Lasers - An Overview

(English only!)

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1. Introduction

In the following a short intrduction into the physics of lasers is given. It will cover topics as the physical properties of laser beams and their generation in different laser sources, as they are used in industrial laser applications. Furthermore the interaction of laser radiation and materials will be discussed, leading to the different possibilities of material processing using laser radiation. So the principal properties of welding, cutting, ablative and combined mechanical/laser assisted processes will be presented. The last chapter covers the important hazards of laser radiation but also the hazards caused by the generation of fumes and secondary radiation.

2. Main properties of lasers, beams and processes

2.1. High power laser sources

2.1.1. Overview

Lasers are devices, that convert electrical or light energy into a light wave, that propagates in principle in a certain direction and shows a small cross section perpendicular to the latter direction, a so-called 'beam of light'. The latter beam - or laser beam - is the general case of a light wave, whereas limiting cases are spherical lightwaves, originating from point sources, and plane waves, generated by infinitely large sources, the last two cases applying to natural light, whereas *beams* are generated usually by artificial sources as lasers.

Lasers in principle consist of three main assemblies, the first being an energy source used for *pumping* energy into the active medium, the second part, the *Active medium*, that serves to amplify a beam of light. The third assembly, the *Optical Resonator*, serves to carry out a feedback for the light-amplifier mentioned above and makes thus a light-generator out of the amplifier. Moreover, it serves to focus the beam and to tailor its shape, as for instance its diameter, in order to make optimum use of the volume of the amplifying medium. Thirdly, it serves also for the extraction of a certain amount of beam-energy from the laser source and last not least, according to its name it selects a certain wavelength of the emitted light.

In the case of high power lasers with their application in material processing, the active medium can practically be an ionized gas (Gas laser) or an insulating or semiconducting crystal (Solid state laser). In the first case of the gas laser ultraviolet or infrared light with a CW beam power up to many kW´s can be generated, whereas in the second case of the solid state laser visible to infrared light also with a maximum beam power of many kW´s can be generated.

Pumping energy into the active medium, that allows amplification of light energy, can be carried out either by electrical currents, as in the case of Gas lasers and Semiconductor lasers, or by natural light, provided by lamps or by LED´s, whereas the latter pumping method is usually applied for Solid state lasers with insulating crystals. The latter crystals serve only as a host for laser active atoms, that are contained in the crystal as an impurity and serve for the amplification of laser light.

The optical resonator in the most simple case consists of two mirrors, one of them with a slightly concave shape, that serves to focus the beam, thus compensating the natural spreading up of the beam diameter due to diffraction. The geometry of these two mirrors, namely the radius of curvature and the distance of the mirrors determines the diameter of the beam, that builds up in the resonator due to light amplification in the active medium and feedback by reflection at the two mirrors. According to its name, the resonator selects a certain wavelength, since due to feedback lightwaves are running forth and back between the mirrors, thus building up a standing wave with nodes in a distance of one half of the wavelength, whereas at the mirrors nodes must be situated due to the condition of a zero field. One of the two mirrors is then semitransparent, what leads to the extraction of a certain fraction of the beam power, that is present between the mirrors.

The spreading up of the light beam mentioned above, especially inside the laser, depends on the wavelength, whereas due to the properties of diffraction a rising wavelength λ causes stronger spreading up. Further on a larger distance between the mirrors L of course leads to enhanced widening of the beam in the laser and finally a smaller diameter of the mirrors also enhances spreading up of the beam, since in the extreme case of a very small mirror, that acts as a point source of light, a spherical wave with hundred percent spreading up would be obtained, so the Fresnel number

$$N = \frac{a^2}{\lambda L} \qquad (1)$$

determines the amount of beam widening in the laser, what in turn has a strong impact on losses due to light passing the mirrors without reflection (diffraction losses).

As mentioned above, one of the resonator mirrors has a spherical shape with the radius of curvature R , the latter determining the focusing strength of the mirror. Since the radius R determines focusing and the product λ L spreading up of the beam, the diameter of the latter that builds up due to a balance between focusing and widening is determined by the wavelength, mirror distance and mirror radius.

Due to the well-known properties of diffraction one mirror regarded as a source of light generates an intensity pattern in the plane of the second mirror with a main maximum in the centre and in the case of circular mirrors surrounding by ring shaped side maxima, separated by circles with zero intensity. So, if the extension of the mirrors is relatively large, that means if the Fresnel number N » 1 , a beam builds up with a maximum intensity in the centre surrounded by one or more rings, where the intensity again reaches a maximum, a so-called 'Higher radial mode'. Only if the Fresnel number N = 1 , the relatively small size of the mirrors leads to a confinement of the intensity-distribution, cutting out solely the main maximum. In this case a so-called 'Fundamental mode' on 'Gaussian beam' is generated, that shows only a central main maximum and a smooth decrease of the intensity in radial direction. Lateron it will be mentioned, that only this type of a beam can best be focused and is thus the favourable beam mode. In this case not only the focus extension shows its smallest value, but also the divergence, that means the spreading up of the beam outside the laser is as small as possible, whereas the product of the *beam radius* - an artificial quantity, that is defined as the radius, where the intensity falls below approximately 10 % in the focus - and the *divergence*, that is defined as the opening angle of the beam, is given by the wavelength:

$$w_0\Theta = \frac{\lambda}{\pi} \tag{2}$$

It is important to mention, that higher modes as mentioned above have a higher beam parameter product due to the higher volume they occupy:

$$w_0\Theta = \frac{1}{K}\frac{\lambda}{\pi} \quad \text{with} \quad K \le 1 \tag{3}$$

K is called the beam quality number and is 1 for a pure Gaussian beam and smaller than 1 for higher modes.

So finally the main dimensions of the optical resonator, as the distance of the mirrors, their radius of curvature and their diameter together with the wavelength determine the geometrical properties of the laser beam, whereas the active medium and pumping source as well as the losses of the resonators mentioned above have a decisive influence on the output power of the laser source.

2.1.2. Carbon dioxide (CO_2) lasers

CO_2 lasers use an ionized mixture of mainly helium and equal, but much lower contributions of nitrogen and carbon dioxide for the generation of invisible infrared light with a wavelength around 10 µm, whereas free electrons always present in a considerable concentration in ionized gases are accelerated by an electrical field, cause vibrations of the nitrogen molecules due to collisions and the latter handle this energy over to CO_2 molecules, that start to carry out vibrations, whereas the central carbon atom remains resting and the two oxygen atoms move synchronously to the right or to the left (Figure 1). If now an infrared lightwave of appropriate wavelength falls on these vibrating molecules, the electrical field strength of the wave polarizes and second decelerates then the atoms, what causes them to deliberate some part of their vibration energy, thus amplifying the light wave. The amplification of this laser is as high as 100 % across an active length of 1 m and the efficiency is theoretically up to 40 % and practically 20 % for the conversion of electrical energy into light energy. So, for higher beam powers practically 80 % of the electrical energy supplied to the ionized gas must be removed to avoid overheating, what is practically done by circulating the hot gas from the active region, where electrical energy is fed into the plasma to a water-cooled heat exchanger. The higher the gas speed, the higher the output power can be, whereas modern carbon dioxide lasers yield beam powers up to 10 kW CW out of a length of the active medium of 1m, so they are practically the strongest lasers, that are available nowadays. An example for an industrial laser is given in Figure 2.

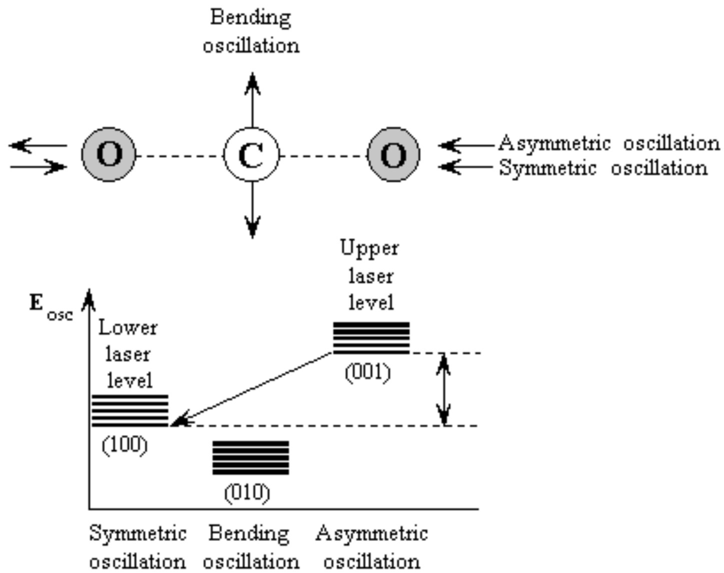

Figure 1: Vibrations of the carbon dioxide molecules

Figure 2: 6 kW CO_2 laser for industrial applications (Wild Kärnten GmbG, Austria)

Since the length of the active medium can be in the order of magnitude of meters as mentioned above, and the size of the mirrors in the order of centimetres, it is not too difficult to obtain a Fresnel number near 1 and so CO_2 lasers can generate Gaussian beams, that are excellently suited for beam focusing and producing very high intensities. Due to the beam parameter product given by the wavelength mentioned above, the focus spot diameter is roughly determined by the wavelength and so intensities up to many million W/cm² can be obtained, that are able to rapidly heat, melt and even evaporate nearly all materials available on the earth, thus allowing materials processing.

2.1.3. Excimer lasers

Excimer lasers use noble gases, as for instance xenon, that are brought to excited states again in ionized gases due to collisions with energetic electrons to form artificial molecules with halogen atoms, as for instance chlorine. These artificial molecules called 'excimers' are of course unstable and dissect after the excited atom has returned to the ground state, thus releasing their binding energy. Since the latter energy is in the order of eV, ultraviolet light - precisely with a wavelength of $\lambda = 0.3$ µm in the case of xenon chloride - is deliberated. An industrial excimer laser is shown in Figure 3.

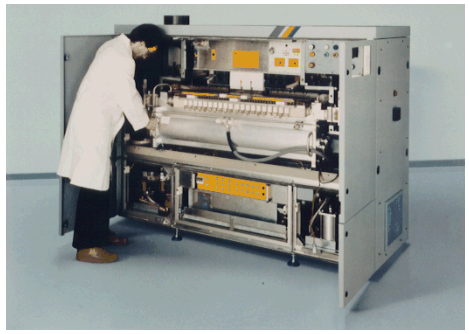

Figure 3: Industrial excimer laser with a pulse energy of 600 mJ at a repetition frequency of 250 Hz when operated with XeCl (Lambda Physik GmbH, Göttingen, Germany)

The latter light emission due to the breaking up of excimers can also be stimulated by an incoming lightwave, thus leading to light amplification.
The stimulating action of an incoming lightwave can be understood, if it is considered, that the one electron, that is on a higher energy level what means in a larger orbit for the excited atom, can become decelerated due to the electrical field strength of the light wave under the condition of a resonance between the frequency of the electron rotation and the lightwave, thus going back to its initial energy level and a smaller orbit, whereas the deliberated electron energy is used to amplify the stimulating lightwave.

Due to the properties of this kind of lasers, the active medium is rather wide and relatively short, what means that the Fresnel number becomes rather high, thus inhibiting the generation of a Gaussian beam and causing an intensity distribution with many, many side maxima distributed across the large cross section of the excimer laser, thus finally leading an average intensity profile, that remains constant across a large part of the laser cross section, a so-called 'top hat mode'. It should be mentioned that due to the specific conditions of gas discharge excitation of excimer lasers with their relatively high gas pressure necessary to rise the probability of the formation of excimers and high electrical power input to provide the necessary concentration of excited atoms and strongly limited time of electrical current flow to eliminate overheating of the ionized gas and the electrodes, allows only an operation in a pulsed mode. Typical repetition rates are in the order of some kilocycles and pulse energies can become as high as several Joule, thus yielding an average beam power in the order of magnitude of kW. Since this kind of a laser beam is far away from a Gaussian beam, its density remains rather low and the divergence is quite large. Nevertheless, the photon energy given by the frequency of the ultraviolet lightwave is rather high in the order of magnitude of several eV´s, what means, that the photons can break up molecular bonds, what is on the one hand very favourable for some kind of material processing as ablation, but on the other hand can do serious harms to human tissue, finally even leading to cancer.

It is an obvious disadvantage of the excimer laser, that it generates a beam far away from a Gaussian beam, although this turns out as an advantage for certain processing applications, where the beam is used to illuminate a workpiece through a mask, leading to ablation in certain prescribed regions. Nevertheless, the beam parameter product is very low due to the small wavelength. It is also a serious draw back of the excimer lasers, that it uses very aggressive gases as halogens, that ask for specific safety precautions.

2.1.4. Nd:YAG lasers

These lasers use transmissive crystals as yttrium aluminium garnet (YAG), that contain impurities of rare earth atoms as neodymium, erbium or holmium, whereas the latter atoms are excited to higher energy levels of their electron shell due to pumping with visible natural light. If these excited atoms are then irradiated with light with a wavelength of roughly 1 µm (infrared light), they are stimulated to jump back to the ground state, thus deliberating energy that is used to amplify the incoming lightwave. Er and Ho lasers generate light with λ = 2 and 3 µm.

The output power of these lasers is somewhat limited, since they have a very low efficiency of a few percent for the conversion of natural light energy into laser light and since pumping with extremely high light energies is prohibited due to the bad heat conduction properties of the host crystal, that makes an efficient cooling impossible. Nevertheless, from an active rod with a cross section of 1 cm^2 and a length of 10 cm roughly a beam power of 100 W can be extracted, what means that an arrangement of several rods can generate a beam power in the order of many kW and more. An example of an industrial Nd:YAG laser is given in Figure 4.

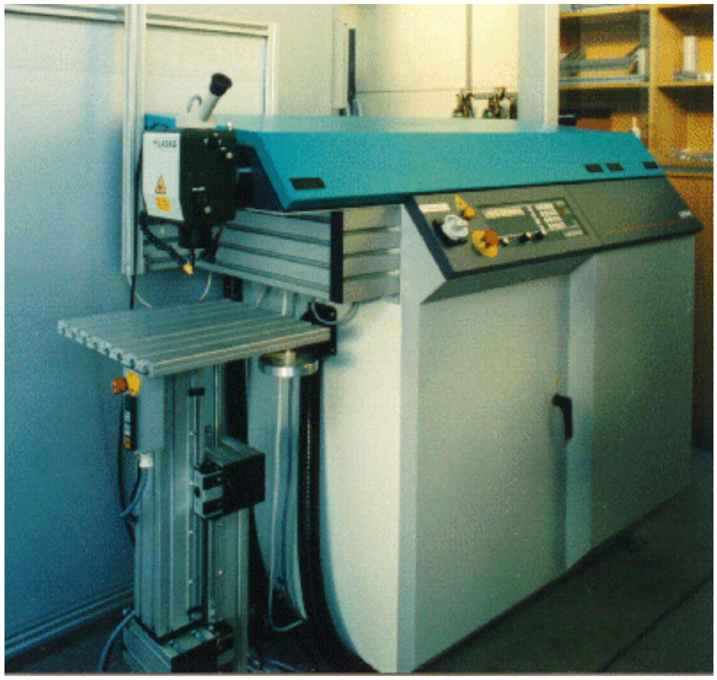

Figure 4: Industrial excimer laser with an average output power of 300 W (Lasag, Switzerland)

Although the ratio of the length of the active crystal and its cross section can be made similar to the carbon dioxide laser, the ten times smaller wavelength leads to an increased Fresnel number, that makes the generation of a Gaussian beam with a considerable power, determined by the cross section of the active medium, quite difficult, so that these lasers generate higher modes, that cannot be focused as well as carbon dioxide laser beams, although the beam parameter product would be ten times smaller due to the smaller wavelength in the case of a Gaussian beam. Infrared light with a wavelength of the Nd:YAG laser behaves quite similar to visible light, since its wavelength is not far away from visibility. Therefore it is a large advantage, that optics, that are transmissive and refractive for visible light, can also be used for light of the Nd:YAG laser. Especially flexible glass fibres can be used to transmit the radiation of YAG lasers.

The stimulating action of the lightwave, that causes the impurity atoms to jump to lower energy states under the influence of the incoming lightwave, can be understood in a similar way as explained for the excimer laser atoms, where a deceleration of electrons on their orbits by the electrical field strength of the light wave has been mentioned.

2.1.5. Semiconductor lasers

These lasers use pn-junctions as they are used in diodes and transistors to force a unidirectional current flow, thus rectify alternating currents, for the generation of light due to the recombination of conduction electrons with so-called holes, that means locations where an atom has a lack of an electron, that behave much like free particles and can move around in the semiconductor. Since the generation of electron hole pairs needs a certain energy supply, the recombination of these particles deliberates energy, preferably as light energy. Since this energy is in the most important semiconductors below 1 eV, usually visible or infrared light is emitted.

In detail in p-semiconductors appropriate impurities generate a high concentration of holes, that can conduct currents and similarly in n-semiconductors impurities cause the appearance of many free electrons. If now these two types of semiconductors are in contact with each other in a so-called 'pn-junction', applying a current that flows from the p-side to the n-side of the junction, holes are swept into the n-semiconductor and electrons are swept into the p-semiconductor, thus yielding a high concentration of electrons and holes in the vicinity of the contact plane between the p and the n-part. If the concentration of the electrons and the holes in this region becomes strong enough due to a sufficiently high current flow across the junction, an incoming lightwave with a wavelength that corresponds to a quantum energy equal to the binding energy of the electrons can stimulate electrons and holes to recombine, thus deliberating energy that is used to amplify the incoming lightwave. That light amplification mechanism can be made plausible by the idea that holes with their positive charge, that resemble atomic nuclei, and free electrons with their negative charge form so-called *excitons*, that means entities that are similar to hydrogen atoms, where the electron moves around the hole on a certain orbit. The more electrons and holes are present, the more probable is the formation of these excitons. In these excitons the electrons can assume distinct levels of energy of the movement around the hole corresponding to distinct orbital radii. So if now a lightwave enters the semiconductor, its electrical field strength may decelerate the electrons on their orbit around the holes in the excitons, what means that the elctron or the exciton loses energy that can be used to amplify the wave. Of course this mechanism can only appear, if a high concentration of electrons and holes is present.

The latter high density of electrons and holes must be swept into the active zone around the pn-interface by a high current density. To obtain this density, the cross section of the semiconductor laser is made quite small in the order of magnitude of some 10 µm by etching. Therefore the beam cross section generated by semiconductor lasers is comparatively very small, thus causing according to the beam parameter product a high divergence of the radiation. Due to the small cross section of semiconductor lasers and the high current density severe thermal problems arise, that can only be handled by an integrated cooling system with a closed loop control. Nevertheless the output power of a single semiconductor device is limited to several Watts CW operation. However, very high beam power up to the kW-range can be obtained, if a large number of semiconductor laser diodes are arranged as an array on a common substrate see Figure 5). Nevertheless the radiation of these arrays does not show spatial coherence, that means phase coordination, since the individual laser diodes work entirely independent. So the radiation of semiconductor laser arrays can not be focused so well as in the case of the other lasers treated before, since it resembles natural light, where Eq. (1) for the beam parameter product does not apply.

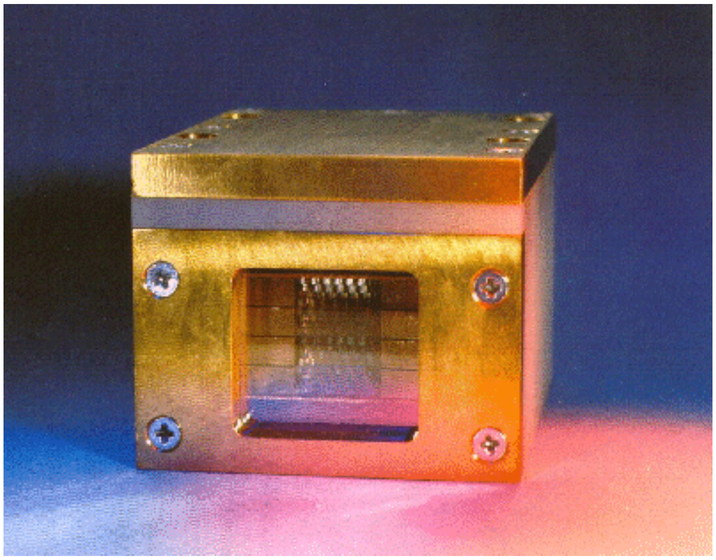

Figure 5: Stack of diode laser arrays for an average output power of several 100 W (DILAS GmbH, Germany)

2.2. Laser beams and natural light

Natural light sources, as for instance the sun, emit light in all directions of the space. If this source has a finite extension, in a distance that is much smaller than the source extension, all maxima, that have left the source at the same time, are situated on a plane that is called the wavefront and the wave is called a plane wave. If on the other hand the distance from the source is much larger than the source extension, the source looks as if it would be a point source and the wavefronts are then spheres, that means, a spherical wave is generated.

The mechanism of light generation of natural light sources as the sun or lamps is the following:

A high temperature of more than 1000°C as e.g. in the wire of a lamp causes a violent thermal movement of the atoms in the material, that leads to a great number of collisions between the atoms. During these collisions mechanical energy can be transferred from one to the other atom and this energy is used to excite the latter atom to a higher energy level. Since those higher energy levels are essentially unstable, the atom comes back to the fundamental state after a very short time on the order of 10^{-9} seconds and the energy gained during the collision is deliberated usually as radiation, either invisible or visible (electromagnetic radiation). The amount of energy deliberated during these emission processes determines the frequency and thus the colour of the emitted light according to fundamental laws of atomic physics. Due to the broad distribution of energies that are transferred during the collisions mentioned before, a wide spectrum of light frequencies is emitted during these processes, thus forming *White light* that contains all frequencies of visible light. Since the duration of the collisions and subsequent emission processes is quite low according to the above mentioned lifetime, the duration of the waves emitted during these processes is also quite short. Since the collisions take place in all directions of the space, it can also be argued that light is emitted in all directions. So finally natural light consists of subsequent short packages of waves with many different frequencies that are emitted in all directions.

In contrary laser light is generated by an amplification and feedback-mechanism as explained in 2.1., where always the same wave runs forth and back between the resonators and therefore the wave does not consist of short packages, but forms a continuous train and is thus called "coherent". Due to the frequency wavelength selecting action of the resonator, it contains also more or less only one single frequency and is thus called "monochromatic". Finally, due to the focusing action of the resonator mirrors, it propagates only in one direction and is a beam rather than a spherical or a plane wave and is thus called "unidirectional".

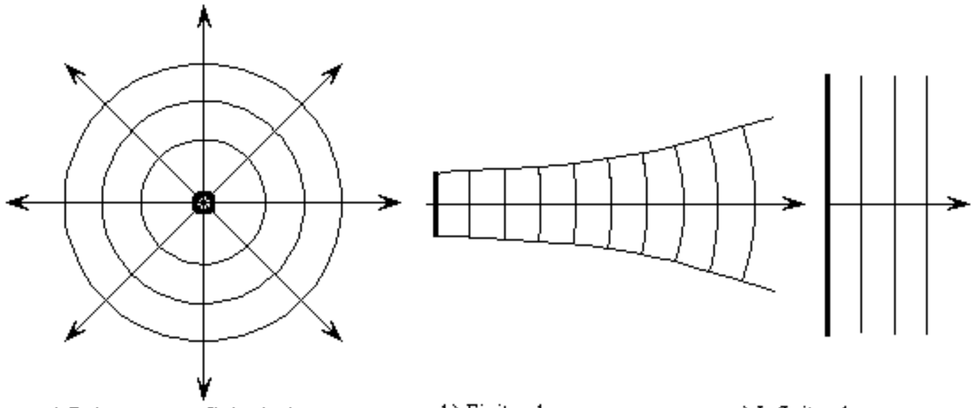

Figure 6: different light sources

Usually light sources have a finite extension, but however, if the observer is far away from the source with a distance much larger than the extension of the source, the source looks like a point source. In this case the light wave emitted travels in all directions with the speed of light c = 10^8 m/s. In detail (Figure 6), if the electrical field strength associated with a light wave and oscillating with frequency f at the source shows a maximum at a certain time, this maximum of the field strength travels in all directions of the space with speed c, reaching a sphere with radius cT (T = duration of a period, T = 1/f), precisely at the time, where at the source the next maximum appears. So a snapshot of the wave shows, for instance in radial direction, subsequent maxima separated by the distance λ = cT, the 'wavelength'. The spheres, where all maxima of the field strength, that have been emitted at the same time by the source, are situated, is called a 'wavefront' and a wave with spherical wavefronts is called a 'spherical wave'.

If now the observer comes very close to the light source with a distance much smaller than its extensions (Figure 6), the light source looks infinitely large, what means that all wavefronts are also planes and the wave is called a "plane wave". If now a medium distance is regarded, the situation of a light source with finite extension must be considered. In this case neither a plane wave nor a spherical wave is emitted, whereas both would have an infinitely large cross section. Actually, a wave must be emitted with a finite cross section corresponding to the finite dimension of the source. Very close to the source this kind of a generalized wave must show a cross section similar to the surface of the light source with a rectangular distribution of the intensity, that means the energy that crosses a unit cross section per unit time. From the edges of this beam, according to Huygen´s law, that says that each point hit by a lightwave emits light in all directions, it can be deduced, that light will also propagate from the edge of the beam in radial direction, thus reducing the intensity of light in the centre of the intensity distribution. For this reason, with increasing distance from the source, the initially rectangular intensity distribution becomes smoothened with a maximum in the axis of symmetry and continuously decreasing intensity in radial direction, reaching in principle to infinity. In this situation the wave emitted here is called a 'Gaussian beam'. As mentioned already in 2., since the mathematical treatment shows, that the intensity distribution described above is given by a Gaussian curve

$$I = I_0 \exp\left(-\frac{2r^2}{w^2}\right) \qquad (4)$$

(w = nominal beam radius, see also 2.)

Due to the emission of radiation in radial direction mentioned above, the intensity distribution must widen with increasing distance from the source, thus reducing the maximum in the centre.

If a source with a relatively small extension (diameter) is regarded, the distribution widening effect of the radial emission has a strong effect due to the initially low diameter of the intensity distribution and therefore the spreading angle must be quite large. On the other hand, if the source extension is large, the widening effect of the radial emission is quite small compared to the initially large diameter of the intensity distribution and therefore spreading up of the wave with increasing distance from the source will be low, what makes the constant beam parameter product already treated in chapter 2. again plausible.

'Higher modes', that have been introduced in 2.1. show intensity distributions with more than one central maximum, whereas in principle a rectangular or a circular structure is possible. In the first case the maxima are arranged in rectangular pattern (Figure 7) and in the last case rotational symmetry appears. Since in a light wave an electric field strength and a magnetic field strength perpendicular to the first one and both perpendicular to the direction of propagation appear, they are also called Transversal Electro-Magnetic (TEM-) modes. If a Gaussian beam is described, it is called a TEM_{00}-mode, since there are no side maxima. If in a rectangular mode there is one side maximum in radial direction besides the main maximum in the centre and no maximum along a circle around the centre, it is called a TEM_{10}-mode. A very specific kind of mode, that is obtained by the superposition of two specific rectangular modes, shows no central maximum, but only a ring-shaped intensity maximum, what is called a 'doughnut-mode' and is frequently generated by high and ultra-high power lasers.

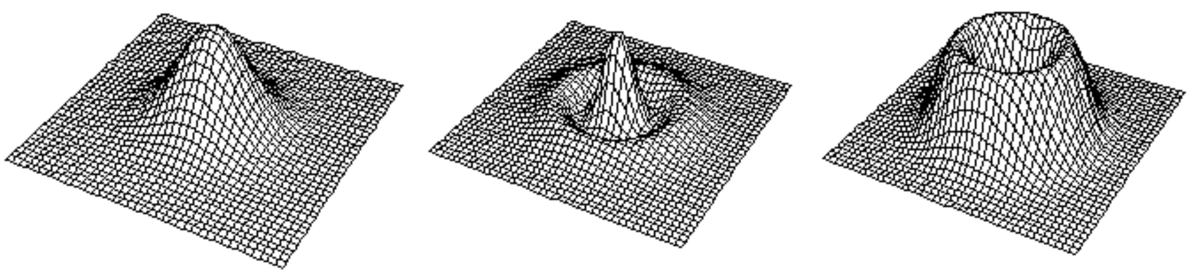

Figure 7: Examples of TEM modes

Since the main reason for the appearance of higher modes is interference and coherent light waves can of course interfere over larger distances, the latter mode structure is only fully developed in the case of laser light, being of minor importance for natural light with its incoherent and polychromatic nature.

Under certain circumstances, lasers do not generate radiation continuously, but as a train of pulses, whereas the height of the pulses and their duty cycle determine the average power transported in the beam, that can be changed by altering the duty cycle between a power corresponding to the maximum pulse power and zero, thus giving a possibility to adjust the beam power to a desired value e.g. to avoid overheating of the workpiece along processing contours with sharp corners, where the processing speed is strongly reduced. In this case, the laser is simply operated at its nominal CW power and is switched on and out in a certain sequence.

A second possibility are so-called 'superpulses', where the power supplied to the laser is for a short time increased by two or three times above the power level of CW operation, thus yielding pulses, that are correspondingly larger than the CW power. Since during this pulsing mode the thermal balance of the laser, that under CW-condition avoids overheating of the laser, is violated, these pulses must be terminated after a short time, leaving the laser the possibility to reach again thermal equilibrium. After that, the next superpulse can be generated. Superpulses are often used to reach high temperatures in material processing and allow then to melt materials with high melting point as e.g. chromium oxides, that appear in cutting of stainless steel.

3. Applications of lasers

3.1. Survey

Although lasers are used in many fields of technique, as in consumer electronics, data processing, telecommunication, measurement techniques and medicine, especially the application of high power lasers is restricted mainly to material processing and therefore the subsequent chapter is devoted solely to the latter application. The main property of lasers that is used in material processing is the high beam power, that can be achieved with lasers, and the small focus radius. Both properties together yield an ultra high intensity in a very much restricted region, that can be used to rapidly heat, to melt and to evaporate nearly any material in this region, thus offering the possibility of many manufacturing processes as for instance those with material removal (e.g. cutting) or with material addition (as e.g. welding) or finally for processes without a change of workpiece mass as in the case of forming. It is a very valuable advantage of laser technology, that a heating of the workpiece takes place in a very small region around the focal spot, what means that for instance for cutting and welding only a small workpiece volume is molten and therefore narrow cut curves and weld seams are obtained, that in turn make only a moderate heat input to the workpiece necessary, since only a relatively low part of the workpiece volume must be molten. Therefore on the one hand side laser processes are very efficient, that means they can be fast with given laser power or need only moderate power for a given speed and thickness and on the other hand they require only a very restricted heating of the non-processed part of the workpiece, what means that no thermal tensions, that could lead to deformations or cracks, are built up. Many other and additional advantages, as for instance the absence of strong forces acting on the workpiece and the total absence of tool-wear as well as environmental advantages lead finally to a preferable situation compared to conventional production processes. Therefore all over the world conventional processes are substituted more and more by laser technology.

The mechanism of laser manufacturing processes in general comprises absorption by the radiation by the workpiece, under certain circumstances - as in laser cutting - the generation of additional energy due to the reaction of oxygen with a hot metal, heating of the material, melting, sometimes the ejection of melt by a strong gas flow - as in the case of cutting and ablation - and material vaporisation, in very specific cases followed by plasma formation, as in deep penetration welding. According to the specific processing task all these phenomena are present to a larger or to a smaller extent, whereas a specific processing task is usually obtained due to a special geometry, for instance of the gas flow that is very often applied in laser technology, and by the specific choice of some parameters as laser power, gas pressure and processing speed. To understand how the many phenomena contributing to laser processing as mentioned above can be utilised for the realisation of a specific processing task and which relative importance they exhibit, in the following the phenomena contributing to laser processing as listed above are treated in more detail as absorption of laser radiation, generation of reactive energy, heating of the workpiece, melting, evaporation and plasma formation. This chapter is then followed by an overview over the various processing possibilities offered by lasers.

3.2. Absorption, heating and phase changes in laser processing

3.2.1. Absorption of radiation

The amount of absorption of laser radiation by a workpiece mainly depends on the wavelength, the electrical properties of the workpiece as the conductivity, the angle of incidence of the laser beam on the workpiece as well as polarisation and finally the intensity of the focused laser beam.

As far as it concerns the influence of the *wavelength and the material properties*, in this introduction only two wavelengths, namely the wavelength of the Nd:YAG laser (λ = 1 µm) and that of the carbon dioxide laser (λ = 10 µm), will be discussed, since only these lasers find at the moment a broad application in the industry.

To begin with the longer wavelength of the carbon dioxide laser, its absorption is governed by the electrical conductivity of the material, since the latter is connected to the density of free conduction electrons in the material. The latter electrons can carry out oscillations in the electrical field of the carbon dioxide laser due to its relatively low frequency and thus reflect the incoming lightwave due to the secondary emission of a wave as it always appears if fast charge displacements take place. For this reason highly conducting metals as gold, silver, aluminium and copper absorb only a very small amount of carbon dioxide laser radiation and reflect the large majority, whereas medium conductors as for instance steel show an absorption of around 10 %, and finally insulators as plastics or wood-based materials show a perfect absorption. Coming to the smaller wavelength of Nd:YAG lasers, here the electron reflection mechanism doesn't apply due to the much higher frequency.

So absorption is governed by the lattice atoms for this wavelength, whereas in the case of insulators as e.g. plastics with their large energy necessary to be ionised, what could lead to absorption of radiation, only negligible absorption and nearly perfect transmission appears. Nevertheless in metals the latter mechanism leads to good absorption, that is even higher than in the case of the carbon dioxide laser wavelength.

As mentioned in a chapter before, the electrical field strength is perpendicular to the direction of propagation of a light wave. If now the electrical field strength always remains in a certain plane, the situation is called "*linear polarisation*", whereas two possibilities exist, if the wave impinges on a workpiece surface, namely that the electrical field strength is in parallel to the latter or that it is inclined with respect to the workpiece surface. In the first case of linear polarisation, the absorption for perpendicular incidence is given by the amount mentioned above and does not essentially change with increasing inclination of the laser beam with respect to the absorbing surface until it drops to zero for a striping incidence, since then the wave does not enter the workpiece at all. Nevertheless, if the wave has the opposite polarisation, the same absorption is obtained for perpendicular incidence, but then with increasing inclination a totally different situation appears, since then an increasing component of the field perpendicular to the workpiece surface appears, that gives rise to current flows in the workpiece, that are also perpendicular to the surface. Since these current flows dissipate energy, correspondingly a stronger absorption of radiation takes place. So, with rising inclination the absorption increases. However, finally at striping incidence no part of the wave can enter the workpiece and so the absorption must also drop to zero, what means that at a certain specific angle, the so-called 'Brewster angle' (Figure 8), a maximum of absorption takes place. Due to this effect the initially low absorption of steel around 10 % can rise up to 80 %, whereas the Brewster angle is only slightly lower than 90 %, that means nearly striping incidence of the wave. The latter influence of the angle of incidence is of major importance for material processing, since in most applications, as in laser cutting or welding, a nearly striping incidence of the beam to the workpiece appears.

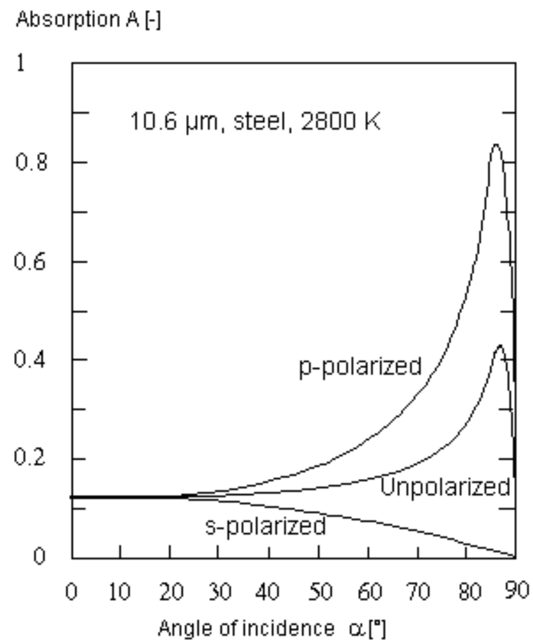

Figure 8: Absorption of laserlight with different polarization

For *intensities* up to 1 Mio W/cm² no influence of the latter quantity on the absorption can be observed. Nevertheless, beyond this limit heating of the workpiece is so strong that it causes evaporation. Due to the high temperature of the vapour strong collisions between the vapour atoms take place, that can eventually lead to ionisation of the atoms, what means that then electrons are deliberated. The latter electrons can then be accelerated by the electrical field of the incoming lightwave and thus absorb energy to a large amount. Therefore above a critical value of the intensity above a few MW/cm² a plasma forms, what leads to a strongly enhanced absorption of the radiation, that can reach nearly 100%, what is called "abnormal absorption". The formation of a plasma does not only have a beneficial effect by enhancing the absorption, but it leads also to the emission of UV radiation, that is dangerous for the human body.

If then the intensity of the lightwave is still increased, so many electrons are deliberated, that a very high electron density is generated as in a metal. In this situation the reflecting properties of electrons mentioned before can become important, thus leading finally to full reflection of the laser beam by the plasma - a phenomenon that is called 'plasma shielding'.

3.2.2. Reactive energy gain

If a workpiece is heated due to the absorption of laser radiation as treated above and if additionally a gas jet, for instance of oxygen, is directed into the focus of the laser beam, oxygen atoms will react with the metal atoms, forming oxides, for instance in the case of steel FeO or Fe_2O_3, whereas then due to the exothermic character of this reaction additional energy is generated and enhances workpiece heating. The amount of energy deliberated due to reaction depends of course on the kind of reaction, that determines the reaction energy per atom and the number of collisions between oxygen and pure metal, finally determined by the pressure of the gas flow and the speed of a relative movement between the gas jet and the metal. In practical laser material processing the amount of energy generated due to reactions can get into the same order of magnitude as the amount of energy absorbed from the laser beam, a typical situation of oxygen assisted laser cutting of steel.

3.2.3. Heating of the workpiece

In laser material processing usually the laser beam heats up and melts, sometimes evaporates the workpiece in a small region mainly given by the focal spot. If a treatment of the workpiece along a certain contour, as in cutting, welding and other applications is desired, the laser beam and the focal spot must be moved along the latter curve. The speed of this movement, the processing speed, has a strong influence on heating of the workpiece along the track of the focus on the surface of the workpiece, since with increasing speed a larger volume must be heated per unit time, what means, that for constant laser power, that means energy supply to the workpiece per unit time, a lower temperature can be obtained along the track. Further on, thermal conductivity of the material also has a strong impact on the temperature reached along and near the track mentioned above, since it leads to heat losses in the bulk of the material, that do not serve to heat the desired volume of the workpiece around the processing contour. In the case of laser treatment of sheet metals with their small extension perpendicular to the surface of the workpiece compared to the lateral dimension, heat conduction mainly takes place in parallel to the surface, thus yielding a constant temperature across the depth of the workpiece. Under these circumstances the thickness of the workpiece has a similar influence as the thermal conductivity, since thicker workpieces allow larger heat flows and the heat flow per unit cross section is determined by the gradient of the temperature and the thermal conductivity. Of course also the specific heat and the density of the workpiece material influence heating, since the temperature reached for a given heat input per unit volume decreases with increasing specific heat and density. So the temperature finally reached on the surface of the workpiece and inside along the processed track is mainly given by the processing speed, the thermal properties of the workpiece and its thickness. If for instance now heat conduction is neglected in the above considerations, a very simple equation for the temperature T can be found:

The energy generated due to absorption of laser power is AP_L and the latter must be equal to the energy used to heat up the volume of the workpiece, that is scanned by the laser beam per unit time, the latter given by processing speed v, thickness of the workpiece d, diameter of the focus $2r_F$ and the thermal properties of the workpiece, as the specific heat c_p and the density ρ:

$$AP_L = 2r_F d v \rho c_p T \tag{5}$$

The latter equation is of course only a very rough approximation of the actual situation, but allows to judge if for instance the melting point is reached, what means that cutting becomes feasible or if only the transformation point is exceeded, what means that hardening takes place.

If now heat conduction is considered again, obviously the maximum temperature is obtained at that point where the laser hits the workpiece, decreasing continuously in lateral direction in a co-ordinate system moving with the beam with respect to the workpiece. In the direction of relative movement between beam and workpiece the laser beam hits regions that had not initially been heated, so strong heat conduction takes place and a large temperature gradient appears. For the same reason in the opposite direction initially heated regions are left and therefore a weak decrease of the temperature is obtained.

In this temperature distribution the lateral gradient perpendicular to the direction of propagation of the heat source, the focused laser beam, depends on the ratio between the specific heat, that is responsible for the energy necessary to heat up the scanned volume, and the heat conductivity K ,that is responsible for lateral heat losses. The latter ratio is described by the thermal diffusion $\kappa = K / c_p \rho$, whereas a small thermal diffusion leads to a small lateral decrease of the temperature. The temperature gradient in forward and in backward direction is determined by the speed of the relative movement as mentioned before, whereas for a resting heat source the asymmetry mentioned above vanishes and the isothermal become circles. If the speed becomes relatively high, a strong asymmetry builds up and so the isothermal are near to the centre of the laser beam in the direction of movement and much more separated on the backside. If the temperature in the centre of the beam is considerably above the melting point, the melting isothermal is larger than the beam focus and inside of this isothermal material is molten. Due to the relative movement between beam and workpiece, the volume scanned by the melting isothermal with a width given by the lateral extension of the latter is molten, whereas it is blown out by a gas jet in the case of laser cutting, where a curve is produced due to material removal. If the melt is not blown out, since no gas jet removes the material, it is resolidified after moving on of the laser beam, thus joining two workpieces by a weld seam, if they are fixed close together and the laser moves along the separating line. Moreover, if a gas jet is employed that is not in parallel to the laser beam, but more or less inclined with a striping incidence on the surface of the workpiece, liquid material is ejected in horizontal direction and therefore no through-cutting is obtained, but a groove is formed, what can be used for material removal in planing or milling. So it points out, that melting plays a most important role in material processing and so do intense gas jets, since they serve to remove material. There are only very few laser processes where no melting occurs, as in the case of transformation hardening, where only the transformation point - in the case of steel that means a little bit more than 200°C - must be reached to convert a material near the track of the laser beam from the initial ferritic lattice to an austenitic structure, that changes to ultra-hard martensite due to the rapid cooling, that takes place by heat conduction after the laser beam has moved on.

The ejection of liquid material by a gas jet is caused by forces acting on the liquid. These forces are composed from the stagnation pressure force, that is caused by the deceleration of the gas, that hits the liquid and is given by the square of the directed speed of the gas flow and a force acting in parallel to the surface of the melt due to friction, that rises linearly with the directed speed of the gas flow. The force acting on the molten body leads to a gain of momentum, that compensates losses of momentum by the ejection of liquid material. So the material removal rate can directly be calculated from the above forces, mainly determined by the speed of the gas jet.

There are also some applications, where evaporation of the workpiece material takes place at its surface. Evaporation takes place, if the material becomes so hot, what means a temperature above or near 3000°C, that the thermal energy of the atoms becomes strong enough to compensate the binding energy and then the atom can leave the lattice and move away from the surface of the workpiece. Thus above the evaporation temperature a strong flow of metal vapour leaves the surface of the workpiece. The loss of momentum by the workpiece causes a strong pressure acting on the workpiece, a so-called "recoil force", that can be understood if it is considered in a similar way as mentioned above, that a loss of momentum is equivalent to a force acting on the workpiece.

The rate of flow leaving the workpiece and its vicinity is not only determined by the temperature but also by the ability of the surrounding volume to absorb vapour, what also determines the magnitude of the recoil pressure. The latter has a significant importance, if the material doesn't sublimate, that means evaporate from a solid surface, but must be molten prior to evaporation. Under these circumstances the recoil pressure acts on the surface of the melt and leads to a lateral ejection of the latter due to its incompressibility, what may lead to violent and uncontrolled explosion-like melt flows. Nevertheless, due to the above phenomenon the removal of liquid material is feasible without any additional gas jet.

3.3. Principal possibilities of materials processing with lasers and other beams

3.3.1. General considerations

Primarily high power beam materials processing as cutting, welding or surface treatment is carried out with a relative movement between the beam and the workpiece. The beam then moves along the desired cutting contour or the curve between two workpieces to be joined by welding. In this case a stationary temperature distribution builds up in a co-ordinate system that moves with the beam. Usually in the centre of the intersection of beam and workpiece surface a maximum temperature is obtained that remains constant throughout the full duration of the cutting or welding process.

Nevertheless there are also certain applications, as for instance drilling, where the beam rests with respect to the workpiece and no relative movement is carried out. This processing scenario does not lead to a constant temperature in any co-ordinate system as long as no evaporation takes place. If the latter sets on due to the reach of a sufficiently high temperature, strong heat losses appear, that are high enough to compensate the energy input by the absorption of beam energy and then a saturation of the temperature is obtained.

Due to these considerations a clear distinction has to be made between processing tasks without a relative movement and processes with an essential relative movement between beam and workpiece. In the latter case four possibilities have to be distinguished: The most simple situation concerns processes, where for instance a laser beam acts on the workpiece without any additional means with the exception of a rather weak gas flow that prevents the processed spot and its neighbourhood from oxidation. This scenario applies to transformation heartening, to forming and to welding.

A second case concerns processes where the beam, melting the workpiece in a certain area, is assisted by a sharply focused gas flow that removes the liquid material and leads thus either to cutting or ablation.

A third case is given by the combined action of a beam and supply of a powdered material of a certain composition. The beam melts the powder and also the workpiece, thus leading to the building up of a thin layer of the initially powdered material covering the surface of the workpiece and being joined with the latter, a situation, that applies to cladding or also to the generation of three-dimensional workpieces e.g. by the selective laser sintering process.

A fourth possibility can be obtained by the combination of beams with mechanical forces, whereas deep-drawing is facilitated by selective heating of those regions of the workpiece, where strong deformations occur, especially at those locations, where the initially flat material is bended (see 3.3.3.1).

3.3.2. Material processing without a relative movement between beam and workpiece

As mentioned above, for instance a laser beam resting with respect to the workpiece and sufficiently high intensity and absorption heats up the workpiece continuously until evaporation sets on and an equilibrium between evaporation heat loss and absorbed laser radiation has established. Since the evaporation heat loss is primarily determined by the vapour stream emitted by the evaporating surface, the latter equilibrium is associated with a considerably high vapour stream, that leads to a remarkable loss of material from the workpiece. Therefore the evaporating area that is initially situated at the surface of the workpiece and is limited more or less by the focus spot, the so called 'evaporation front', moves into the depth of the workpiece with a certain speed, thus producing a bore in the workpiece, what means that a drilling process is performed. Of course, this process cannot only be utilised for through-drilling but also for producing 'blind holes', what can be used for a point wise ablation and in consequence due to an application of the point wise treatment to the whole surface of the workpiece for the generation of relieves.

A second possibility of laser material processing with a resting laser beam is the use of unfocused beams with an intensity distribution that remains relatively high and nearly constant across a large part of the cross-section of the unfocused beam, as it is the case for excimer lasers with their wide and nearly rectangular intensity distribution. In this case the laser beam passes a mask with an opening that corresponds to the cross section of a hole or a blind hole to be formed in the workpiece, whereas the extension of the mask pattern is usually reduced by optical imaging with lenses in order to obtain the desired dimensions at the surface of the workpiece. An example for the ablation of micro-structures with an excimer laser is given in Figure.

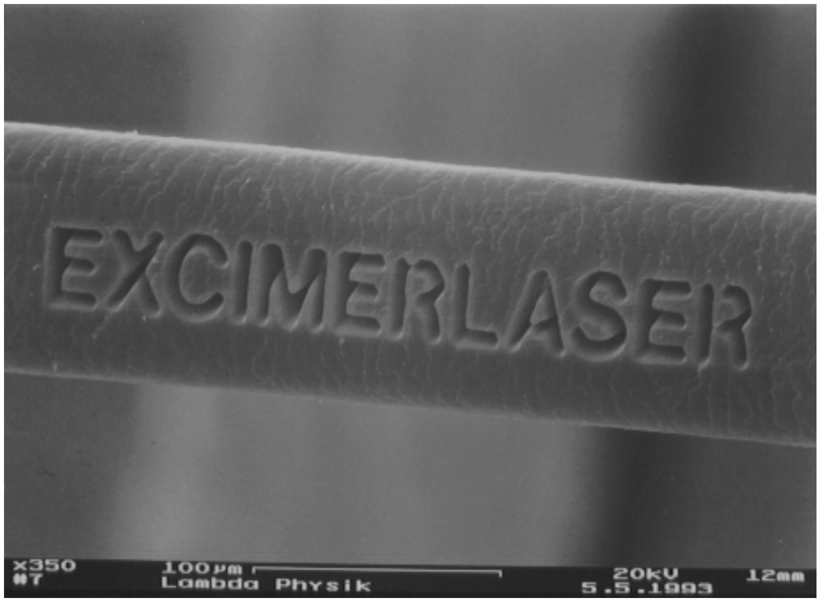

Figure 9: Micro-machining of a human hair with the excimer laser (Lambda Physik, Göttingen, Germany)

3.3.3. Material processing with a relative movement between beam and workpiece

3.3.3.1. Beam processing without additional means

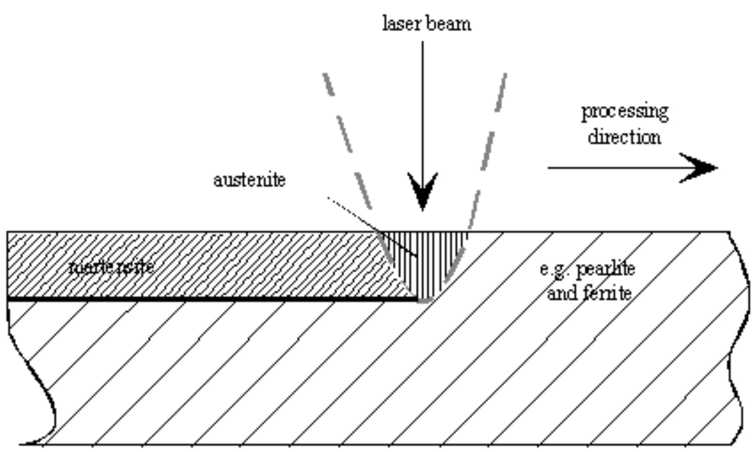

Figure 10: Transformation hardening

Figure 10 shows a situation where the focused laser beam or any other beam scans over the surface of the workpiece with a speed v. If the intensity is in the order of magnitude of 100 kW/cm^2 and the processing speed is in the order of magnitude v = 1 m/min or higher and carbon steel (for instance of eutectoidic type with 0.8 % carbon or somewhat higher or lower) is regarded, than a maximum temperature in the focus of the laser beam, that lies above the transformation temperature of 726°C is obtained and the initially ferritic crystal structure is changed to an austenitic type. Due to the movement of the laser beam initially heated regions get cooled due to heat conduction into the bulk of the workpiece rather rapidly, and therefore the structure of the material changes to the martensitic type with a strongly increased hardness. Therefore the beam scanning over the workpiece generates a narrow trace, that shows a strongly increased hardness at and near the surface of the workpiece. If for instance a laser beam moves over the workpiece with a slight movement in lateral direction after the completion of each line, the whole surface of the workpiece or at least a certain part can be hardened.

A similar process that leads also to an improvement of surface hardening and other properties of the surface is performed, if the beam intensity is increased to such an amount, that not only the transformation point is reached but also melting takes place, what means in the case of steel, that a temperature of around 1300°C must be reached. In this case a small part of the material adjacent to its surface and the laser spot is molten and resolidifies after the laser beam has moved on. Due to this melting and resolidification process, usually the crystal growth is quenched due to rapid cooling and therefore a refined structure with improved hardness and wear resistance is obtained. This process is referred to as 'laser remelting', if a laser beam is used.

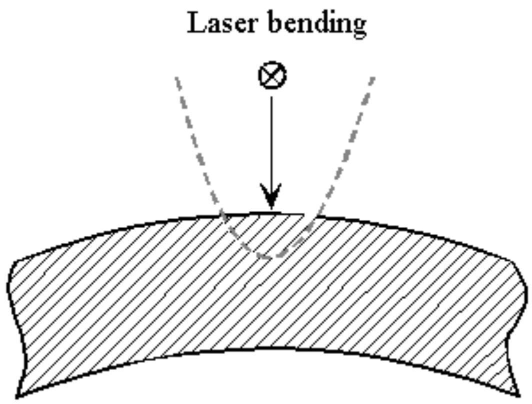

Figure 11: Laser bending

Usually, during the above processes, the workpieces are fixed to a mounting table to avoid any deformation of the workpiece, especially if it is relatively thin. The latter unwanted deformations of the workpiece due to thermal stress can turn to a useful application, if the workpiece, especially sheet metal is not fixed, thus allowing a free movement at least in vertical direction (Figure 11). In this application, for instance a laser beam moves quite slowly over the surface of the workpiece, thus building up thermal stress in a direction perpendicular to the movement, that leads initially to bending to a convex shape. Astonishingly enough, this initial convex deformation turns to a concave one, what is caused by heat conduction from the initially hot surface of the workpiece to the cold bottom of the latter and accumulation of the heat there, what leads finally to a thermal expansion at the bottom of the workpiece, thus causing the concave shape of the processed piece.

Finally, if the intensity of the beam is increased to 1 MW/cm^2 or more, two workpieces fixed together in a butt geometry with a beam moving along the gap between the two workpieces, leads to melting of both workpieces throughout the full depth, whereas the two molten bodies merge and form then the weld seam after resolidifaction due to cooling down that follows heating by the laser beam.

Since this process is characterised by an absorption of beam energy at the surface of the two workpieces and heat conduction into the depth of the latter, it is referred to as 'heat conduction welding' and can be utilised for instance in the case of steel up to a thickness of a few millimetres.

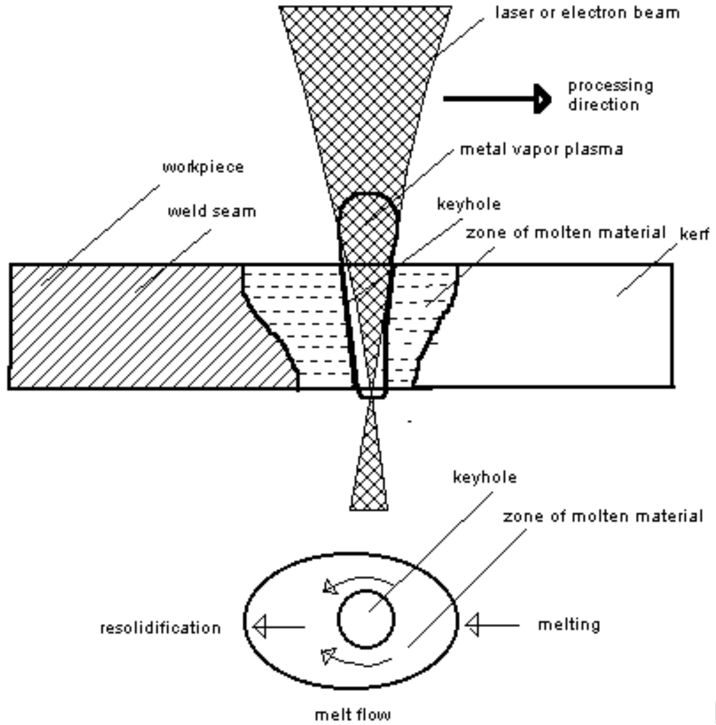

Figure 12: Deep penetration welding with laser or E-beams

The welding depth can be improved by one order of magnitude if the intensity of for instance a laser beam reaches a magnitude of at least 3 MW/cm^2, since in this case the material starts to evaporate at the surface, finally leading to the establishment of a narrow channel that extends throughout the full depth of the workpiece and allows the beam to penetrate into the depth of the workpiece, thus providing direct heating of the workpiece throughout the full depth of the latter (Figure 12). The vapour channel is also called 'keyhole' due to the geometry of melt-isotherm around the vapour channel.

This process is called 'deep penetration welding' and can not only be carried with lasers but also with E-beams or plasma jets. It should be mentioned that a change from heat conduction welding with lasers into deep penetration welding is associated with the appearance of a bright, white/blue luminosity at the focus of the laser beam. The latter is caused by the ionisation of metal vapour generated under the conditions of deep penetration welding and leaving the workpiece at the upper opening of the keyhole, leading to the formation of a plasma cloud due to heating up by laser radiation.

Under the conditions of deep penetration welding with lasers, especially with a similar beam intensity in the focus but largely increased speed, evaporation is restricted to the surface of the workpiece or to its vicinity, what means that the laser beam, moving over the surface of the workpiece, produces only a narrow and shallow groove, a process, that can be utilised for scribing symbols or drawings into the surface of the workpiece and is revered as 'laser scribing or grooving'. The patterns produced by this process find graphic applications but can also be used to generate geometrical patterns for instance for optical grids for holographic applications or, totally different, to assist the breaking of semiconductor wafers into smaller pieces.

3.3.3.2. Beam processing assisted by gas jets

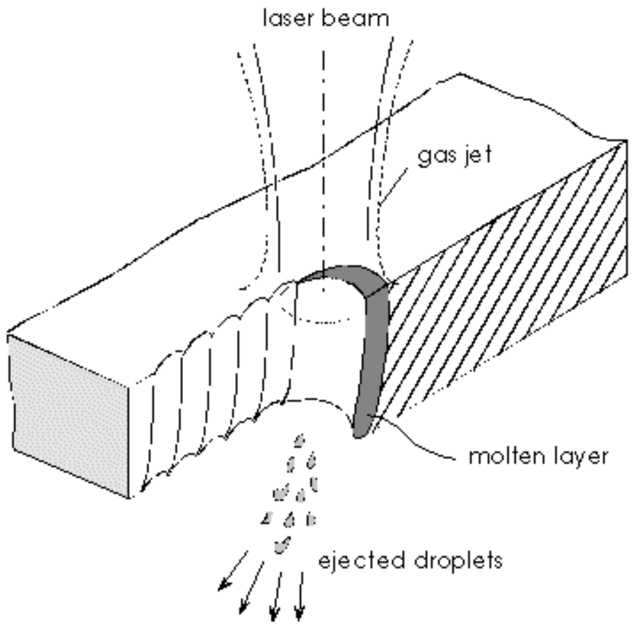

Figure 13: Laser cutting

Intense gas jets can be used to remove material, that has been molten due to the absorption of laser radiation, what finally leads to the removal of material, as it is necessary for laser cutting and laser ablation.

In the case of laser cutting, that is shown by Figure 13 a gas jet propagating in vertical direction is used to blow out the molten material that is produced due to heating of the workpiece by the laser beam at the momentary end of the curve. This process is usually called 'laser fusion cutting' or 'gas assisted laser cutting'. If the assisting gas jet has a considerable content of oxygen, the gas jet does not only have a mechanical effect as blowing out liquid material, but leads also to an additional heating of the workpiece due to the exothermic reaction of oxygen, for instance with steel. In this case, with the same laser power, an improved thickness can be cut or a higher processing speed can be obtained. These processes are referred to as 'reactive gas assisted laser cutting' and have to be distinguished from 'high pressure inert gas cutting', where no oxygen is used and the enhancing effect of oxygen on the cut performance is compensated by the use of a considerably increased gas pressure with the advantage that no slag layers which are typical for oxygen cutting are covering the cut surfaces, thus either facilitating rewelding or maintaining the corrosion resistance of the laser cut pieces. Inert gas assisted laser cutting is also quite efficient in cutting of stainless steel and similar materials since it avoids the formation of e.g. chromium oxides that show an extremely high melting point, and make thus laser cutting quite difficult. With oxygen assisted laser cutting with a 2 kW CO_2 laser, steel up to a thickness of 20 mm and aluminium up to a thickness of 5 mm can be cut, whereas for rather thin sheet metals a maximum speed up to 20 m/min. can be obtained.

Quite similar, a plasma jet can be used for cutting, whereas heating is carried out by the electrical energy transported by the plasma and ejection of molten material is accomplished by the argon/hydrogen gas flow, that accompanies the plasma jet.

Instead of blowing out the molten material by a gas jet, the melt can also be sucked away by a vacuum nozzle, a process called 'laser suction cutting' (Figure 14). In this case expensive gases can be abandoned.

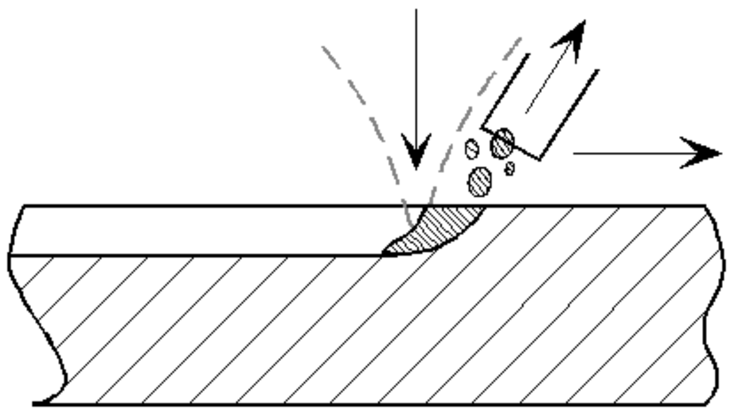

Figure 14: Laser suction

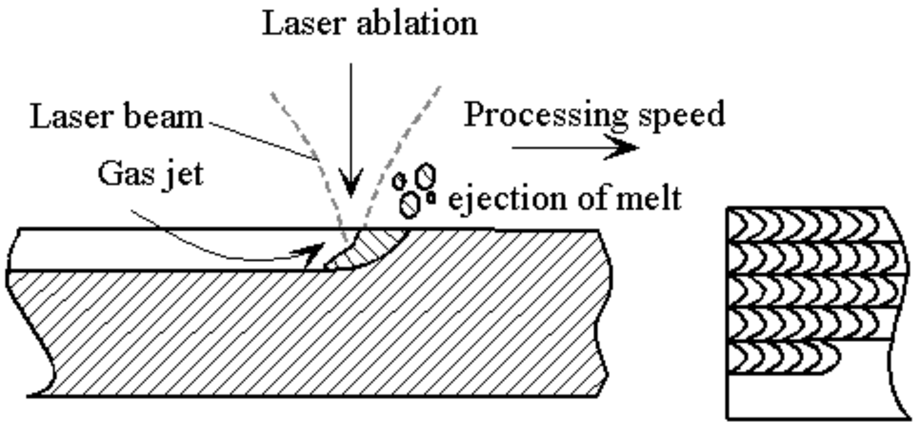

Figure 15: Laser planing

So far only cutting through the full depth of the workpiece has been treated. Nevertheless, under certain circumstances, for instance with modified strength or direction of the gas flow, that blows away the molten material, through cutting can degenerate to the mere production of a groove, that does not extend through the full depth of the workpiece. If for instance the gas jet blowing out the liquid material is directed in parallel to the surface of the workpiece, the melt is ejected in parallel to the surface of the workpiece. Due to a movement of for instance a laser beam in the same direction a 'planing process' is obtained, whereas a narrow and shallow grove is generated on the surface of the workpiece (see Figure 15). By arranging one grove beneath the other due to an appropriate movement of the laser beam over the surface of the workpiece, material can be ablated over a certain part of the surface. The repeated treatment of a certain area in the above way leads to the formation of caves.

A similar process uses a gas flow perpendicular to the surface of the workpiece, where the necessary gas flow speed in parallel to the surface of the workpiece is obtained by a pendulum like motion of the processing head. The latter process is called 'laser caving'.

In the case of the latter process, the main movement of the processing head is in vertical direction in order to perform ablation into the depth of the workpiece, but there is also a movement in the two horizontal directions in order to extend the volume of the cave. Due to these movements the caving process is primarily very well suited for the generation of vertical walls due to its basically vertical gas flow, but suffers from a very low processing speed due to its inefficient material removal mechanism. In contrary the laser planing process is best suited for the generation of horizontal surfaces due to its essentially horizontal gas flow. Since the material removal mechanism is very efficient, its processing speed is much higher than that of the caving process.

There is also a third process, called 'laser chip removal', where due to the combined action of laser melting, oxidation due to an oxygen flow and resolidification material is removed in the form of small chips.

The suction principle can also be applied to ablation processes quite similar to 'suction cutting' with similar economic advantages.

3.3.4. Material processing with the addition of powdered material

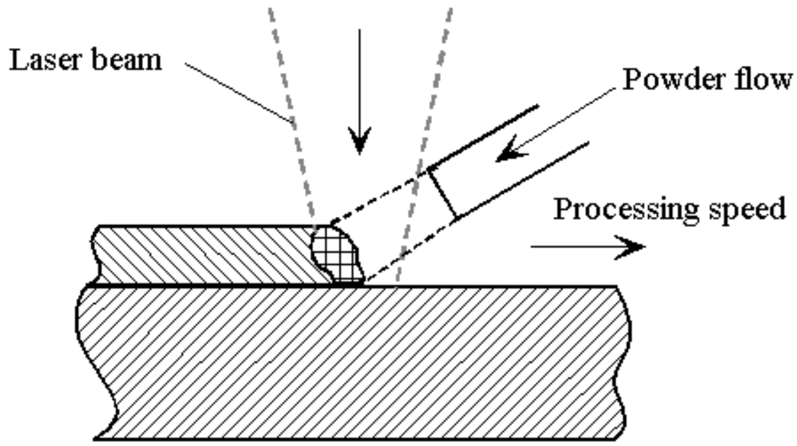

Figure 16: Laser cladding

Powdered material can be used either to change the composition of the material of a workpiece near to its surface ('laser disperging' and 'laser alloying') or to cover a certain portion of the surface of the workpiece with a thin layer ('laser cladding'). Moreover, by subsequent generation of thin layers, one on the top of the other, even three dimensional structures can be built up ('rapid prototyping', see Figure 17). In these processes the powdered material can be put in place by distributing it over the area to be treated ('preplaced powder process'), a method usually employed for rapid prototyping or it can be blown on the surface of the workpiece as a thin jet into the focus of the laser beam, both moving with respect to the workpiece ('blown powder process', see Figure 16). This usually is used e.g. in laser cladding but also for certain options in rapid prototyping.

In detail, in the first case of the *preplaced powder process*, the powder is distributed on the surface of the workpiece across the area to be treated as mentioned above. The laser beam is then moved over the powder and the workpiece. Due to a sufficiently high intensity of the beam and an appropriate processing speed the workpiece is molten in a thin region near the surface at the momentary position of the focus. If the melting point of the powdered material is higher than the melting point of the workpiece the powder remains unmolten but is submerged in the liquid material of the workpiece. After the laser beam has moved on in processing direction, the material resolifies due to cooling by heat conduction into the bulk of the workpiece and then the powdered material is built into the lattice of the workpiece in a thin region near the surface of the latter, what can be used for an improvement of certain properties of the workpiece as for instance wear or corrosion resistance. The latter process is referred to as 'laser disperging'. If the melting point of the powdered material and the workpiece material are not very different, then the powder is also molten and mixed up with the molten surface of the workpiece, thus performing 'laser alloying' after resolidification as mentioned above. If the powdered film on the surface of the workpiece is relatively thick, the molten powder will not totally be submerged into the molten surface of the workpiece, but will cover the initial surface, thus forming a thin layer of the additional initially powdered material on the surface of the workpiece that is fixed to the latter by a region, that resembles a weld seam and is formed from a mixture of both the additional and the workpiece material. The latter process is called 'laser cladding' and can be used to cover the surface of a material with low hardness with a noble layer that provides enhanced hardness and thus shows strong wear resistance and under certain circumstances also corrosion resistance. Similar effects can be obtained with the *blown powder process.* Powdered material is blown through a thin tube into the focus of the laser beam that moves over the surface of the workpiece (see Figure 16), where with the latter powder jet for instance laser cladding can be performed. In both process options, that of the preplaced powder and that of the blown powder process, the laser beam is moved for instance along a straight line across the surface of the workpiece, thus producing a narrow and thin trace with added material. By arranging one trace beneath the other one processing of a desired area is possible. So the added material can be *disperged* in the surface layer of the workpiece. Otherwise the workpiece is *alloyed* or *covered* with the additional initially powdered material only in those areas, where wear or corrosion resistance are desired and thus in many applications only a small part of the total surface is to be treated, finally saving material and time and thus finally costs.

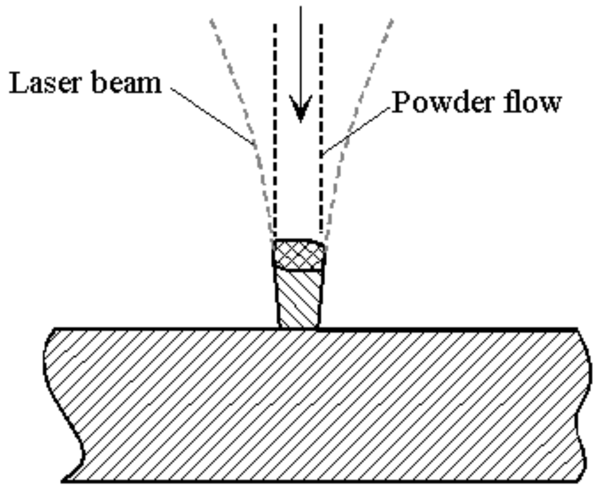

Figure 17: Selective laser sintering process

3.3.5. Materials processing with beams combined with mechanical forces

So far only a combined action of high power beams as e-beams, laser beams and plasma jets with additional gas flows or mass flows have been considered. Nevertheless, in the case of cutting with gas assistance, for instance laser cutting, the gas flow exercises also a mechanical force on the molten material leading to its ejection. So mechanical forces are an important ingredient of several beam processing tasks, although in the latter example mechanical forces are provided by the momentum of the intense gas flow. Also water jet cutting, where a highly accelerated and thin water jet hits the workpiece and removes small chips due to cavitation and similar phenomena, is an example for beam processing with mechanical forces. Thirdly 'flame flattening' is a good example for this kind of processes, since a gas burner warms up and weakens a workpiece and subsequently directly applied mechanical forces provided by hammers or presses remove deviations of the workpiece from its initial flat shape, as in the case of damaged car body parts.

Clearly, an initial heating of the workpiece followed by mechanical deformation or restoration of the workpiece can be carried out not only by high power beams, but also by other heat sources, whereas beams are only beneficial if a weakening of the workpiece along or near to a certain curve on the surface of the workpiece is desired. This can be the case if for instance a deep drawing process is regarded.

In this process an initially flat piece of sheet metal (called blank) is pressed by a stamp, that is subject to strong mechanical pressure into a forming tool and drawn through this tool (see Figure 13), whereas the final shape of the circumference of the workpiece is determined by the shape of the die and the height of the final workpiece is determined by the vertical way of the stamp. A third tool, the blankholder, serves to avoid unwanted deformations of the upper flat portion of the workpiece by the tangential forces associated with the drawing process.

During this process strong forming actions take place in that region of the workpiece, that is in the vicinity of the upper edge of the opening of the die plate. In this region of the workpiece stretching of the material in radial direction and compression in tangential direction as well as bending takes place, what means that in this region most of the energy needed for forming is spent. This energy could be reduced if some part of the energy is supplied prior to the forming process by pre-heating. Since that has to only take place in the narrow and ring-shaped region where the above forming processes take place, the heating of the whole workpiece would be very inefficient and so heating by narrow beams would be more beneficial, thus reducing the mechanical energy needed for forming and thus also the mechanical forces that are necessary. Two possibilities exist for high power beam treatment of the narrow ring-shaped region mentioned above in the vicinity of the opening of the forming tool:

First, a narrow beam could be moved along the centre line of this ring-shaped region in closed loops, so heating it up in each point. For this purpose especially plasma jets or laser beams could be used. Nevertheless, in this process the temperature in a certain point reaches a maximum temperature if it is hit by the beam and shows a certain decrease of the temperature after the beam has moved away and therefore a temperature distribution similar to a saw tooth, that contains of course a certain medium value, is obtained. For the purpose of pre-heating prior to forming only the average temperature is relevant, whereas the maximum of the temperature must not exceed the melting point. This condition can only be achieved safely if beams of sufficiently high power move sufficiently fast along the desired contour. The better solution would be a simultaneous heating of the whole region by ring-shaped beams. For this purpose modern high power lasers, for instance with unstable resonators or with a hollow-cylindrical plasma geometry, are excellently suited. There is only one problem that has to be overcome: Usually the blankholder covers the whole flat portion of the workpiece and comes very close to the stamp, thus leaving no part of the workpiece uncovered. To solve this problem (see Figure 13), the blankholder has to be redesigned in order to show a somewhat increased inner diameter and an inclined inner edge, thus allowing a laser beam to reach the workpiece under a certain angle, for instance 45°. A second possibility would be the substitution of the blankholder by three or more rotating rolls that reach each point of the workpiece frequently and press it down but leaving space for heating by the beam (see Figure 19). Also, small slots cut into the blankholder could allow laser radiation to reach the workpiece. In a similar way mechanical bending could beneficially be supported by laser heating.

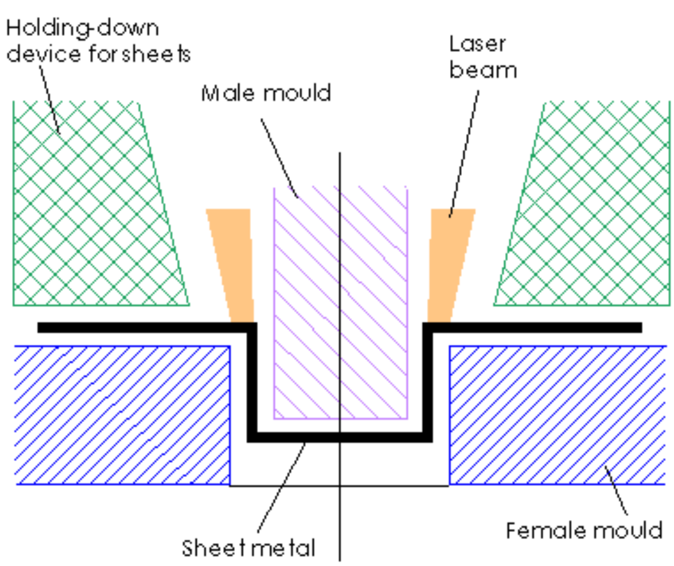

Figure 18: Conventional blankholder

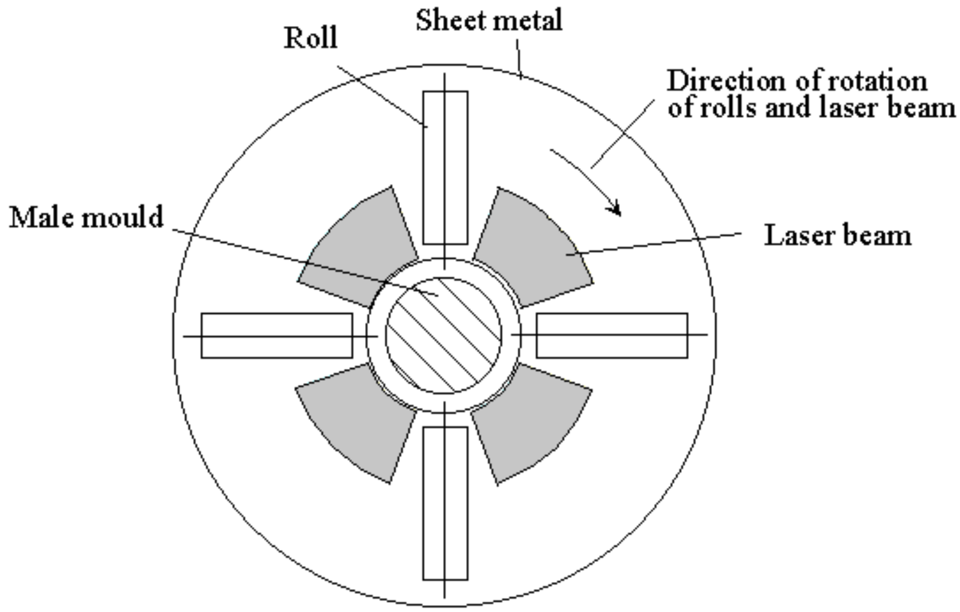

Figure 19: Rolls as blankholder

4.Hazards of lasers, beams and applications and relevant safety precautions

4.1. General remarks

From the above treatment of the most important properties of lasers, beams and application processes it became obvious, that certain hazards are associated with them, whereas these hazards are not restricted to the dangers of the laser radiation, but also cover the wide field of dangerous electrical energy, dangerous gases, hazardous reflections and emission of secondary radiation as well as splashing out of hot molten materials, strong flows of very hot vapour, that may even be poisonous or may carry small particles as aerosols or dust, that are likely to cause cancer.

So in the following - based on the above treatments of lasers, beams and processes - a short overview describing the main hazards associated with laser technology and the relevant safety precautions is given.

4.2. Hazards of high power laser sources

Obviously pumping of the active medium, that is carried out in the case of high power lasers for materials processing with considerably high powered energy can be a source of hazards, whereas in the case of CO_2 lasers either DC-voltages with a magnitude of several 10,000 Volts or short-time pulsed voltages with an even much higher magnitude (also in excimer lasers) or even high power rf-currents are used. It is obvious, that high and ultra-high tensions are very dangerous, since they can kill humans. It is less obvious, that also rf-currents can become quite harmful, although they are usually conducted along the skin and cannot penetrate into the depth of the human body due to the well known skin effect at high frequencies. Nevertheless, freely propagating rf waves, that are similar to light, but have a much larger wavelength, can be absorbed by human tissue and heat it up, whereas several organs show a strong sensibility against overheating of a few centigrade. One example is for instance the root of the teeth, a second example are the male testicles.

In the case of pulsed voltages for carbon dioxide lasers a special threat are the large capacitors, that are used to store electrical energy, that is then deliberated in the form of a short and powerful pulse.

In order to prevent harmful actions of high tensions, all parts, that are connected with high tensions, must be safely mantled with secure grounding of the shielding material. Moreover, the removal of shielding parts must activate the so-called 'interlock' switches, what leads to an immediate interruption of the power supply to the laser. Moreover all capacitors, for instance used to smoothen rectified currents, must be safely discharged on power-off. Special attention must of course be paid to capacitors used for the storage of energy as mentioned above, that have not only to be discharged, but also - to be safe - must be short circuited and grounded. So far, in the case of DC- and pulsed voltage the prevention of a direct contact between parts under tension and the human body is necessary. In the case of rf waves, that appear in modern high power carbon dioxide lasers, since they are not excited by DC currents but rather by rf energy with its advantages of elevated power-to-volume ratio, the emission going out from the laser must be avoided. Therefore a so-called 'Faraday cage' formed by an electrically conducting grid or net, that covers all parts that could emit rf radiation and is safely grounded, can totally prevent harmful radiation. In practice instead of a grid or net also sheet metal parts with holes, that allow to look inside the laser and that reduce the weight, are used. To be totally safe, it would be a good idea to include in the arrangement of the cage mentioned above also some sensors, that indicate the presence of an rf-field, for instance if for any reason the shielding of the Faraday cage must be removed. Nevertheless, those shielding must also be protected by interlock switches. In the case of the Nd:YAG laser, that is excited by lamps or flash tubes which emit intense white light with eventually strong ultraviolet tails, shielding that permit trespassing of light especially in the ultraviolet region must be used. Since the lamps or other light source of Nd:YAG lasers are also powered with elevated tension, similar safety precautions concerning electrical energy must be taken as mentioned above.

A further source of hazards is the active medium, especially in the case of some gas lasers, since gases can leave the laser and then do harm to people, if they are poisonous or aggressive. A typical example is the excimer laser mentioned above, since the latter uses halogens as chlorine and others, that can etch the eyes, the lungs and also the skin. So severe safety precautions must be taken to prevent a deliberation of halogens, as for instance safe gas supply systems, fixed metallic tubes instead of flexible hoses and of course storage of gas bottles in safe and locked shelters and the immediate availability of gas masks for the case of an accident.

Finally, the third main assembly of a laser, namely the optical resonator with its at least two mirrors, is only a source of hazards as far as it concerns the shape and the direction of the beam, for which the resonator is responsible. Hazards connected to these beam properties are treated below.

4.3. Hazards associated with laser beams, especially of high power

Laser beams due to their small cross section carry highly concentrated light energy, that can hurt the human eye, especially by a destructive overload of the photo receptors or even by burning and it can also do harm to the human skin, at least as a sun burn or even by more severe burning. These threats of laser radiation are enormously enhanced, if the ultraviolet radiation, as for instance generated by excimer lasers, is considered. In the case of the human eye the dangers of laser radiation are multiplied due to the focusing action of the human lenses and the excellent focusability of laser light, what leads to strongly magnified intensities acting on the photo receptors. All these dangers do not only appear, if the direct laser beam hits the human body, but also if radiation is reflected, what can happen if bending mirrors on the way of the laser beam between the source and the workpiece are misalign or if the laser beam hits highly reflecting material, that is not safely fixed, or finally if during a process reflecting surfaces are formed as melt or plasmas, the latter especially in deep penetration welding as mentioned above. Besides a dangerous reflection of the direct beam also the emission of secondary radiation, even with lower wavelength, that is more dangerous, if it is in the ultraviolet, can take place, what has also been treated before. Besides a reflection of the direct beam or secondary emissions also diffuse reflection, where the reflected wave is no longer a sharply collimated beam, but shows a broad spatial distribution, can be harmful, if the initial laser beam is of high power. To judge on the danger potential of a certain given laser, lasers are divided into four main classes, whereas in class 1 even looking into the direct beam is secure, whereas laser powers in the order of microwatts (µW) are covered. In the case of class 2 lasers, the beam power can be elevated, but they must be in the visible range, since in this case closing of the eye due to the irritation limits the time of exposure. Finally class 4 lasers are so strong, that even the diffuse reflection, as mentioned above, can do harm to the eye. To be protected against the hazards of the laser beam, one must first look after the class of the laser, that must be indicated on the latter. If a class higher than 2 is stated, safety goggles must be used. The latter are small narrow band filters, what is matched to the small band width of laser light, but makes the use of different goggles for different lasers, as for instance excimer lasers, Nd:YAG lasers or CO_2 lasers, necessary. Of course safety goggles must clearly indicate their wavelength of protection. Specifically dangerous is the situation, where deep penetration welding with carbon dioxide lasers is carried out, since in this case strong ultraviolet radiation, due to the formation of a plasma as mentioned before, is emitted and so the safety goggles must protect against ultraviolet and against infrared radiation. Besides this direct protection of the eye, the whole laser system or at least those parts, that are reached by the laser beam, must be contained in housings, that prevent laser radiation to come out or people coming into contact with the beam. Usually only the near surrounding of the processing system, where the laser carries out its work, is housed in and the laser is standing apart, whereas the beam is guided to the workstation by metallic tubes. As in the case of protection against electrical hazards, these tubes and all other parts of the housing must be protected by interlock switches against removal. Of course the diameter of the tubes guiding the laser beam to the workstation must have at least twice the nominal beam diameter due to the intensity distribution of the beam mentioned above. Otherwise the beam would lose energy and the tubes would heat up in a dangerous way. Concerning the housings of the laser processing system, doors that allow operating personnel to load and unload the workpiece and to adjust the system must also be protected by interlock switches and floor contacts, for instance carpets which react on stepping on, must ensure, that the laser can only be turned on, if nobody is inside and if the doors are locked. Nevertheless the practical experience shows, that all these systems can fail and for this case emergency off-switches must be located also inside the processing station housing. To be totally safe, it is advisable, that operating personnel, when entering the processing station housing, take with them the ignition key of the laser to prevent a second person from an erroneous switching on.

4.4. Hazards of laser processes

4.4.1. Overview

Laser processing can mainly be divided into three categories, the first one with an essential material removal as in the case of cutting and ablation, the second one with material addition as in the case of welding or cladding and rapid prototyping and thirdly processes without a change of the workpiece mass in the case of hardening, bending or laser assisted forming.

Each of these three categories is subject to specific hazards, that are in the first category associated with the removal of material. In the second category the hazards are associated to violent evaporation, that does not really lead to a loss of material, but gives rise to the formation of plasmas, that emit strong light, even in the ultraviolet, and may also lead to a reflection of the working beam. The third category seems to be much less dangerous, since neither material nor radiation is emitted and therefore no interaction with operating personnel takes place.

4.4.2. Processing with material removal

In this case a fast gas jet removes liquid material as droplets, that are resolidified after separation from the bulk of the melt and form grains, if they originate from liquid material flowing out at the bottom of the workpiece, as in the case of laser cutting, or a powder, if they are thrown away from the surface of the liquid material due to friction with the gas jet. In the latter way also dust and aerosols can be emitted by the liquid material, that are by the way extremely dangerous and they can cause cancer in the lungs. Finally, if the liquid is hot enough to evaporate, metal vapour is formed. Solid material and vapour emitted during material removal can show a different chemical composition than the workpiece material, on the one hand due to decomposition of molecules, what may result in the emission of poisonous products, and on the other hand can be caused by reaction, for instance with oxygen used or contained in the gas jet, what also can deliberate dangerous materials, as for instance chromium oxide in the case of processing stainless steel. By the way the liquid material ejected from the molten layer, that immediately after separation from the latter is still liquid and thus above the melting point, can also do harm to people by burning, if the ejected material hits the skin or even more dangerously the eye before resolidification and cooling down. This phenomenon of the ejection of liquid material of high temperature can be observed in laser cutting, where on the bottom side of the workpiece a so-called 'spark shower', that consists of molten droplets with high temperature, appears.

For certain materials, that do not melt, but directly evaporate, that means sublimate, the recoil pressure of the leaving vapour stream acts on the solid surface and induces microcracks, that leads to the separation of fine particles from the surface and thus dust etc. can be emitted. If evaporation takes place via the intermediate step of melting, due to the same recoil pressure also small liquid droplets are splashed out and form after cooling down and resolidification also dust and similar particles.

So during ablative laser processing with material removal due to various mechanisms finally solidified particles of either size from larger grain sized particles to very fine particles, so-called 'aerosols', and also vapour and - after cooling down - gases, that might have a different chemical composition than the workpiece material leading to a poisonous character, can be emitted and form the main perils of this category of processes.

Safety precautions that prevent particles emitted during material processing with material removal from doing any harm, comprise housing in of the workstation to prevent the emission products to leave the workstation and exhaustion of the latter by blowers via appropriate filters, that are matched to the nature of the various emission products as microscopic particles, powders, dust, aerosols and also vapour. Moreover, since most of the material is ejected as initially liquid and hot droplets, that cool then down and are thus resolidified, appropriate means must be used to collect these particles and allow them to cool down without hitting parts that could be damaged. Therefore specific traps are used, that do not only collect resolidified droplets, but also catch that portion of the beam that is not absorbed by the workpiece and leaves the latter e.g. at its bottom. So in the case of laser cutting usually a metallic box is situated below the workpiece in the vicinity of the location, where the beam hits the workpiece and serves on one hand to absorb the unused beam power, that leaves the workpiece at its lower surface, by multiple reflections in the box and subsequent absorption, and on the other hand collects the resolidified droplets ejected at the bottom of the workpiece, thus preventing them to burn anything. Under specific circumstances this box can also be connected to an exhaustion system that carries away dangerous particle emissions, for instance in the case of laser cutting by suction through the cut-curve.

4.4.3. Hazards associated to processing with material addition

Material addition can be accomplished either by welding a first workpiece to a second one or by building up layers of initially powdered material on a workpiece as in the case of cladding, where thin layers finally cover the surface of the workpiece, or by building up three-dimensional structures on a substrate in rapid prototyping.

In the first case of laser welding, especially in deep penetration welding, the two workpieces fixed together in a butt geometry must be heated by the laser beam at the separation line up to the evaporation point in order to form a thin channel, extending throughout the full depth of the workpiece and thus allowing the laser beam to penetrate into the depth of the workpiece. Due to this mechanism of deep penetration welding the latter vapour channel blows out metal vapour especially at the upper side of the workpiece, thus giving rise to a vapour cloud above the channel mentioned above. The latter plasma cloud can now absorb laser radiation, as mentioned before, what leads to ionisation and to the formation of a plasma with a temperature well below 5000°C. Although the formation of this plasma is desired, since it leads to a better coupling of laser radiation to the workpiece by abnormal absorption, it is associated with the dangers of strong ultraviolet emission, that corresponds to the high temperature mentioned just before. This secondary emission is typical of all manufacturing processes, especially cutting and welding, where hot plasmas are formed and used and therefore the hazards associated with ultraviolet radiation are well known by craftsmen. The protection against this secondary radiation can be done by housings, as mentioned several times before, and of course also most essentially by safety goggles, that have also been treated above.

Moreover, deep penetration laser welding is also dangerous, since the high recoil pressure generated by violent evaporation acts on molten surfaces, that are always present in the case of welding by definition, and therefore usually very hot and molten material splashes around, what damages on the one hand especially the focusing optic and can also do harm to operating personnel or can also cause a fire, if combustible materials are near to the welding system. Again housing of the workstation is the most important prerequisite for a safe operation. Concerning the destruction of optical elements by splashing melt, fast gas flows in the processing head, that catch molten droplets and carry them safely away, have been used successfully.

In the case of laser cladding and workpiece generation from powdered material, a certain amount of powder is always lost to the environment of the workpiece and can do harm to the lungs of operating persons, that breathe it in. Therefore again housing in of the workstation and a connection of the latter to an appropriate exhaustion system is also necessary for this kind of manufacturing processes.

Concluding the hazards and relevant safety precautions for material processing with lasers, the most important measures comprise mantling of the processing system, that protect the operating personnel on the one hand against the emission of dangerous particles, aerosols, dust and vapour and on the other hand against radiation, stemming from the working laser beam either directly or reflected and also emitted by hot workpiece material as secondary emission with eventually much lower and thus more dangerous wavelength. So with housings made of an appropriate material, that transmits neither laser radiation nor secondary emission, but is preferably at least in some parts transparent for visible light, thus allowing the operation personnel to observe the workstation and that cannot be penetrated by material emissions of either kind, a safe operation of laser processing can be ensured, whereas also organisational measures, as a well designed system of interlock switches, give additional security.

So far all safety precautions mentioned before have only been designed to protect the operating personnel. Nevertheless it is also important to avoid a pollution of the environment by dust, aerosols or poisonous gases. Thus it is not sufficient to exhaust the workstation as mentioned above, but appropriate filters must be used that catch emitted matter in various stages, that are matched to the size and nature of the dangerous emissions and to prevent them from being deliberated to the environment. So filter techniques are of major importance for a safe operation of laser material processing systems.