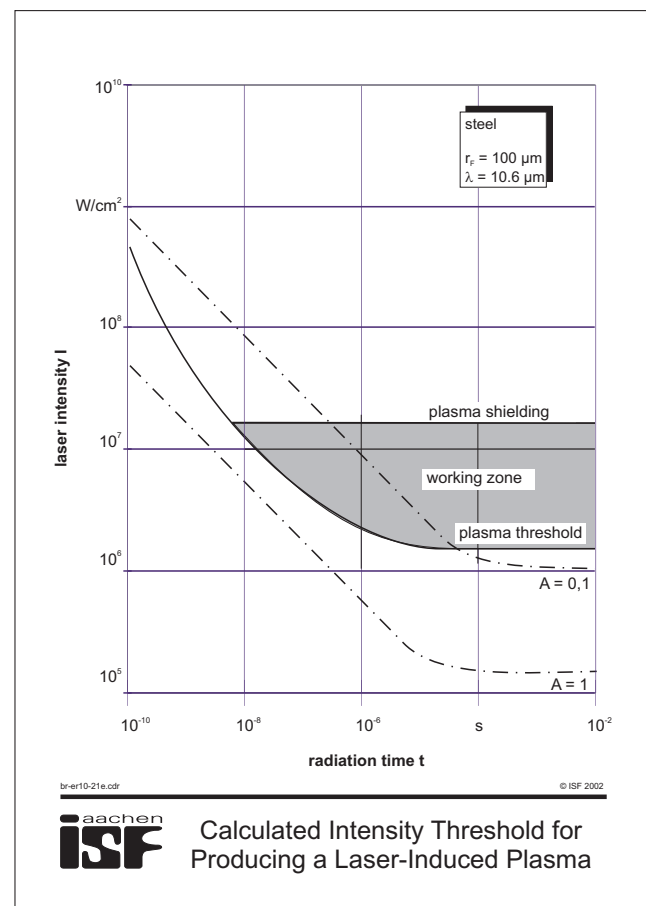
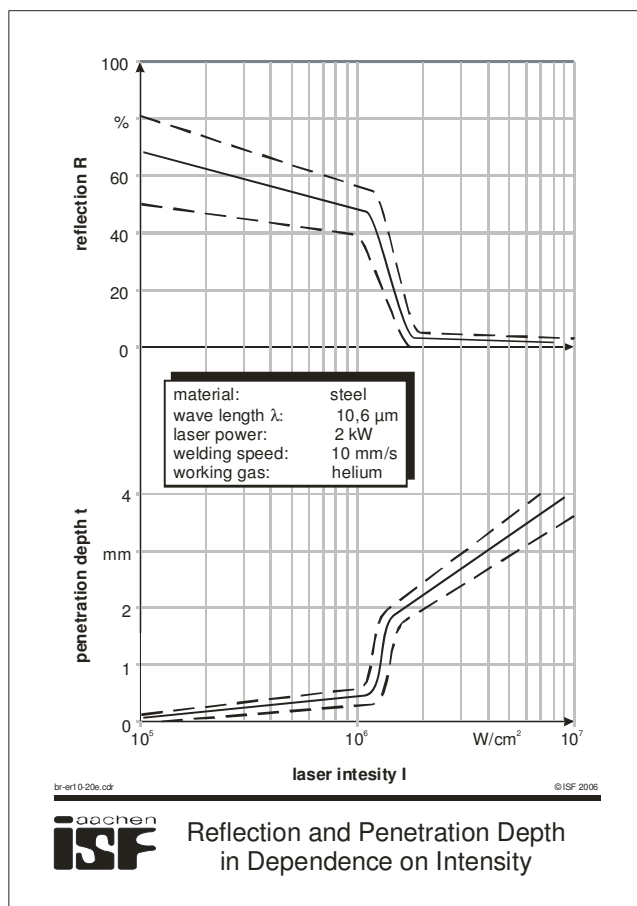


Figure 10.20

Figure 10.21

However, in dependence of the electron density in the plasma and of the radiated beam intensity, plasma may detach from the workpiece surface and screen off the working zone. The plasma is heated to such a high degree that only a fraction of the beam radiation reaches the

workpiece. This is the reason why, in laser beam welding, gases are applied for plasma control. The gases' ionisation potential should be as high as possible, since also the formation of "shielding gas plasmas" is possible which again decreases the energy input.

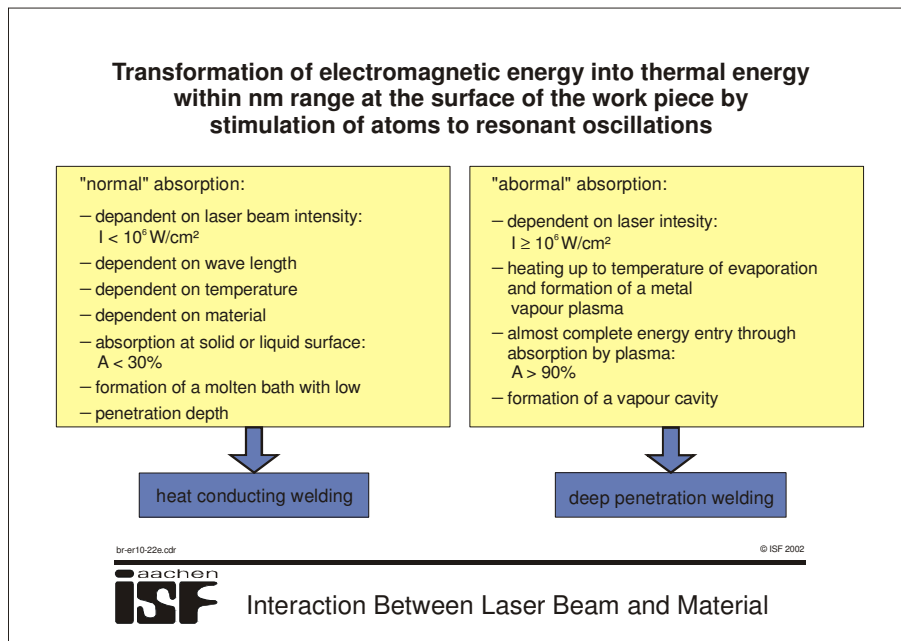


Figure 10.22

Only a part of the beam energy from the resonator is used up for the actual welding process, Figure 10.23. Another part is absorbed by the optics in the beam manipulation system, another part is lost by reflection or transmission (beam penetration through the vapour cavity). Other parts flow over thermal conductance into the workpiece.

Figure 10.24 shows the most important advantages and disadvantages of the laser beam welding method.

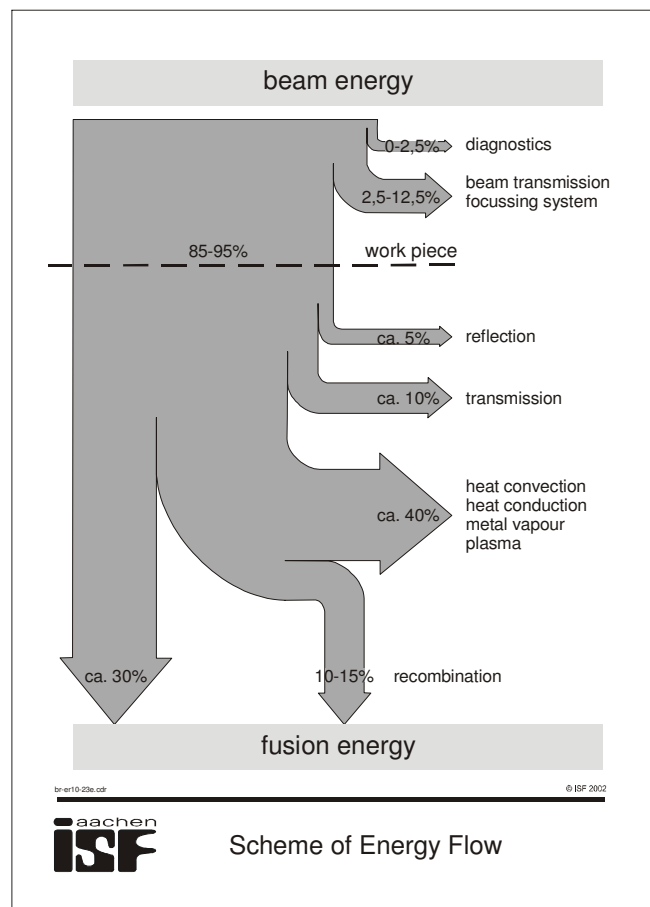


Figure 10.23

**Penetration depths** in dependence of the beam power and welding speed which are achievable in laser beam welding are depicted in Figure 10.25. Further **relevant influential factors** are, among others,

the **material** (thermal conductivity), the **design of the resonator** (beam quality), the **focal position** and the applied **optics** (focal length; focus diameter).

Figure 10.26 shows several joint shapes which are typical for car body production and which can be welded by laser beam application.

	advantages	disadvantages
<b>process</b>	<ul style="list-style-type: none"> <li>- high power density</li> <li>- small beam diameter</li> <li>- high welding speed</li> <li>- non-contact tool</li> <li>- atmosphere welding possible</li> </ul>	<ul style="list-style-type: none"> <li>- high reflection at metallic surfaces</li> <li>- restricted penetration depth (<math>\leq 25</math> mm)</li> </ul>
<b>work piece</b>	<ul style="list-style-type: none"> <li>- minimum thermal stress</li> <li>- little distortion</li> <li>- completely processed components</li> <li>- welding at positions difficult to access</li> <li>- different materials weldable</li> </ul>	<ul style="list-style-type: none"> <li>- expensive edge preparation</li> <li>- exact positioning required</li> <li>- danger of increased hardness</li> <li>- danger of cracks</li> <li>- Al, Cu difficult to weld</li> </ul>
<b>installation</b>	<ul style="list-style-type: none"> <li>- short cycle times</li> <li>- operation at several stations possible</li> <li>- installation availability &gt; 90%</li> <li>- well suitable to automatic function</li> </ul>	<ul style="list-style-type: none"> <li>- expensive beam transmission and forming</li> <li>- power losses at optical devices</li> <li>- laser radiation protection required</li> <li>- high investment cost</li> <li>- low efficiency (CO<sub>2</sub>-Laser: &lt; 20%, Nd:YAG: &lt; 5%)</li> </ul>

br-er10-24e.cdr © ISF 2002

**Advantages and Disadvantages of Laser Beam Welding**

Figure 10.24

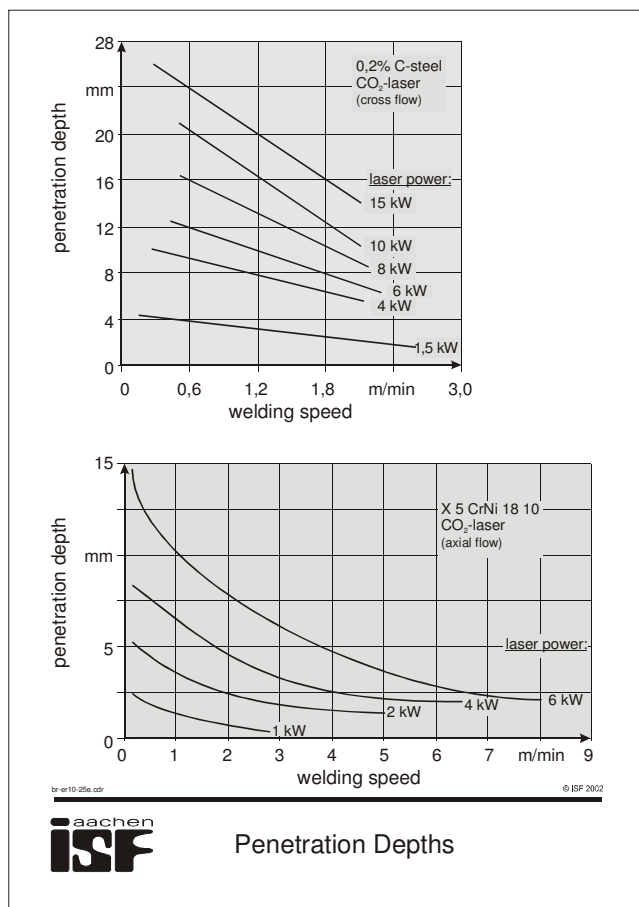


Figure 10.25

The **high cooling rate** during laser beam welding leads, when transforming steel materials are used, to significantly **increased hardness values** in comparison with other welding methods, Figure 10.27. These are a sign for the increased strength at a lower toughness and they are particularly critical in circumstances of dynamic loads.

The small beam diameter demands the very precise manipulation and positioning of the workpiece or of the beam and an exact weld preparation, Figure 10.28. Otherwise, as result, lack of fusion, sagged welds or concave root surfaces are possible weld defects.



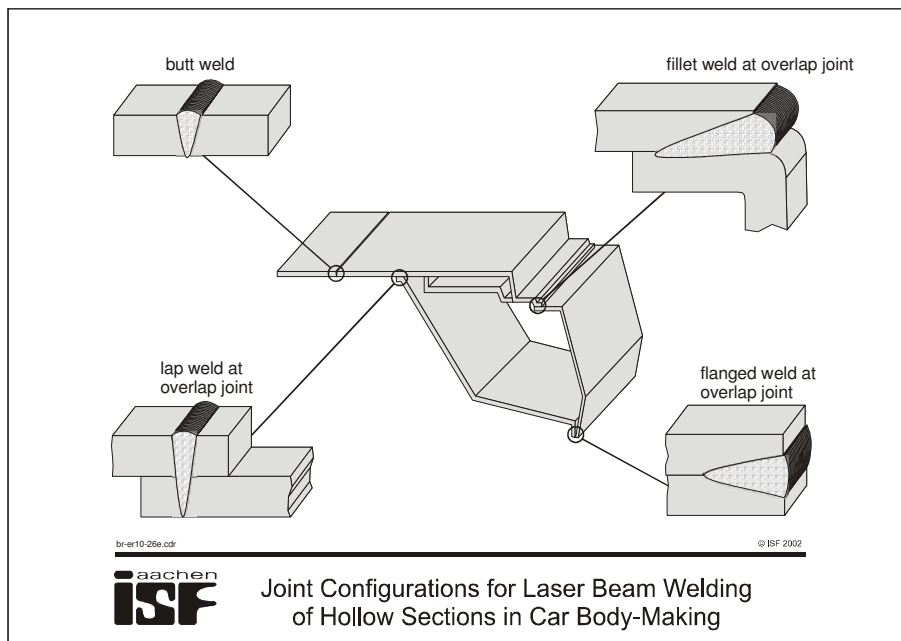


Figure 10.26

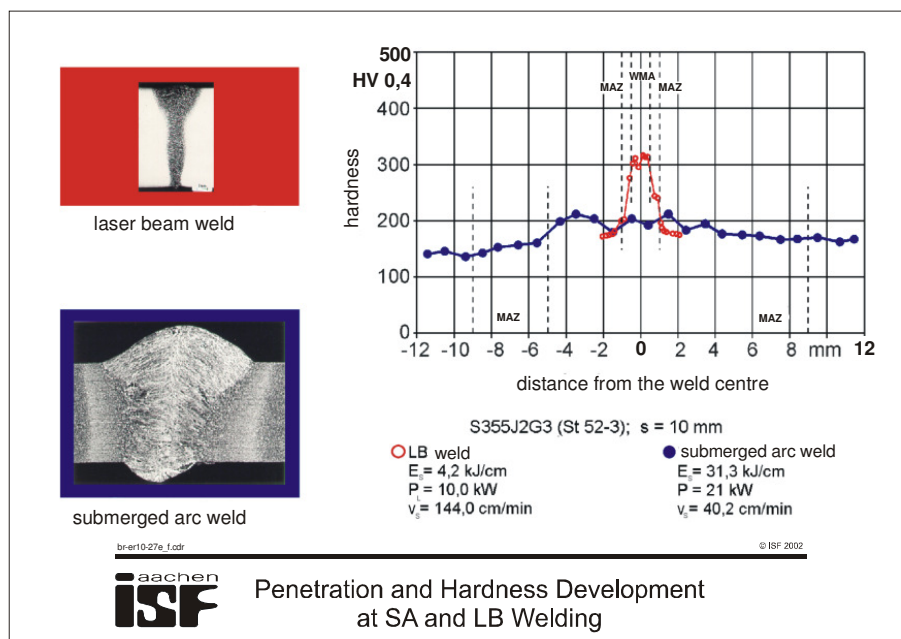


Figure 10.27

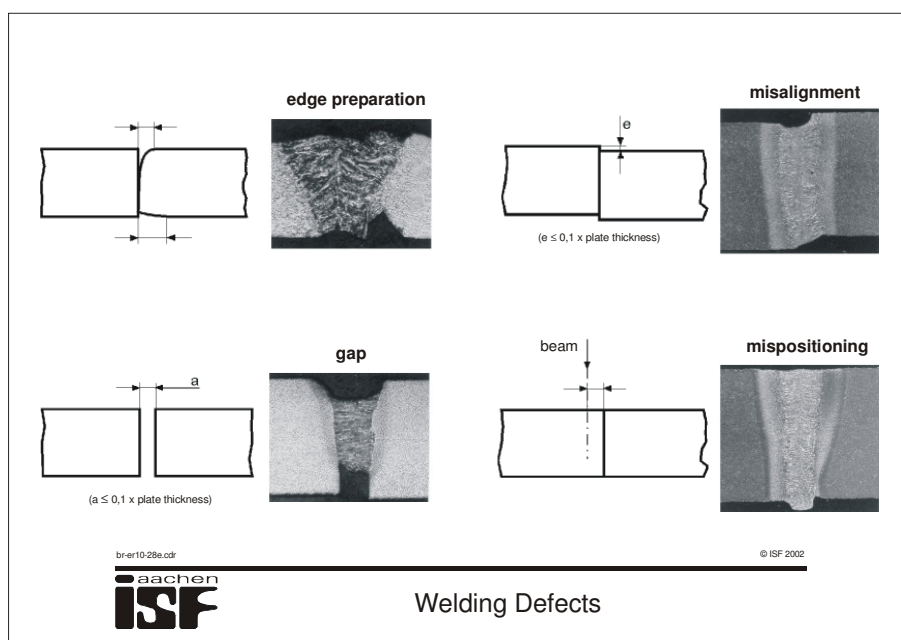


Figure 10.28

Caused by the high cooling rate and, in connection with this, the insufficient degassing of the molten metal, **pore formation** may occur during laser beam welding of, in particular, thick plates (very deep welds) or while carrying out welding-in works (insufficient degassing over the root), Figure 10.29.

However, too low a weld speed may also cause pore formation when the molten metal picks up gases from the root side.

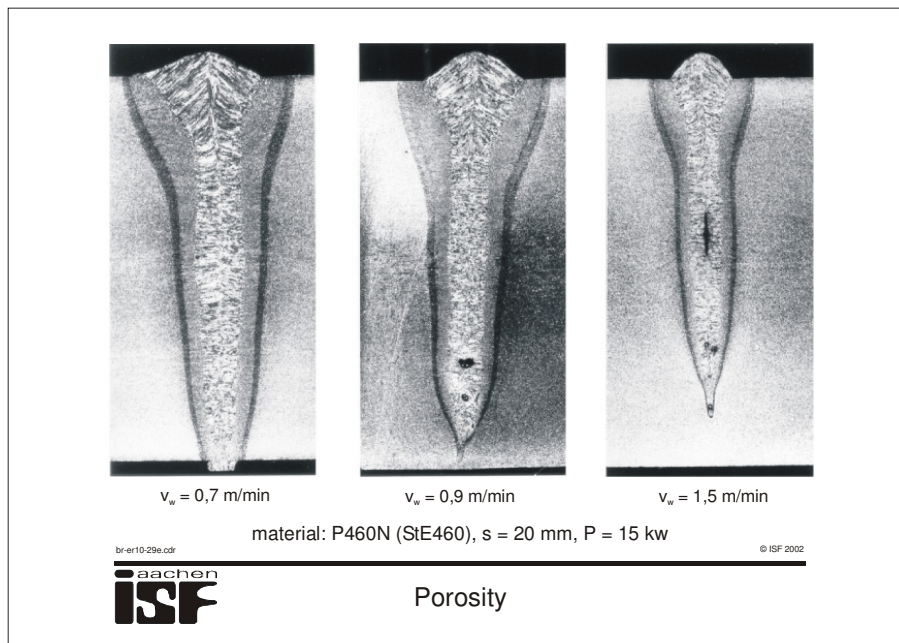


Figure 10.29

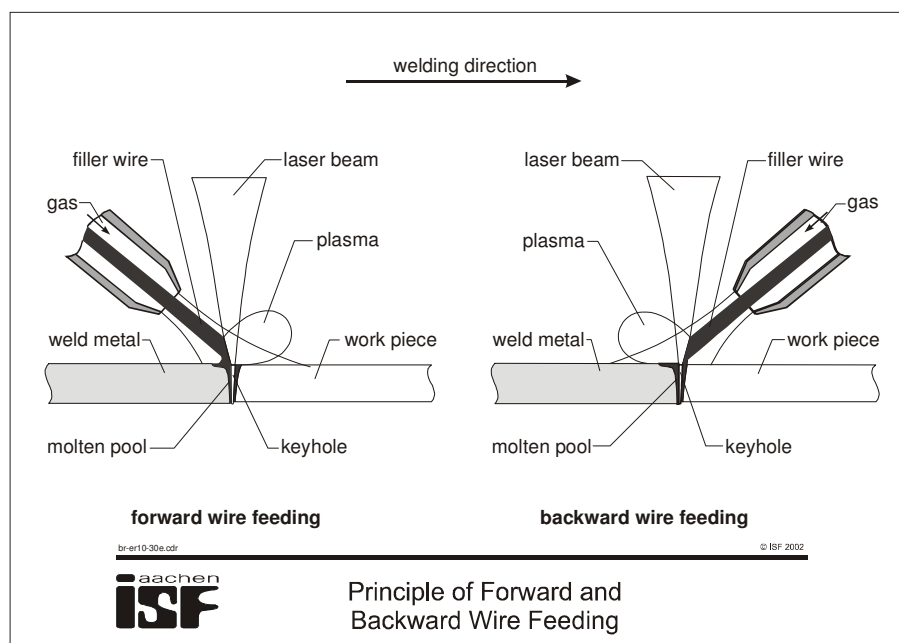


Figure 10.30

The materials that may be welded with the laser reach from unalloyed and low-alloy steels up to high quality titanium and nickel based alloys. The high **carbon content** of the transforming steel materials is, due to the high cooling rate, to be considered a critical influential factor where contents of  $C > 0.22\%$  may be stipulated as the limiting reference value. Aluminium and copper properties cause problems during energy input and process stability. Highly reactive materials demand, also during laser beam welding, sufficient gas shielding beyond the solidification of the weld seam. The sole application of working gases is, as a rule, not adequate.

The application of laser beam welding may be extended by process variants. One is laser beam welding with filler wire, Figures 10.30 and 10.31 which offers the following advantages:

- influence on the mechanic-technological properties of the weld and fusion zone (e.g. strength, toughness, corrosion, wear resistance) over the metallurgical composition of the filler wire
- reduction of the demands on the accuracy of the weld preparation in regard to edge misalignment, edge preparation and beam misalignment, due to larger molten pools
- “filling” of non-ideal, for example, V-shaped groove geometries
- a realisation of a defined weld reinforcement on the beam entry and beam exit side.

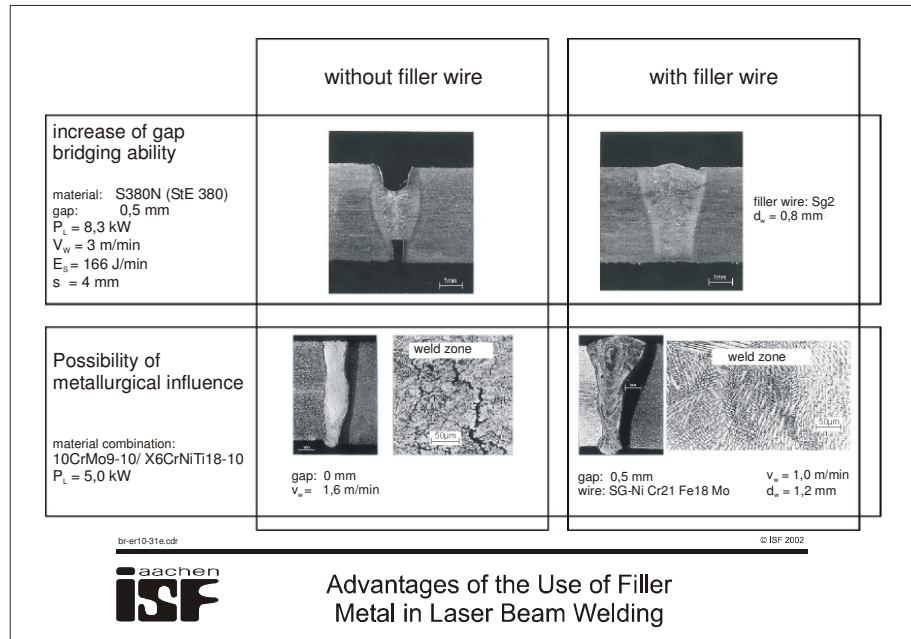


Figure 10.31

The exact positioning of the filler wire is a prerequisite for a high weld quality and a sufficient dilution of the molten pool through which filler wire of different composition as the base can reach right to the root. Therefore, the use of sensor systems is indispensable for industrial application, Figure 10.32. The sensor systems are to take over the tasks of

- process control,

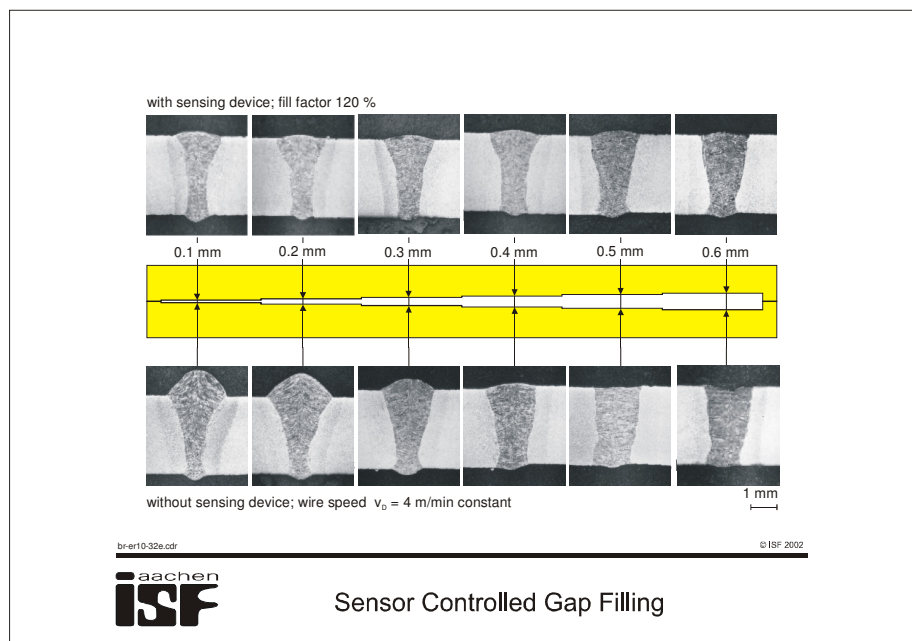


Figure 10.32



- weld quality assurance
- beam positioning and joint tracking, respectively.

The present state-of-the-art is the further development of systems for industrial applications which until now have been tested in the laboratory.

Welding by means of solid state lasers has, in the past, mainly been applied by manufacturers from the fields of precision mechanics and microelectronics. Ever since solid state lasers with higher powers are available on the market, they are applied in the car industry to an ever increasing degree. This is due to their more variable beam manipulation possibilities when

comparing with CO<sub>2</sub> lasers. The CO<sub>2</sub> laser is mostly used by the car industry and by their ancillary industry for welding rotation-symmetrical mass-produced parts or sheets. Figure 10.33 shows some typical application examples for laser beam welding.

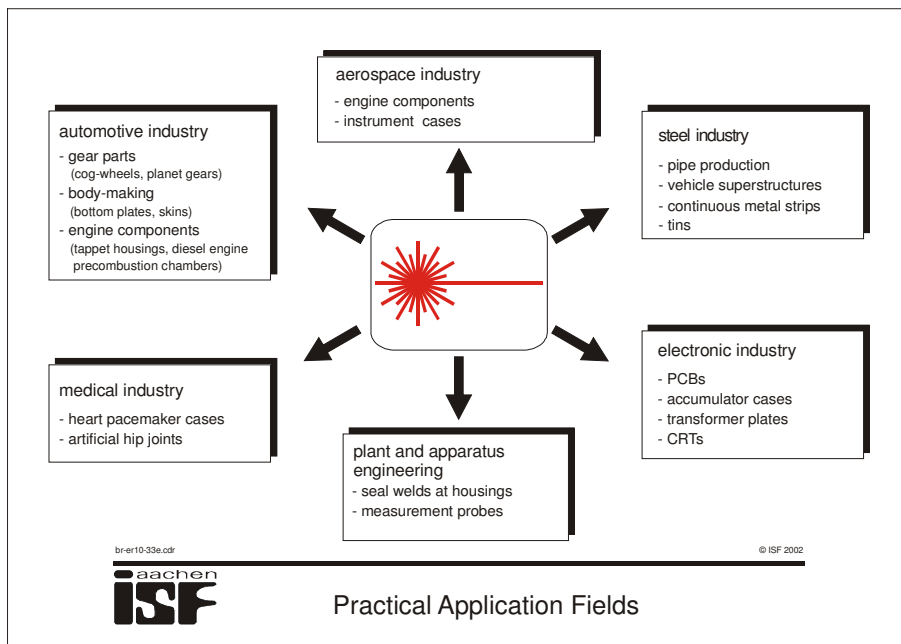


Figure 10.33