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ICS Lectures on Industrial Applications of Lasers

N. U. Wetter and W. de Rossi

with contributions by F. Grassi and W. M. Steen

Spero Penha Morato, Editor

2000

104 p
tables
graphs
diagrams

INTERNATIONAL CENTRE
FOR SCIENCE AND HIGH TECHNOLOGY

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Niklaus Ursus Wetter and Wagner de Rossi have provided most of the text; contributions have also been made by Fabricio Grassi and William M. Steen.

Spero Penha Morato is the publication's general scientific editor. Editorial coordination and advice were provided by Susan Biggin, senior information coordinator at the International Centre for Science and High Technology.

Foreword

Industrial applications of lasers in countries with developing economies

Spero Penha Morato

Growing market opportunities have fostered the development of aggressive management strategies and the search for new technologies. Laser technology has attracted, worldwide, a number of persons working on transformations in industry, mainly in metallurgy, electronics and biomedical companies. Today, the metallurgy sector in developing countries is searching for information on new technologies because, in a globalized economy, competition for markets pushes more efficiency, better quality and low production costs. The industrial application of lasers, mainly for cutting, drilling and soldering, is a response to these needs.

Countries with economies in transition still lag behind in the utilization of high technologies in some of their products and processes. For these countries, high technology is all the technology that they still do not have or have yet to master. Another characteristic of developing countries is the lack of interaction between their universities and research institutes and industry. University professors in these countries sometimes act as an impermeable barrier, failing to respond to the technical demands of the local private sector. On the other hand, local industrialists in general do not trust indigenous science, even though its level is sometimes as high as that of more economically advanced countries.

Taking account of these facts, a programme of training courses designed by ICS-UNIDO to teach applications of industrial lasers focused on the local industrialist, taught by lecturers from local universities and R&D institutes, turned out to be a successful experience. Training courses in several countries, over a period of two years, showed that there is a demand for these high technologies and that there are excellent business opportunities in this area.

A group of experts on industrial laser applications composed of a mix of laser specialists and representatives of laser industries from developing and developed countries met in Trieste, Italy, on October 1996, coordinated by ICS. This group discussed regional necessities, identified local resources and devised a programme directed to industrialists and managers of local metal/mechanical industries. As a result, training courses on industrial laser applications in the metal/mechanical industry were carried out in Brazil (Sao Paulo—May 1997), Peru (Lima—October 1997), Tunisia (Tunis, November 1997), Argentina (Buenos Aires—June 1998) and Fortaleza (Brazil—October 1998).

Latin America, for instance, is a continuously interesting region for investment because of the economic building blocks already in formation. The North American Free Trade Agreement (NAFTA) (Canada, Mexico and United States of America) is a reality. The Southern Common Market (Mercosur) (Argentina, Brazil, Paraguay and Uruguay) is a fantastic promise. El Pacto Andino (Bolivia, Chile, Colombia, Equator and Peru) cannot be denied. For example, it is estimated that in 1994 the commercial exchange between the four countries of Mercosur reached US$12 billion. The potential for new business is even higher than this, as the sum of the business volume with other countries is about US$100 billion per annum. However, laser applications in countries such as Argentina and Brazil are limited by some factors: high initial equipment investment, geographical distance when maintenance is needed, lack of a "cultural approach" to new technologies and inefficient communication between university specialists and the private sector.

The training courses provided some basic knowledge of laser principles, technical information and some job-shop training that allowed for strong interaction and contact between local university people and local industries. A wide spectrum of possibilities was presented and thoroughly discussed, ranging from simple cutting and drilling applications to the fabrication of tailored blanks. These training courses also acted as a high-tech "show room" because laser producers were always present with videos, catalogues and material from their own companies. They also gave lectures and distributed pertinent information, sometimes aided by equipment demonstrations. These activities facilitated the exchange of information and the internalization of the concept that lasers are new tools that do both old and new things.

The courses attracted considerable attention and were highly welcomed by the host countries and by the participants from other countries in the region. They were attended by an audience composed mostly of engineers, technicians, managers and industrialists that came mostly from the metal/mechanical industries. The audience also included local and regional university people (mostly physicists and engineering students). In general, the number of participants was higher than the official number of registrations. In all courses, there were many positive results, especially considering that some of the laser technologies have been around for more than 20 years in developed countries. These technologies were not always known to most of the participants of the countries that sent representatives. The participants very much appreciated the laboratory demonstrations, visits to local industries, visits to job-shops and the participation of the laser supplier companies in a "show room" type presentation.

Evaluation of these courses gave composed ratings of "very good" and "excellent" concerning the programme, lecturers and organization. This fact alone is a clear indication that these ICS activities fill part of a repressed demand for such technical knowledge in these developing countries.

The general conclusion is that it is possible to transfer high technology and it should be fostered in those countries that have a minimal industrial basis and infrastructure and above all, the technical capacity to absorb it. Otherwise these activities should be structured as an awareness-building activity and, consequently, the format of a training course should have a totally different approach. The role played by ICS-UNIDO was demonstrated as being an important one since countries with developing economies have a high demand for this kind of knowledge. Technology transfer plays a tremendous role for the implementation of value into the products and services of those countries, enabling them to be competitive in a growing economy.

The courses also showed that it is possible to identify in regional research centres and universities resource people willing to transfer local or foreign laser technology to local industries. As a consequence of this experience, ICS charged me with the mission of producing a training package based on the lectures that were given during these courses. As a consequence, this book was written by N. U. Wetter and W. de Rossi, two laser researchers from the Instituto de Pesquisas Energéticas e Nucleares, Sao Paulo, Brazil, who participated actively in most of the training courses. Two chapters were written by F. Grassi from Prima Industria, Torino, Italy, and by W. M. Steen from The University of Liverpool. Many other lectures and participants also made contributions by discussing industrial laser applications. I would like to mention and thank D. Belforte, editor of the Industrial Laser Solutions for Manufacturing, PennWell, Pittsfield, Massachusetts, United States of America; E. Gallego Lluesma and M. Garavaglia from CIOp, La Plata, Argentina; and F. O. Olsen from Institute for Product Development, Lyngby, Denmark.

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Overview

Over the last decade, a number of developing countries have been actively engaged in applying laser technologies in a wide variety of areas, such as medicine, the metals industry, electronics, optics and graphics. The goal throughout this effort has been the improvement of their industrial and economical development, and clearly the key to this interest lies in the high added-value attached to laser applications and the extent to which they can revolutionize both R&D and industry. An equally important factor is their extremely low ecological impact.

The chief goal of *Industrial Applications of Lasers* is to examine and describe the most common types of laser in use in industry, while providing a basic scientific background. The various areas of industrial laser applications—cutting, welding, drilling, marking and scribing as well as the all-important subject of the laser market—are covered in detail. The end-goal is the provision of a working guide aligned with UNIDO's strategy of international cooperation towards developing and emerging countries.

This strategy emanates from United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992, and Agenda 21, which was adopted by the Conference, as well as subsequent international forums, and promotes a policy of sustainable development that balances the endogenous industrial capacity of developing and emerging countries with environmental issues. In this context, the laser applications described here are tailored to the objectives of the high-tech industrial sectors of Latin America and focus on the expanding endogenous capacity in the laser field in the region.

In accordance with its institutional goals, ICS-UNIDO has given strong support to the preparation and publication of this book, in particular as an opportunity for emphasizing the importance of advanced technologies of this kind to the industrial development, social welfare and economic growth of Latin America.

Francesco Pizzio
ICS-UNIDO
Managing Director

1 Lasers

Doctor N.U. Wetter and Doctor W. de Rossi

This document focuses on the development and industrial application of lasers. The laser is a flexible and powerful tool with many relevant applications in industry. Its uses are spreading worldwide as a consequence of the development of modern laser systems towards improvements in cost and reliability. Today the laser provides effective solutions to many problems in industry and technology and replaces many established technologies, mainly owing to its ability to increase a company's profitability by improving productivity. Its unique features include versatility, reliability, speed and automation, all with very high precision and flexibility.

1.1 Laser overview

The first material to demonstrate laser action was the synthetic ruby crystal. The ruby laser (a solid-state laser) was developed by Theodore Maiman in 1960. Shortly thereafter researchers around the world developed a vast assortment of laser-capable materials. These materials can be in the solid, liquid or gaseous state.

The first gaseous laser was the HeNe laser, developed in 1961. It was also the first laser to emit continuous – not pulsed – radiation. In 1964 the first liquid laser, a dye laser, was invented. Dyes are organic compounds that, when optically pumped, exhibit luminescence often spanning a large portion of the visible spectrum. This makes them very valuable wherever an appreciable tuning range of the emitted wavelength is required.

One laser that does not fit into the three categories mentioned is the free electron laser (FEL). A FEL converts electric energy into light through the interaction of an electron beam with a periodically changing magnetic field (wiggler). These lasers produce very high flux densities in the ultraviolet (UV) portion of the spectrum, making them interesting whenever high flux densities in the UV are needed.

Although a wide variety of lasing materials exists today, only a few have found their way to industrial applications. Even for scientific applications, out of dozens of lasers with interesting characteristics, only a few are commercially sold. The few that remained on the market and probably will continue to enjoy wide acceptance are the focus of the following discussions.

Before turning to the discussion, however, it is important to identify the most valued characteristics of industrial lasers. From an end-user viewpoint, reliability is the number one criterion for an industrial laser [1]. Most importantly, the laser must be able to operate on demand, in lengthy production schedules, in a routine and uninterrupted manner while being maintained by semi-skilled personnel. Using the industry-accepted 80% efficiency number, these lasers must run 6,000 hours per year with 95% availability (which is also the industry benchmark).

The dye laser is an example of a product that has not been accepted by the manufacturing world. The main disadvantage is that dyes have a short lifetime in high-volume continuous applications.

Reliability is one of several laser performance requirements, many of which are process and material specific. Wavelength, spatial power distribution in the laser beam, power and energy limits, power stability, temporal output modes such as pulse duration and repetition rate are examples.

Many more laser parameters interact and affect output characteristics and performance. A good example is the HeNe laser. It has an output power limit of a few hundred mW and therefore is of no use in high-power industrial applications. Nevertheless it is the most widespread laser in the world, mainly used in educational and scientific applications owing to its low cost and visible emission wavelength. Another key issue is the laser system price. The investment must be justifiable to meet accepted plant return-on-investment practice.

Other important requirements for industrial lasers are physical size, operating efficiency, operational cost, safety and ease of maintenance. Today's lasers must be compact, light, easily integrated into existing systems and they must place no special demands on power sources, water or other auxiliary services. The operational costs must be sufficiently low in order to manufacture competitively-priced products and most importantly, the laser should be easily maintained by plant personnel.

Due to the exacting requirements outlined above, to date only a few laser systems are (and will in all probability continue to be) widely accepted by industrial users. The following discussion explains the basic principles by which these well established lasers emit coherent radiation.

1.1.1 *Industrial gas lasers*

Since the invention of the laser as many as 90,000 systems have been installed in industrial environments: 38% in cutting applications; 20% in marking; 17% in welding; 13% in micro-processing; 2% in drilling and the remaining 10% in applications such as surface treatment. The most-sold laser systems contain a gas laser and show sound characteristics in almost all of the above applications.

As its name suggests, the active media in this type of laser is in a gaseous or vaporous state. Most gases show laser capability. They are generally classified as atom (HeNe), ion (Ar^+) or molecule (CO_2) lasers. There are also lasers that use metallic vapour (for instance the Cu vapour laser used in micro-machining applications) or excimer. Excimers are rare-gas halides consisting of two atoms that emit coherent radiation in the UV region and are therefore specially suited to micro-drilling and surface ablation processes.

The gases are excited in a discharge tube that contains the gas mixture. Depending on gas pressure, the gain media is produced by passing a current through the tube which ranges from 0.1 A/cm^2 to > 10 A/cm^2. Two types of gas-excitation through electron collision need to be distinguished:

1. Collisions which directly excite or even ionize the atoms (Cu laser)

$$e + X \rightarrow X^* + e$$

2. Collisions which excite metastable energy levels of one of the constituents in the gas mixture which then resonantly transfers its energy to the gain media. A good example is the N_2 which transfers its energy to the CO_2 (see also figure 1).

$$N_2^* \quad CO_2 \quad \blacktriangleright \quad N_2 \quad CO_2^*$$

Some of the gas lasers developed so far are shown below.

Gas lasers
gaseous or vaporous gain media

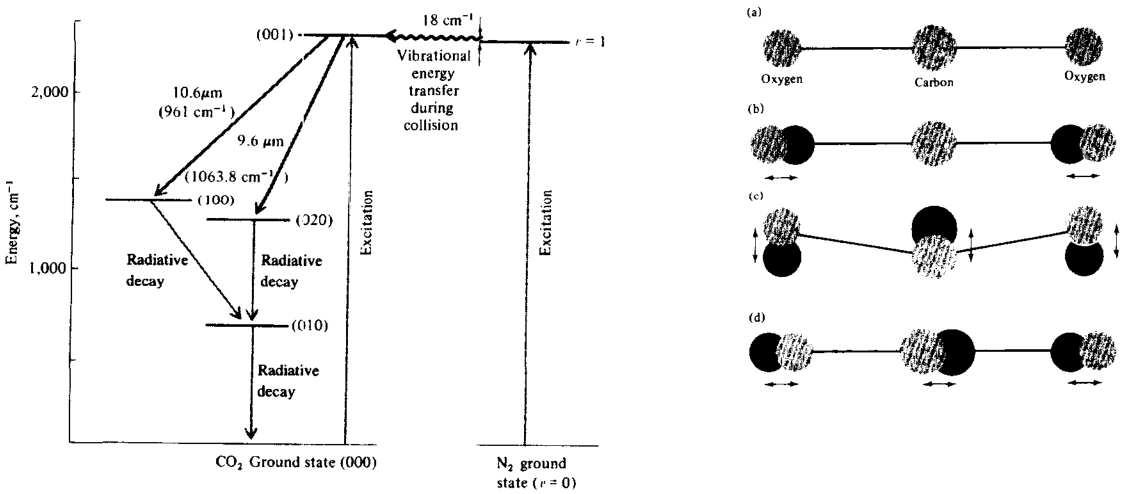
Atoms	Ions	Molecules
He, Ne, Ar, Xe, N, C, Si, Sn, Pb, H, P, O, S, F, Cl, Br, I	Ne, Ar, Xe, Kr, Ca, Cu, Mn, Cs, Zn, Cd, Mg, In, N, C, Si, Sn, Pb, Ge, Se, Te, P, O, S, F, Cl, Br, I	H_2, O_2, HO, H_2O, HF, HCl, HCN, CN, CO, CO_2, CS_2, N_2, NO, NO_2

The CO_2 laser

CO_2 lasers show an availability in excess of 95% and exceed most of the conventional materials processing operations. They are used three shifts per day, six days per week and are therefore extremely reliable. For these reasons, CO_2 lasers are the most-sold industrial laser, showing good performance in almost all of the main manufacturing applications. They possess high overall working efficiency, achieving in some cases 30% [2].

Several recent innovations have enhanced CO_2 laser technology, now placing it among the most competitive technologies on the market. Sealed-off units up to 1 kW of output power are now available. These systems do not require a continuous supply of CO_2 and therefore maintenance requirements are significantly decreased. Other innovations include an improved beam quality for high-power 6 kW systems. The CO_2 is also the most powerful laser installed on a factory floor. An example already in use is the 135 kW laser.

Figure 1. CO_2 vibrational energy levels and modes [2].
Left: some of the vibrational energy levels of CO_2; right: normal mode of CO_2 *(a)* ground state (unexcited); *(b)* symmetric stretch mode; *(c)* bending mode; *(d)* symmetric stretch mode.



CO_2 lasers typically operate in a mixture of carbon dioxide, nitrogen and helium. Electron collisions excite the metastable state in nitrogen molecules with subsequent energy transfer to carbon dioxide laser levels (see figure 1). The helium gas acts to keep the average electron energy high in the gas discharge region and to cool and depopulate the lower laser level [3]. Since the CO_2 molecule consists of three atoms, it can execute three basic internal vibrations, called the "normal modes" of vibration. These normal modes represent the energy states that the molecule can accept. Transitions between energy states are accompanied by energy loss or gain in the form of heat or light radiation.

After the vibrational energy transfer from an excited nitrogen molecule to the CO_2 molecule, by means of a collision between both, an asymmetric stretch mode of the CO_2 molecule is carried out. From this energy level, the molecule decays after a couple of milliseconds (ms) to the lower laser level through the emission of a photon which is added to the laser radiation. The lower laser energy level is in either a symmetric stretch mode (10.6 μm laser radiation) or a bending mode (9.6 μm laser radiation). From there the molecule returns quickly to the ground state, owing to an efficient energy transfer to the He molecule which is added to the gas mixture where it can recommence the process. The emission spectra of the carbon dioxide laser consist of many neighbouring laser transitions because apart from the vibrational modes, rotational modes also exist that split the vibrational energy levels into many, much smaller, levels. This allows the laser to be tuned from 9 to 11 μm on up to 80 transitions, though industrial lasers generally only lase on the 10.6 μm transition due to their construction type and gas pressure inside the discharge tube.

The CO_2 laser represents an "old" technology, developed mostly in the 1960s. In view of the product innovations mentioned, it is not difficult to understand why the future of this laser remains assured. Some of the newer constructive methods of this laser are discussed later.

The excimer laser

Until recently, excimer lasers operating in UV were noted for their frequent maintenance requirements. This record has been improved with an extended mean-time-between-failure performance, and dramatically increased intervals between maintenance [1]. This, coupled with an increased output power in ArF units, has expanded and opened new applications in micro-drilling and surface ablation processes.

Rare-gas halide excimer lasers operate in a pulsed output at a wavelength of 193 nm for ArF, 248 nm for KrF, 308 nm for XeCl and 351 nm for XeF. The ArF is the market leader in excimer lasers because of its shorter emission wavelength. Other excimer lasers are gradually substituted by newly available solid-state technology which is less expensive and more reliable. All-solid-state lasers now exist that emit high power and short pulses down to a wavelength of 266 nm.

The noble gas lasers are relatively efficient: up to 8% is feasible. When pumped by energetic electron beams, their output is from 0.2 to 1 J/pulse, with a pulse duration of between 10 and 50 ns and repetition rates up to one or two hundred Hz. The accelerated electrons collide with rare gas molecules that become ionized and at the same time dissociate the halogen molecules to form negative ions. These two species then combine to form an excited molecular state of the rare-gas halogen molecule which represents the upper laser state [3].

$$Ar + F \rightarrow (Ar^*)^+ + F \rightarrow (Ar^+F\ )^* \rightarrow ArF \rightarrow Ar + F$$

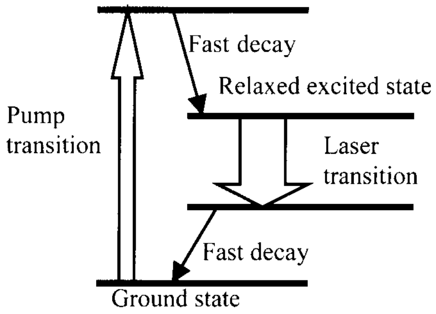
In a very short time ($\sim 10^{-8}$ s), this excited state relaxes to the lower laser level under emission of a photon and dissociates thereafter into the ground state.

A newcomer to excimer lasers is the F_2 laser that emits at 157 nm. Its main application is in optical lithography. The small wavelength emitted by this laser has promising potential for many other industrial applications, the limitation being the laser's low-output power (~5 W) available to date.

1.1.2 Industrial solid-state lasers

In a solid-state laser, the gain media is embedded in either a crystalline or amorphous host. For example, Nd:YAG indicates that the crystal is composed of yttrium aluminium garnet and that the gain media inside is neodymium. The concentration of the laser-active dopant ions in the host is generally very small, about one part per hundred. Nevertheless this means that active centres to the order of 10^{19} per ccm exist. This explains why some of these lasers have extremely high gain and therefore very high power in the laser output pulse. Peak powers of about MW per pulse are common and, owing to the high-gain centre concentration, they are also very compact devices. A 10 cm crystal rod can generate 5 J of energy per pulse at 100 Hz repetition rate.

A very wide range of laser hosts and laser-active dopant ions exists. The hosts need to be transparent at the laser emission wavelength and have good optical, mechanical and thermal characteristics in order to support the severe operating conditions. The amorphous (glasses or ceramics) or crystalline host must also have specific sites that can accept the active ions. These dopant ions are generally rare-earth or transition-metal ions with distinctive free-ion electronic configurations which permit the population inversion necessary for the laser action. The third basic element of a solid-state laser is the optical pump source with its peculiar spectral irradiance and geometric characteristics. Excitation is supplied to the solid by radiation which is absorbed by the dopant atom. In practice, this pump radiation is generally supplied by xenon and krypton lamps or semiconductor diode lasers which efficiently raise the absorbing atoms from the ground state into an excited, higher energy level. The electrons, which carry the absorbed energy of the excited atom, relax to a less energetic level after a very short time. In this process the energy lost by the electron is converted into heat of the solid (i.e. it is heating the crystal). From the new level the electron returns to the ground state by emitting a photon. This transition is responsible for the laser action.



Although a vast assortment of different solid-state lasers exists with many interesting applications, very few make it to the factory floor. Again, reliability and performance requirements are the main reasons for this. By far the most-sold solid-state laser is the Nd:YAG which exhibits performance, reliability and maintenance benchmarks similar to the CO_2 laser.

Several new materials promise to improve solid-state laser technology for specific applications. All of them are based on the neodymium dopant ion but use different host materials. Neodymium-yttrium-lithium fluoride (Nd:YLF) shows good properties for short pulse lasers (Q-switching) and has less thermal lensing than YAG but also less mechanical strength. Yttrium-vanadate (Nd:YVO_4) shows good properties but is difficult to grow. Both crystals have found commercial applications, particularly in micromachining, but still represent only a small fraction of the volume of industrial solid-state lasers sold.

A new material-ablation mechanism with great potential for industrial microprocessing applications has generated a search for different and efficient solid-state lasers. Metal-transition ions, embedded in an appropriate host, emit under certain operating conditions a large, almost continuous band of frequencies. As the shortest possible pulse duration is indirectly proportional to the width of this band, these lasers are capable of generating pulses of between 10^{-12} and 10^{-14}s. These pulses are too short to create either a plasma on the working surface or to induce thermal or mechanical damage to the workpiece. The absence of laser beam reflection by the plasma and of absorption by Joule heating makes this the most efficient of all laser-ablation mechanisms. It is also a very precise process, removing only about 1 micron per pulse. Efficiency is maintained using high repetition rates (< 10 kHz) where heat does not affect the remaining material. Because this is a non-thermal process, the material-ablation efficiency is almost independent of material type or defects, permitting laser processing of a whole new assortment of materials.

Intense research is being undertaken into systems employing Ti-sapphire or Cr:LiSAF as laser-active materials. There is at least one industrial version already on the market that uses an erbium-doped fibre as femtosecond oscillator, where pulses are frequency-doubled to 775 nm before they are amplified. Other industrial versions of these ultra-short pulse lasers are expected to be entering the market as this document goes to press or shortly after and possibly, to become a market factor in years to come.

The Nd:YAG laser

The first Nd:YAG for industrial applications was installed in 1972. Since then the Nd:YAG has undergone major product changes and, gradually, is taking market shares away from the CO_2 laser. The Nd:YAG technology developed over the past five years has significantly increased the number of applications for this laser and is therefore worthy of a closer look. The multi-fibre beam delivery capability permits time and/or power sharing of the laser and therefore optimizes production speed, flexibility and efficiency. The same unit can be used at the same time for several welding and soldering jobs, thus significantly lowering production costs. Multi-element Nd:YAG lasers with cw output powers of about 6 kW now exist. These new lasers are used today in high-tech applications such as tailored welded blanks, sometimes with better results than the CO_2 lasers.

1.1.3 Diode lasers

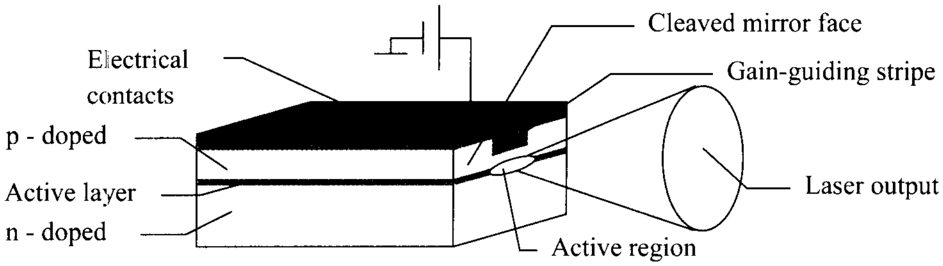
Diode lasers, also known as semiconductor lasers, have been on the market for a considerable length of time. They are built in large quantities mainly for the telecommunications industry. A few years ago these devices were made to output higher powers, necessary for industrial material processing. Today these lasers are among the most reliable, with lifetimes of up to tens of thousands of hours without need for maintenance. They have the highest wall-plug efficiency of all lasers, approaching in some cases 40%. Due to their emission wavelength, they may be coupled into fibre-optic cables, permitting flexibility and process efficiency. In addition, they are very small and, on a dollar-per-W basis, cheaper than the other laser systems. Due to their high electrical efficiency there is no need for costly and bulky chillers for refrigeration.

The main drawbacks of these lasers are their limited cw output power and beam brightness. For cw powers up to 120 W, these lasers are commercially available with fibre delivery and at similar or lower prices than other competing technologies. Beyond 120 W, their cost is too high. Diode lasers with fibre delivery are used above all in welding and soldering applications because their beam quality is not suited to generate a tight and intense beam focus or large depth of focus (necessary, for example, in cutting and drilling applications of hard materials).

The main difference between a diode laser and a conventional solid-state laser is that the diode laser converts electric power directly into light without the need of an optical pump (flashlamp). The favoured crystal growth techniques for semiconductors are liquid phase epitaxy and chemical vapour deposition using metal-organic reagents (MOCVD). In a semiconductor all the electrons occupy the whole crystal volume and are not bound to specific ions. In this way the constituents of the crystal are grown in layers. Generally a very thin undoped layer (0.2 μm to 0.02 μm) is grown between two layers, one of which has a high electron concentration whereas the other has a contrasting absence of electrons (called holes). When a current is applied perpendicular to the layers, electrons and holes are forced into the undoped layer where they recombine under emission of a photon. Due to the difference in index of refraction with the doped regions, the photons are forced to move inside the undoped layer. At the cleaved facets, which have a natural reflectivity of about 30%, the photons are reflected back into the active region. By growing the electrical contact in the form of a long stripe, which goes from one cleaved mirror face of the semiconductor device to the other, the photons move transversally in the manner they would in a conventional resonator (see figure 2).

Figure 2. Gain-guided stripe semiconductor laser

When a voltage is applied between the top and bottom electrical contracts, photons are created in the active layer. Because the electrical contact has the form of a stripe, these photons get amplified only in a very narrow area between the two opposed cleaved faces and eventually are emitted at the active region in the form of a highly elliptical light cone.



The above scheme demonstrates the basic unit of a diode laser. The active region is usually between 200 to 500 mm wide and has a maximum output power of several W. In order to achieve the high powers necessary for industrial applications, the size of the active region has to be increased. This is done by growing as many as 24 narrow stripes beside each other which build up to an active layer 1 cm in width with up to 60 W of output power [4]. These diode bars are the engine of all high-power diode lasers.

Stacking diode bars allows large-area semiconductor arrays of up to 4 cm^2, generating several thousands of W peak power. Due to the proximity of the bars, these arrays are difficult to refrigerate and operate generally in a quasi-continuous wave mode at a low- duty cycle of a few per cent. Containing as many as 25 bars in a 1 cm^2 large-area array, stacking is a labour-intensive process that requires wavelength and current threshold selection of every single bar for optimum performance. Therefore cost and complexity of the arrays increases non-linearly with size.

1.2 High-power CO_2 lasers

This chapter discussed CO_2 lasers with average powers extending from 100 W upwards to approximately 35 kW, mainly used for industrial applications. These lasers are primarily designed to work in cw operation although most of them are able to operate in pulsed mode, which is essentially a chopped cw operation. In the pulsed mode, it is common at the beginning of the pulse to achieve a power enhancement of two to three times and a duration of about 100 μs. Called superpulse, this can be very useful for specific manufacturing applications.

As already discussed, the efficiency and output power of the CO_2 laser depends on the cooling of the gas mixture. It is the method of cooling that is usually the most definitive aspect of the laser cavity design. The three main cooling methods are conventional, fast axial flow and fast transverse flow. The first method depends on conductive cooling of the gas whereas the other two methods use forced, convective cooling.

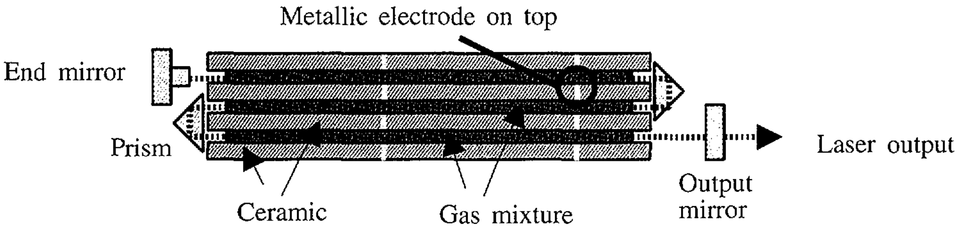
At the lower end of the power range are conventional lasers. With these lasers the cooling is through the walls of the discharge tube and the gain per metre of tube is relatively small. Therefore these lasers are either relatively long or not very powerful. Due to the high aspect ratio of the discharge tube (length of tube divided by its diameter) these lasers emit low-order mode, high quality beams. Over the last 20 years, considerable research and development has gone into improving the optical gain of these lasers, resulting in a very efficient waveguide cavity design.

Waveguide CO_2 lasers

In the 1980s, an important breakthrough in conductive-cooled CO_2 lasers occurred with the commercial introduction of CO_2 waveguide lasers [5]. This was largely due to the unique combination of high specific power, high efficiency, compact size, rugged construction and low cost. This new development became possible with the introduction of transverse radiofrequency (rf) discharges instead of the common longitudinal DC discharge. Advantages of rf discharge excitation are low-voltage operation, no adverse chemical effects due to metal electrodes and stable sustained discharges. Modern waveguide lasers are sealed off which enhances greatly the maintenance intervals as the gas mixtures need replacement only a couple of times per year. The guide construction is usually a combination of ceramic discharge housing and metal envelope for the electrodes. The bore of these lasers is from 1 to 3 mm with the highest specific power being 1 W/cm. This is the reason that these lasers use folded resonator configurations to achieve output powers of up to 250 W (see figure 3).

Figure 3. A folded waveguide laser cavity

On top and on the bottom of the ceramic structure with the waveguide bore a metallic electrode is generally used.
The whole assembly is inside a gas-tight enclosure.



Fast axial flow lasers

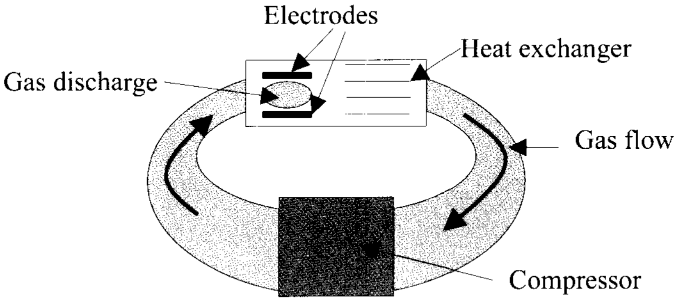
The fast axial flow laser is the most common type of industrial laser with average output powers of up to 6 kW. The glass discharge tube is generally between 2 and 8 m long, has a diameter of several cm and is arranged inside a folded resonator. Metallic electrodes supplied with DC or AC current are either wrapped around the tubes or arranged parallel to the tubes on opposing sides. Gas inlets and outlets at the beginning and end of the tube permit a fast axial flow of the CO_2 mixture which then passes through a heat exchanger, thereby removing the high heat load generated by the gas discharge. A laser gas consumption of 10 to 30 litres per hour is common.

These flow-gas units are very reliable and have good beam quality, working generally on low-order modes (D-mode, see figure 9). On the other hand, they require several cubic metres of space, circulating pumps and a frequent exchange of gas bottles.

Fast transverse flow lasers

Fast transverse flow lasers are the highest power CO_2 lasers. Because the gas flows transversely to the resonator axis a very large volume can be exchanged and cooled at a very high flow rate (see figure 4). These types of lasers are not common in manufacturing applications but are commercially available at up to 35 kW and generally have a very limited beam quality. For higher power, gas dynamic lasers are used. These are fast transverse flow lasers with a supersonic gas expansion in the discharge region that provides for additional cooling.

Figure 4. The cross-section of a fast transverse flow CO_2 laser



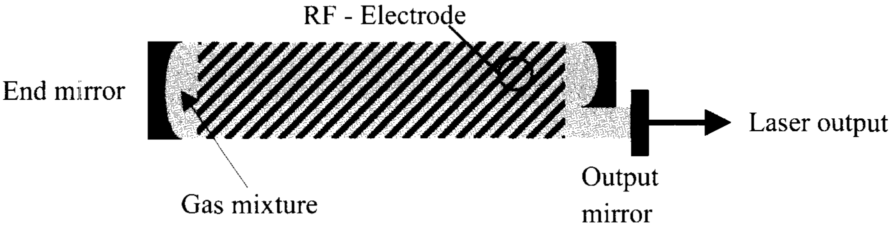
The slab laser

This is a newcomer under the CO_2 lasers with very promising characteristics. The term "slab" refers to the high aspect-ratio, rectangular cross-section of the discharge region. This geometry has the advantage of efficient diffusion cooling due to the proximity of the rectangular, water-cooled electrodes as with the waveguide laser.

The large area electrodes permit stable rf discharges and power scaling of the order of 20 kW/m^2 [5]. For up to 500 W, these lasers are now sealed, whereas higher power slab lasers (up to 3,500 W) need a minimum gas consumption—for which a bottle of gas mixture lasts for about 12 months. The elimination of the gas circulating system practically eliminates routine maintenance. The beam quality is generally not as good as in fast axial flow lasers.

Figure 5. Top view of a slab laser

The distance between the top and bottom electrode is a few mm for efficient cooling whereas the width of the discharge area is large for high-power operation.

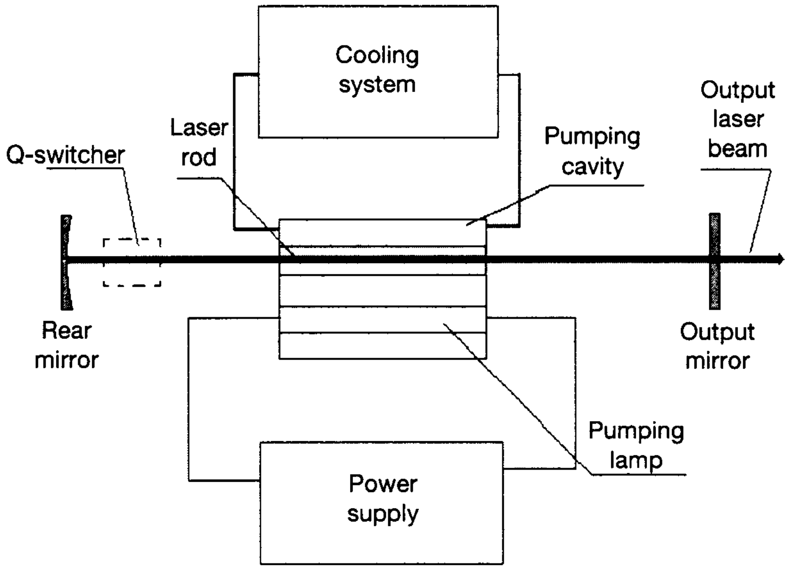


1.3 The neodymium laser

1.3.1 The laser

The main components of a solid-state laser are the active medium, the pumping source and the resonator. The active medium generally is in the form of a long rod with flat and parallel ends, the pumping is provided by one or two linear arc lamps and two dielectric mirrors form the resonator with the rod in its axis. Although most solid-state laser systems pumped by lamps are quite similar, the following description focuses on Nd:YAG because of its large application in industrial processes. Figure 6 depicts the main components of a typical solid-state laser.

Figure 6. Typical solid-state laser system



Nd:YAG laser rod

The Nd:YAG crystal is grown by the Czochralski method, resulting in boules typically of 6 to 8 cm in diameter and up to more than 20 cm in length. After inspection, the boules are processed to extract laser rods (or slabs) with flat and parallel faces. The growth direction and thus the rod axis is commonly the "[1]". Commercially available rods range in size from 3 to 15 mm in diameter and up to 200 mm in length. The rod end-faces are polished flat to $\lambda/10$ and parallel to within 10 s of arc, in addition they are also anti-reflection coated for a reflectivity of less than 0.25%. The rod barrel is fine ground to 400 grit finish or better. The Nd concentrations available range from 0.6% up to 1.3% and depend on the particular application. For continuous operation, a smaller quantity is used while for pulsed operation the larger quantity is preferred. Due to the high homogeneity and the low concentration of scattering centres, the optical quality of the crystal bulk is excellent, presenting maximum wave front distortion of $\lambda/4$ per inch.

Nd:glass

Neodymium-glass is another laser medium also frequently used in industrial applications. The architecture of the laser assemblage is very similar to that of Nd:YAG. The main difference is in the laser medium itself, where dozens of different types of glasses are commonly employed. Being made of glass, the main advantages of these systems are the facility of fabrication, exceptional optical quality, the availability of big sizes and the larger amount of active ions that can be incorporated in its composition compared with crystals. The main drawback brought about by its vitreous structure is the poor thermal conductivity that prohibits continuous operation and limits its employment to low average power applications. Therefore, the main practical uses of Nd:glass lasers are in the high-energy applications where low repetition rates are employed. In the field of industrial-materials processing, drilling and spot-welding are its primary application.

Pump lamp

Most solid-state lasers use linear lamps as the optical pump source for active ion excitation. These lamps are gas discharge tubes made of quartz, usually filled with Xe or Kr and designed to emit high brightness radiation in pulsed or continuous regime. Their commitment is to offer a combination of high brightness, high-power capability, high efficiency, long operating life, low cost and convenient operation. Standard size ranges from 2.5 to 20 cm in arc length and from 1 to 15 mm in bore diameter. The optimum design parameters are well known by manufacturers, whose catalogues give the best operating conditions. Many requirements must be fulfilled by the laser system in order to obtain optimal operation, including electrical, mechanical and cooling requirements that frequently are very restrictive. Apart from these conditions, the main characteristics to be considered in selecting gas discharge lamps for pumping solid-state lasers are the spectral overlap between the lamp emission and the active-ion absorption spectrum and the electric to optical efficiency and reflector requirements.

As the purpose of a pumping lamp is to provide optical radiation (which in turn produces fluorescence in laser material), it is essential that the best possible overlap be achieved between its emission and its active-ion absorption. Hence, Xe and Kr are used almost exclusively as lamp-filling gases. Xe is preferred for high-peak power pumping, as in the case of high-energy pulsed lasers. Kr is selected for continuous or low-peak power pumping. Although very similar in appearance, flashlamps used for pulsed pumping and arc lamps used for continuous pumping are very different in construction. The mechanical design of the electrodes and seals, pressure of gas and cooling requirements may be very distinct.

The main difference between these two gases in laser pumping comes from the spectrum of their emission. The pulsed regime leads to a high current density in the plasma tube, which causes a black body radiation emission. In this case, the Xe gas presents the better efficiency in the conversion of electrical energy to optical radiation. When low-power levels are employed, as in the continuous emission lasers, the black body radiation is of low intensity and the line spectrum of the gas element is more prominent. In this case, Kr is commonly used because, in spite of its lower electrical to optical conversion efficiency, its line spectrum emission presents some intense lines closely matched to the absorption spectrum of Nd ions (into the YAG host).

The requirements for cooling gas discharge lamps are well defined and depend on the relation between the lamp size (the area of the envelope) and the power level operation. Convection cooling is allowable at average powers below 15 W/cm^2. Forced air-cooling is required between 15 and 30 W/cm^2. Turbulent liquid cooling is necessary above 30 W/cm^2. Deionized water is the most suitable coolant, because its high resistivity avoids short-circuiting the lamp starting pulse which causes unreliable firing and reduces corrosion problems.

Pump cavity

The laser rod and the pumping lamp are enclosed in a highly reflecting box that reflects as much of the pumping light as possible into the active medium. This reflecting chamber is called the pumping cavity and several configurations have been used to achieve the same purpose. Every design compromises a degree of efficiency for other desirable properties such as a more uniform pumping of the rod, access to components and long reflector life. In optimizing one or more of these parameters, the choice of pump-cavity configuration plays an important role. There is a range of commercially available cavity types, including single or multiple elliptical, circular and close coupled. The most common are shown in figure 7. The first one is an imaging cavity where the light emitted by the lamp is focused into the rod. The second one is like a white box and can be made of a reflective metal or a diffuse highly reflective material (ceramic or compressed powder). The close-coupled type also employs reflective or diffuse material and in this configuration the lamp and laser rod are put tightly together with the enclosure surrounding them as reduced as possible. The elliptical cavities are relatively simple to manufacture but tend to produce an uneven pump pattern leading to laser beams with irregular transverse mode structure. On the other hand, the close-coupled diffuse cavity provides a more uniform pumping but unfortunately is more difficult to implement. The materials commonly used as diffuse reflectors are ceramics, compressed magnesium oxide or barium sulphate. The metals most commonly employed in imaging cavities are gold and protected silver.

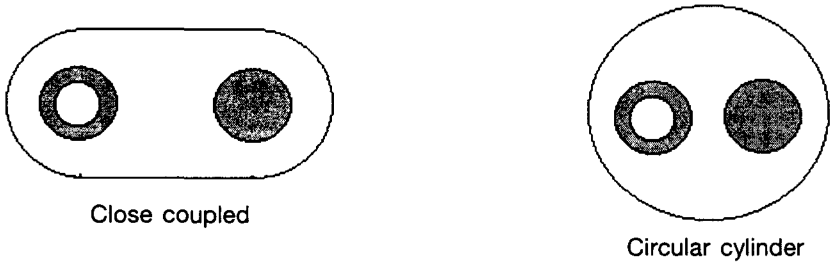
Laser head

The laser head is the name of the assemblage that incorporates all the optical elements together with its related mechanical and electrical support. Generally it contains the pump cavity together with the laser rod (or slab) and the flashlamps, the laser resonator including its mechanical structure and all the input and output ports necessary for the electrical power source, the cooling fluid and the laser beam. Some low-power lasers incorporate the power supply and the cooling system into the laser head, making the assemblage very compact.

Figure 7. Some configurations of pumping cavities

Single ellipse

Double ellipse



Close coupled

Circular cylinder

Power supply

A key factor in the success of using Nd:YAG lasers as a material-processing tool is its capability to operate in many different regimes. It can be run either continuously or pulsed with repetition rates from single shot up to kHz and temporal shape and length of the output pulse following that provided by the pumping source. The current in the pump lamp is therefore the parameter to be controlled in a laser power supply. With today's technology and components, a well-designed switched power supply provides thousands of hours of trouble-free performance.

In a typical switched power supply the AC input power is passed through inrush current-limiting circuitry to the rectifier and filter where it is converted to DC and stepped up to a higher voltage. It then flows to the transformer, primarily through the main transistor switch which chops the DC into high-frequency AC (30 to 50 kHz) to be applied to the transformer. Energy is transferred through the transformer to a voltage multiplier circuit which raises the transformer's secondary voltage to a value necessary for laser operation. It also converts it back into DC. During operation, laser current is sensed and sent back through the control circuitry to the transistor switch where the proper relationship between on-time and off-time is maintained. This controls the amount of current flowing into the laser [6].

Cooling system

Cooling solid-state lasers is frequently necessary because only a small percentage of the electrical input energy is converted to laser radiation. Hence most of this input energy is converted to heat that is deposited mainly in the laser rod, flashlamp and pump cavity. In order to remove this heat, practically all designs use deionized water with a high level of resistivity (10 megohm-centimetre). Through the use of flow tubes, the cooling fluid is forced along the outside diameter of the flashlamps and the laser rod. Frequently the systems employ a closed-loop circuit, including simple air-to-water or water-to-water heat exchangers and refrigerated coolers (water chillers). The drawback of the air-to-water systems is their dependence on the temperature of the ambient air. By contrast, water-to-water systems (which depend on the temperature of the cooling water) are more effective. The use of one of these closed systems to ensure water quality control also provides constant flow and pressure to the laser head which is essential for a constant output power. For high-power industrial lasers, the best system is the refrigerated cooler or water chiller because they can independently control all the important variables of the laser cooling circuit. These units use mechanical refrigeration to maintain a precise temperature and include reservoirs and pumps to provide stable flow and pressure conditions.

Laser cavities

Most solid-state lasers use linear resonators to determine the transverse mode structure of the oscillating beam. Besides the rear and output mirrors, an active resonator incorporates the laser rod that contains excited ions. In order to obtain different conditions of laser oscillation, a set of different components may be included inside it. The structure of the oscillator cavity is often mounted on a rigid base-plate that guarantees the alignment of its components regardless of temperature variations and external mechanical vibrations. The optical components must withstand high power densities and in order to maintain their high damage threshold their surfaces must remain free of dust. Therefore in order to guarantee this requirement, the entire beam path within the laser head is frequently sealed against airborne contaminants.

The thermal lens problem

The active medium of a solid-state laser is heated by optical pumping. The heat generated inside the laser rod depends on the spectral emission of the pumping light, on the spectral absorption of the flow tubes, on the coolant, on the absorption of the rod material and the internal conversion. In the laser rod, heat is produced mainly from the radiationless transitions in the active ion i.e. the energy differential from pump to fluorescent bands. The amount of heat generated is typically in the range of 5 to 10% of the input power for flashlamp pumped systems. In the laser rod, the heat is removed on the surface of the cylinder thereby generating a radial thermal gradient with a quadratic dependence of the refractive index. The principal optical effects that occur as a result of the temperature distribution in the rod are thermal focusing and birefringence [7]. These cause a distortion of the laser beam, influencing its transverse mode structure and seriously limiting the maximum output power that would be achieved with low values of M^2.

The birefringence in the laser crystal is caused by the photoelastic effect of thermal strains. This causes an effect known as thermal bifocusing to arise where two different focal points are created to each input power level, one related to the radial polarization and the other to the tangential one. The birefringence also turns the polarization of the beam, distorting the polarization structure of the transverse modes. Only higher order modes can survive this new condition which in its turn increases the value of M^2.

As seen, the thermal focusing effect of the rod is mainly caused by the temperature-dependent variation of the refractive index. In the case of a Nd:YAG crystal, this effect is equivalent to a positive lens with a focusing length dependent on the input power to the lamp. The higher the power, the shorter the focal length. For high powers, the effect can be severe with focal length being as short as 10 cm. Other focusing effects such as the ones caused by rod-end flatness distortion are also present but are usually negligible.

For continuous pumping, the heat flux and therefore the thermal effects are of steady-state character. For repetitive pulsed operation, the steady-state can only be reached after a few seconds for repetition rates of up to 10 Hz. In the continuous regime, the focusing power rises with pumping power and in the pulsed operation it rises with the medium pumping power i.e. with energy and pulse repetition rate. In the case of a single-shot pump pulse, the distortion of the laser beam is negligible if heating is uniform. This is owing to the slow thermal relaxation of the crystal compared with the development of the laser pulse. If the pulse-input intervals are short with respect to the thermal relaxation of the rod, a temperature buildup inside the material will occur until a steady-state condition is reached. For low repetition rates of a few Hz, the steady-state condition can never be obtained and the spatial beam profile changes during its development. This condition must be avoided for most practical applications.

One of the main concerns of a laser designer is overcoming the thermal problems discussed above. The laser rod is treated as a thick lens inside the resonator that is optimized for several intervals of input power levels. Convex-concave and telescopic resonators are commonly used to compensate such induced thermal lenses. To compensate the birefringence effect, two laser rods are used along with a crystal quartz rotator between them and a Brewster plate. This forces each part of the beam to pass through nearly identical regions of the two rods, with the result that the birefringence induced by one rod is cancelled by the other.

1.3.2 System components

Amplifiers

An amplifier is an alternative way to extract more energy from a laser system. Essentially it is also a laser head with its (own or shared) cooling and power supply. The amplifier head can be an exact replica of the main oscillator head, but generally it uses a larger diameter rod to avoid optical damage of the crystal-end face and at the same time to extract more energy. Single-pass or multiple-pass configuration can be used; the choice depends on the gain and application of the particular system. One or more heads in sequence can be used as amplifiers; the limit is the electrical power available, the optical damage of the components and the saturation of the gain. To avoid damage and saturation, the size of the active element is increased with the number of heads.

Q-switchers

Short and high-peak power pulses better execute many applications of lasers. Some of these applications include scribing, micromachining and laser rangefinding. The Q-switching method is the most common way of extracting such high-peak power from a laser whether pulsed or continuous wave. The technique is employed almost exclusively in solid-state lasers where pulses in the range of ns and multi-kW are commonly achieved.

There are two ways of Q-switching: passive or active. The passive shutters are made of dyes or colour centres. The active switching can be implemented by a rotating mirror, an acousto-optic device, a Pockels-cell or a Kerr cell. The right choice for a switching system depends among other factors, whether the laser is pulsed or continuous wave, the power density and the polarization of the beam.

Harmonic generators

Many non-linear crystals are commercially available to produce the harmonics for a Nd:YAG laser. The particular characteristics of the crystal to be used are mainly related to beam parameters such as power density level, divergence, polarization and spectral line. With these devices, one can produce wavelengths where there are no effective direct laser outputs, especially at shorter wavelengths. The second harmonic of a Nd:YAG laser is green at 532 nm; the third and fourth harmonics are in the UV with wavelengths of 355 nm and 266 nm respectively. The green beam is useful in LIDAR measurements whether the UV is used for micromachining and lithograph as an alternative source for excimer lasers.

1.4 Laser beam propagation

Depending on laser type, optical resonator and other constructive details of the laser cavity design, the light beam emitted by the laser has different spatial intensity distribution and polarization characteristics. These features may profoundly affect the quality and efficiency of diverse laser applications. Different laser beam characteristics are required for welding, cutting and drilling applications. Although some industrial laser systems use the same beam shape for welding and cutting, as a result of constructive difficulties in adapting different shapes inside the same resonator, this is always done at the expense of optimum performance. On the other hand, beam shape flexibility is costly, particularly with gas lasers and system price is an important feature. Therefore most of the gas laser constructors sell machines operating on a single, optimized beam shape that works well for most parts of the usual cutting and welding applications and for the quality tolerances of finished workpieces accepted today.

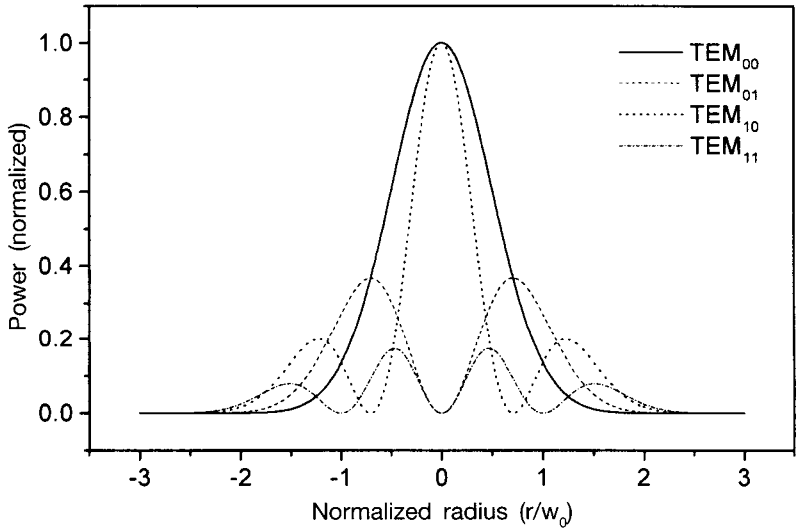
A laser beam's quality is based on its divergence, diameter and energy distribution. These characteristics are governed by the transverse modes of the laser oscillator. Generally, lasers are multi-mode oscillators unless specific efforts are made to restrict the number of oscillating modes which normally implies a reduction of output power. The transverse electromagnetic modes (TEM_{pl}) are the particular solutions of the electromagnetic field amplitude and phase that reproduce themselves upon repeated reflections on the resonator mirrors. The TEM_{pl} modes which are stable inside a specific resonator-cavity design carry the energy of the laser beam. A good quality CO_2 laser beam has between two and four transversal modes whereas a good Nd:YAG laser generally operates on four to ten modes. This is also the reason why CO_2 lasers have a small focal spot size, comparable with the Nd:YAG, despite their longer wavelength, as discussed later.

Unless some optical element is introduced into the beam or resonator that generates an output with a rectangular shape, used only in very specific applications, the energy of the modes is distributed cylindrically around the beam axis. The subscripts p and l denote the mode order and are ascending from the lowest order mode TEM_{00}, also called Gaussian mode, to higher order modes. If an appropriate sensor card were held into the beam path of a laser operating in a single mode, the following burn-in would be seen:

An easy way to remember the designation of the index "pl" is to note that "l" is 1 (one) when the centre spot has a hole and "p" denotes the number of additional rings. Note also that the beam size becomes bigger for higher order modes. The power distribution in each mode, as a function of the normalized beam radius r/w, where w is the beam radius of the TEM_{00} at $1/e^2$ of the peak power, can be seen from figure 8.

Figure 8. Radial intensity distribution for the lowest order modes

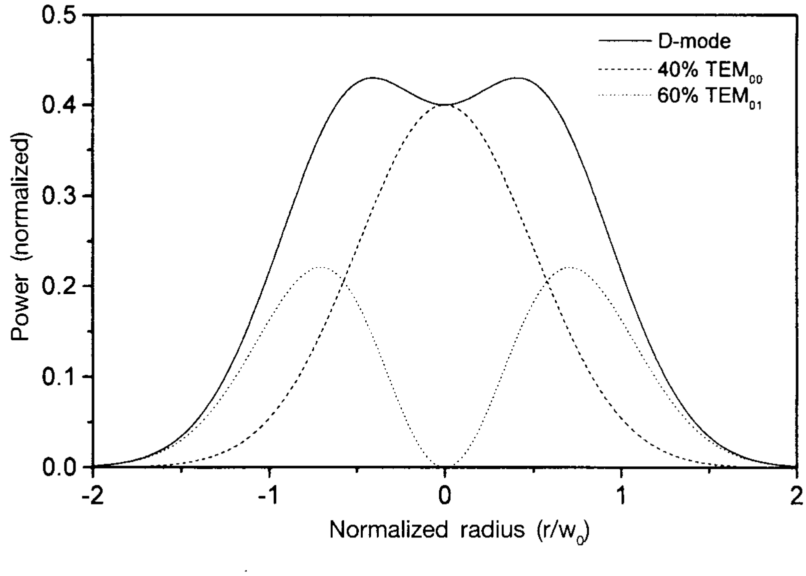
The lowest order modes are TEM_{00}, TEM_{01}, TEM_{10}, and TEM_{11}. The normalized beam radius is r/w_0 and w_0 is the radius of the pure Gaussian mode TEM_{00} at $1/e^2$ (14%) of its peak value.



A normal laser beam is a superposition of several modes. A very well-known combination of modes is the dimodal mode (D-mode) of commercial CO_2 lasers which uses 40% of TEM_{00} and 60% of TEM_{01} as seen in figure 9.

Figure 9. Linear superposition of two modes in a CO_2 laser

The combined mode consists of 40% TEM_{00} and 60% TEM_{01}.



In the propagation of a laser beam, the width of the beam waist can change with the propagation distance although the radial intensity distribution as a function of r/w stays the same. If a lens is put into the beam path, the beam waist will contract to a minimum diameter of $2w_0$ and then expand again. The laws by which this contraction happens are given for the Gaussian mode, TEM_{00}. Given a certain diameter for the beam before the lens, the mode that generates the smallest focal spot size is the TEM_{00}. Because there is no laser mode that can be focused to a smaller size, the Gaussian beam is called diffraction limited or fundamental mode.

Calculating the beam waist for higher order modes is very cumbersome. In order to avoid this problem the quality factor, M^2, of the laser beam is introduced and uses the equations for the Gaussian mode. Any laser beam which is not pure Gaussian has a quality factor bigger than one and its corresponding M^2 factor denotes how many times above diffraction limit the laser beam quality is. Given a certain beam radius for the Gaussian at the focus, w_0, its divergence half-angle is given by:

$\Theta = \lambda/(\pi w_0)$, where λ is the wavelength of the laser

A higher order mode will have a spot radius and a divergence angle each being M times larger. Therefore the following is obtained for the product of divergence half-angle times beam radius of any laser beam:

$$\Theta w_0 = M^2\lambda/\pi$$

Examples for low-order modes are: $M_{TEM00} = 1$; $M_{TEM01} = 1.5$; $M_{TEM10} = 1.9$.

In figure 10 the equation indicates that with both modes having approximately the same divergence angle, the TEM_{10} has a focal spot size about M^2=3.6 times bigger than the Gaussian spot size. This difference can be meaningful when the laser's task is to cut metal with a very small kerf. The same focal spot size can be obtained for both modes when the divergence of the TEM_{10} mode is M^2 times bigger. But this means that the aperture of the beam delivery system needs to be M^2 times bigger as seen in figure 11.

Figure 10. Contraction of the TEM_{00} and TEM_{10} modes

Contraction of the TEM_{00} (M^2=1) and TEM_{10} (M^2=3.6) modes after a lens of 5 cm focal distance. Note that the TEM_{10} mode diverges even before it gets to the lens.

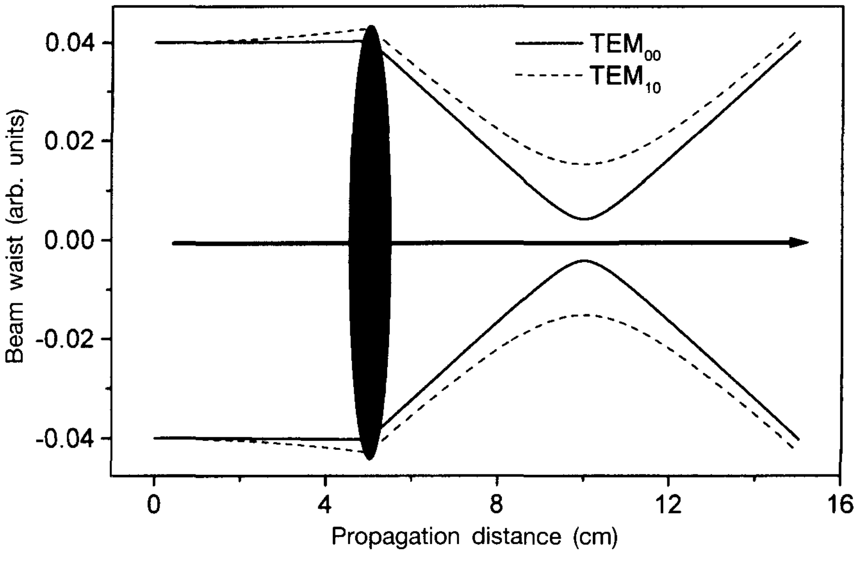
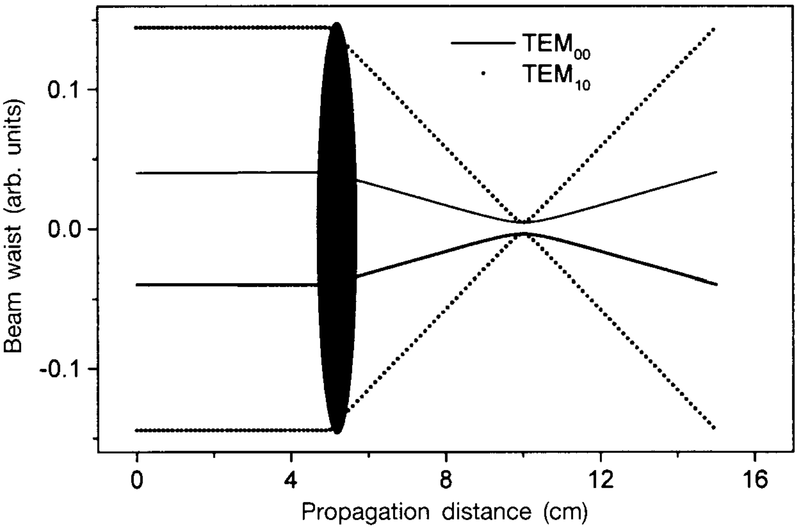


Figure 11. Comparing different modes with same focal spot size

Owing to the M^2 times bigger divergence of the TEM_{10} mode, the beam before the lens also has to be M^2 times larger.

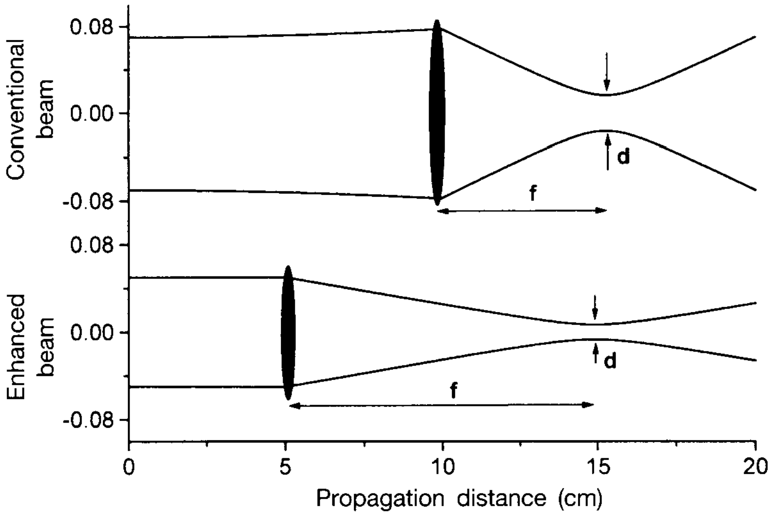


Economic and competitive aspects

Because there are constructive restrictions to a laser system, and larger beam delivery systems mean higher costs, a compromise is needed between beam quality and output power as stated previously. In many manufacturing applications, the efficiency of the process depends on the laser beam intensity at the focal plane and not on power alone. For a given beam diameter, the intensity is proportional to M^2 whereas the output power of most lasers grows generally faster than M^2 for the first few low-order modes and then saturates at its maximum output power. For most applications, the lower the order of the mode at which the laser reaches its maximum output power, the better.

A lot of today's investigations in improving laser systems focus on the research of high-power, high-quality laser beams. Figure 12 shows manifold advantages for materials processing that are consequences of the greater working distance f, smaller spot size d and greater depth of focus. Depth of focus is the distance the laser beam travels at the focus without changing its beam diameter d more than 40%.

Figure 12. The focusing behaviour of conventional and enhanced laser beams



The bigger distance f from the lens to the focus allows less material, evaporated from the working surface, to deposit on the lens and therefore longer intervals between lens exchanges and less spare parts. The larger working distance permits constant kerf width, relaxed positioning tolerances and high aspect drills whereas the smaller focus is responsible for a higher intensity at the focus which allows for new applications previously unrealizable and higher processing speed. Other advantages are smaller and less costly focusing optics, less waste material and power consumption. High beam quality is also an important issue for fibres-coupled Nd:YAG lasers. High M^2 beams need expensive large-core fibres and are difficult to couple to the fibre.

1.5 Laser systems and accessories

To be useful in material processing, a laser system must be able to focus the laser beam on the surface of the material and move the focus point in a controlled manner. These two basic requirements lead to other related systems that make a laser manufacturing system a complex but very versatile machine. Hence, to focus the beam, a series of mirrors must guide the beam from the output coupler to a focusing lens or mirror allowing a precise alignment of the beam with respect to the movement of the axes and the centring of the lens's optical axis. This assemblage is called a beam delivery system.

Another auxiliary system important for almost any laser machine is a workpiece fixture unit that must be coupled to the controller and to a feedback system to close the process control loop. In this manner, a smooth motion of the beam focus with respect to the material surface can be guaranteed. The way these systems are designed and integrated defines the type of production system and depends on the specific application. Therefore not only the type of laser and its power level differ from application to application; the entire optical chain, control system, workpiece handling assemblage and overall integration may also differ significantly. Thus a laser system's capability is determined partly by the power of the laser and partly as a result of the integration of many related factors. The main items to be considered in the design of a laser manufacturing system are type, accuracy and speed of the processing; material, size and thickness of the workpiece; capability and flexibility of the system to perform different tasks; and productivity and level of automation required. The interrelationship of these factors may result in very different machines. This is quite obvious when different processes are compared, such as micromachining of small electronic components, engraving plastics, or cutting and welding thick sheets of metals for the ship industry.

The degree of sophistication and the price also depend on production requirements. Hence systems with tight tolerances are more costly and systems with large processing volume capability are more costly and more difficult to hold to tight tolerances. A higher degree of automation is required in a higher number of sensors and in a higher processing capability of the software. Therefore the correct choice for the system as a whole is a delicate task involving many different fields of knowledge including market and commercial aspects.

According to these demands, laser manufacturing systems are restricted to four basic types:

the beam is moved by means of mirrors in a way that resembles a flatbed plotter, while the workpiece remains static. This approach is called the flying optics machine and is suitable for processing heavy pieces of large areas that do not require tight tolerances

in contrast to this is a moving part system where the part to be processed moves below it. This is called the fixed optics machine and is ideal for light and medium-sized parts where high-precision work is required the third is the indexed beam steering system where the laser beam is swept by means of two mirrors driven by galvanometers and controlled by a computer. The same processing work is repeated in different workpieces that are removed when processing is complete and a new part is put in position until a new cycle can be repeated

lastly and similar to the indexed beam steering is the on-the-fly beam steering system. This is used for constant motion production such as conveyors and converting. Feedback is provided to the computer which makes appropriate adjustments to track the moving target. This is a highly accurate technique which maximizes production output.

Beam steering systems

The last two systems are dedicated to applications where small processing areas are required such as scribing, marking and micromachining of small components. Generally the processing is performed in two dimensions, where a certain degree of depth is possible. In these systems, each mirror has an independent rotational movement giving to the beam two integrated and orthogonal movements. After the scanning mirrors, the beam is directed to a focusing lens and a figure is obtained in its focus. This focusing lens is called the flat-field lens and is specifically designed for this application, allowing precise focalization in flat areas from 1 square inch to more than 7 square inches. Generally the applications involved in this kind of system do not require a high-power laser source and consequently the laser power supply and laser head are small in size. The light weight and small size of the laser head make possible its positioning directly over the working table. There is no need for a long and complex beam-guiding system and consequently the beam handling is simplified. The need for alignment is virtually eliminated. In most cases, the scanning mirrors with their controllers, the focusing lens and some additional optics are closely integrated into a small box directly coupled to the laser head. Immediately below lies the fixed processing table where the workpiece is placed.

As seen above, the architecture of this kind of system is inherent in a fixed laser source and also in a fixed workpiece. Only the laser beam along with the scanning mirrors are moved. The relatively limited average power of the laser allows the use of mirrors that are small and light. This provides a process with a high degree of accuracy and repeatability with high speed and productivity.

The nature of the processing applied with this kind of system frequently results in low production of fumes and scrap. The exhaust unit and the scrap removal system are simplified or completely eliminated. The processing is executed without the use of auxiliary high-pressure assist gas thereby eliminating the need for a complex focusing head and nozzle. In addition, the safety windows and the enclosure of the working table are small and light. This simplicity and automation allows the system to be used either in dedicated tasks or as part of a production line fully integrated by the software and hardware. There are several types of lasers used such as Nd:YAG Q-switched or continuous, CO_2, copper vapour or even excimer. The average power ranges from dozens up to hundreds of W.

1.5.1 Motion in cutting and welding systems

In laser cutting or welding, the large areas processed and the high power of the laser beam used do not allow for the use of a steering beam system as described above. For these tasks, a relative movement is necessary between the beam guiding optics and the workpiece. It is not possible to move only the focal spot and as a consequence the focusing lens must be fixed relative to the beam axis. So as already described, two situations are possible: firstly, the beam is moved along with the guiding and focusing optics while the workpiece is fixed; secondly, the processing bed is moved while the beam and its focus remain fixed. In fact, there is another kind of system that incorporates the two concepts in one machine. This system is called hybrid and part of the moving axes are used to move the workpiece while the other axes are used to move the optics. Figures 13, 14 and 15 show these three structures of laser machines.

Depending on the supplier and on the specific application, the architecture used to incorporate these schemes may differ significantly. Some systems are adaptations of conventional machine tools such as the turret punch press, milling machines and articulated robots. Others are especially designed to operate like a true laser system.

Most laser machines are built with structures that permit full motion in the available working volume with the highest accuracy and simplicity in its movements. This capability is found in the three main systems: Gantry, Bridge and Cantilever. These structures have an isometric Cartesian architecture that permits accuracy and simplicity in a rigid and stiff arrangement.

Figure 13. 2D fixed optics machine

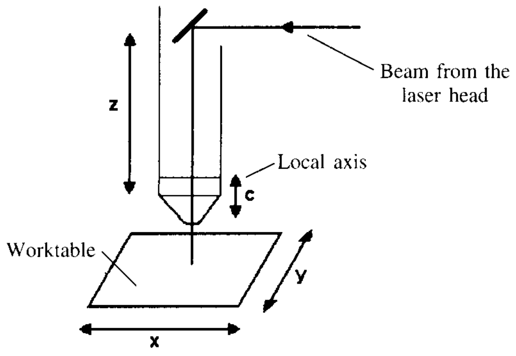


Figure 14. 3D hybrid optics machine

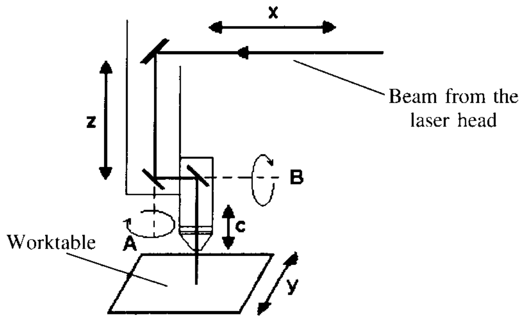
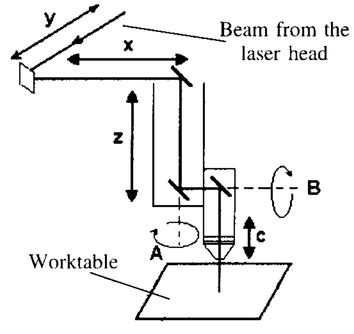


Figure 15. 3D flying optics machine



Some systems still incorporate in the same machine laser processing with other conventional processing such as tooling by turret punch press. Other machines have more than one workstation for just one laser source. This kind of machine is used in cases where the laser processing time is shorter than the workpiece load/unload cycles. While one of the workpieces is being machined, another finished piece is being unloaded in the other workstation.

Axes of motion

In the case of 3D cutting, there are five or six moving axes available and three or four axes in the case of 2D cutting.

The five axes are composed of three Cartesian axes (X, Y, Z) and two polar axes (A, B). The Z axis is related to the height while the X and Y axes are related to the horizontal motion. The polar axes rotate one along the Z axis and the other along one of the horizontal axes. These five axes of movement are enough to allow full flexibility of translation and orientation of the tool axis. In many systems, a sixth axis is also incorporated into the focusing head to maintain the focus of the beam exactly located onto the surface of the workpiece (or at a definite distance below it). Called the C axis, it is generally independent of the movement of the other axes and is driven by a sensitive capacitor. As the function of this movement is to maintain a constant distance between the nozzle and the work surface, only this distance is programmed into the Computer Numeric Control (CNC).

In the case of 2D cutting, only three Cartesian axes are necessary: two horizontal axes (X and Y) to execute the work and one vertical axis (Z) to maintain the focus on the surface of the workpiece and also to compensate for the height of this workpiece. Frequently, another independent axis is incorporated parallel to the Z axis to act as the C axis in the case of 3D systems. This is a local axis that moves the focusing head only and is also driven by a sensitive capacitor.

Fixed optics

In almost all cases, fixed optics machines are used for 2D tasks such as the cutting of flat metal sheets. Either the clamps can move the workpiece over a standing worktable or the workpiece is fixed on the table that executes the movement.

As in the case of flying optics machines, the structure incorporates three Cartesian axes and an independent focusing axis. Although described as fixed, some movement is provided to the focusing head but this movement is not related to the path of the tool. The focusing head is lifted up or lowered in the vertical direction (Z axis) to adjust the height of the work. Once it is positioned it does not change during the processing. To keep the distance between the nozzle and the workpiece surface constant, another independent vertical movement is necessary. This feature is extremely useful to compensate for the deformations in the flatness of the work, especially when cutting thin and large sheets. As this movement is very smooth during processing, it does not affect the stability of the focused spot and some small vibrations during its movement are of minor importance.

One additional rotating axis is sometimes incorporated along one of the horizontal axes. Acting in combination with the other axes, this movement of rotation allows for work on cylindrical surfaces. The workpiece is fixed as for a lathe and rotated along its axes of symmetry. If necessary, the entire assemblage can be moved along the same axis by the table.

Depending on the particular structure, the vertical movement can be made only in the focusing head, in the focusing head plus part of the beam delivery system or even in all the optics system including the laser head. The last structure is more simple, rigid and compact. It generates a very stable and accurate processing because the beam path from the output coupler to the work is short and there is no movable optics. This approach is however only possible with the use of medium or low-power lasers where the laser head is small and light, facilitating its incorporation into the machine structure. The design and positioning of the laser oscillator must provide the possibility of adjustment in its orientation and some alignment of the beam. Once positioned and focused on the material, the characteristics of the focused spot will not change during the work. In any position of the worktable, the focused beam has the same spot size and presents the same depth of focus. Its path follows exactly that given by the CNC program because there are no vibrations. Any inaccuracies of the path are due to instabilities in the pointing of the beam.

As seen above, the advantage of a fixed optics machine is its stability that leads to a higher consistent cut in all working areas, reliability and repeatability. Its simpler construction also lowers its price, making this system a good choice for cutting thin sheets.

The disadvantage of a fixed optics machine is the need for more floor space and its reduced accessibility. Accuracy and speed of cutting is also reduced for large and heavy metal sheets. To maintain the accuracy of the processing, accelerations and speeds must be lowered to move workpieces weighing hundreds of kilograms. In these cases, servo systems used to smooth movements do not work properly. Therefore a fixed optics machine is a convenient choice for cutting relatively thin and light sheets and when low cost is a priority.

Flying optics

In flying optics machines, the focal spot of the laser beam, or the tool, is fully movable in all available axes and the worktable along with the workpiece are fixed. Flying optics machines are suitable for flat cutting and especially attractive for 3D processing where multiple axes are necessary. As the processing table is stationary, the footprint of this system is the smallest and is determined by the size of the workpiece only and not by the range of movement. The design of the fixture assemblage is simpler and the integration of exhaust systems and systems for scrap removal is facilitated. Another advantage of the fixed worktable is its accessibility which is increased in relation to that of the other structures. An easier implementation of a protection cabin and simpler loading/unloading automation is also obtained.

As the motion is fully applied to the optics, the accuracy of movements is not affected by the weight of the processed work. The smoothness of motion in all axes is the same for light or heavy workpieces and the speed and acceleration are more easily controlled by servo tuning systems.

As seen above, the most attractive characteristic of the flying optics machine is its ability to maintain accuracy for large and heavy workpieces. Thus this system is particularly suited to processing large and heavy parts such as commercial mild steel measuring 1.500 x 3.000 mm and 20 mm thick. As a consequence, the laser source should have enough power (i.e. more than 2 kW) to process such work and of course is too large and heavy to be moved together with the optics. Therefore not only the power supply but also the laser head must be external to the processing machine. So the laser beam must be brought from the fixed output coupler mirror up to the focusing head that is "flying" around the workpiece. Since the work envelope is large, the distance travelled by the beam can vary significantly depending on the specific point on the machine table.

The variation of the beam length associated with different points on the machine table gives rise to a non-uniform cutting performance at every point of the working envelope. This is caused by the variation of the beam diameter associated with long paths. Even with small divergence, a laser beam travelling distances of several metres will present a variation in its transversal section. Consequently the area of the focused spot will vary at every point as will the depth of focus and its position. The variation in these parameters also affects the power density at the focal spot and the interaction of the laser radiation with the surface of the material will present a different characteristic. If not compensated, these variations can lead to a different cut quality at every point of the work volume.

One way to minimize this problem is to have a laser beam with very small divergence. This has been done in two ways: firstly, the introduction of a collimator (beam expander) in the beam path and secondly, the development of new laser resonators. The beam expander can reduce the geometric divergence of the beam by increasing its diameter in the same proportion. This procedure has a drawback because an increase in the diameter of the beam leads to a decrease in the depth of the focus, limiting the thickness cut capability. So a compromise is made between the divergence and the depth of focus, and the magnifications are rarely larger than two.

With the development of new resonator technology, it is now possible to obtain lasers of very high power with low divergence and low-order transversal modes (or even pure TEM_{00} mode). A divergence of a fraction of milliradians is normal in lasers with output power in excess of a few kW. In addition, the new resonators minimize interference, lack of homogeneity in the active medium and other effects that increase the diffractive divergence of the laser beam. The beam quality factor M2 can be made very close to 1 and the mode shape can be very symmetric and stable. Despite these improvements, some small variations in divergence persist. One of the causes is the thermal lens induced in the optics, especially in the focusing lens, that depends on the power density of the beam. To eliminate this problem, some machines use a numerically-controlled focal axis. So a program previously set in the CNC automatically controls the variations in size or in position of the focal spot. As the cutting quality varies for each type of material and depends on the position of the focus in relation to the work surface, the same program is also used to position the focus according to material type in order to optimize the result. Hence the focusing lens is moved up and down as a function of the position in the working volume. The gap between the nozzle and the material surface is kept constant while the lens is moved to compensate for variations in the focused spot.

The introduction of the numerically-controlled focal axis and the development of related programs have increased the performance of the flying optics machines which in turn have become more reliable and accurate. Thus in spite of its higher price, the flying optics design can be a good choice for heavy and high-volume tasks.

Hybrid machines

Hybrid machine systems are used either for 2D or 3D works. Here neither the tool nor the workpiece is fixed during the work and both are moved synchronously to complete the contour of the processing. Many combinations among these movements are possible but generally the linear horizontal movements are dedicated to the table while the movements of rotation and the vertical axis is dedicated to the head. In the case of 2D processing, the table is moved in one horizontal axis while the head is shifted in the other orthogonal axis. A vertical adjustment is also provided in the same way as in the other systems.

Hybrid machines are used particularly when the maximum flying optics range is smaller than the required working area. In these cases, apart from the tool, the workpiece must also be moved in one or two directions to complete the processing path. With this design, some hybrid machines can reach very large dimensions, having a work envelope of 4,000 x 12,000 mm^2.

An interesting combination of movements is when the part and the beam move in the same axis but in opposition. Provided there is enough power, this design allows the processing speed to increase without loss of accuracy. Rates of up to 40 m/min. are now available [8]. Another advantage of this system is the smaller floor space needed due to the reduced overall motion. This particularity is still enhanced when medium-power lasers are used (up to 1,500 W in the case of CO_2 lasers) and incorporated in the machine structure. The stability of the beam and the consistency of the cut in the full working envelope are also positive aspects of these machines.

Hybrid systems are also frequently used when processing with Nd:YAG lasers which use fibre optics to guide the beam. In these cases, the size and weight of the focusing head facilitate the motion and positioning of the focused spot in areas of difficult access.

Robots

Always used for 3D work, the use of articulated robots to manipulate the beam allows enormous possibilities for laser tool motion. The use of robots also facilitates access to internal areas such as in mounting a panel for a car body. The drawbacks arise from its lower accuracy in positioning and repeatability and also from its difficulty in aligning the beam. These problems are significantly increased in the case of a 10.6 mm wavelength because it can not be guided by fibres and because it is difficult to incorporate mirrors in the arms of a robot. Such systems perform better, however, when using Nd:YAG lasers coupled to a fibre-optics delivery. In this case, the robot structure may be a good solution to on-line 3D laser processing. An example of its use is areas of automotive industry where high accuracy is not required such as in welding and cutting of some car-body parts.

1.5.2 Laser subsystems

Apart from the laser source, the work fixture with motion assemblage and the controller, an industrial laser machine is composed of many other subsystems and associated ancillary apparatus. Again, the types and characteristics of these subsystems depend on the particular type of processing and on the requirements of the system. These subsections are related to laser equipment, optics, the machine structure itself, safety and process control. Hence, the main subsystems found in an industrial laser machine are:

- the laser head, its power supply and cooling system
- the optical manipulation system, the beam delivery and the cutting (focusing) head
- the protection cabins and safety devices
- the CNC and Programmable Logic Controller
- the gas supply and fume exhaust systems
- the diagnostic system.

The laser

As already seen, the two most-used industrial lasers are the CO_2 gas laser and the Nd:YAG solid-state laser. These are used for light-load tasks with lower power; other sources may be preferred such as excimer, copper vapour and diode lasers. Depending on the power level, a cooling system is required. Low-power systems are frequently cooled by simple air-cooling equipment, while medium or high-power lasers demand a complex water cooling system. In the same way, the size and complexity of a laser-power supply depends on the power level and automation of the system. It can be fully integrated into the laser head for low-power systems, or if very large, isolated from the machine and the laser head.

Beam delivery system

The manipulation of a laser beam in an industrial laser system is achieved by means of articulated mirrors or prisms. Other optical elements, such as apertures, expanders, lenses and filters change the shape of the beam and its distribution of energy. Optical shutters, beam splitters and deflectors are also frequently used in the optical chain. In the case of CO_2 an additional optical device is incorporated into beam delivery to ensure the laser-light output is circularly polarized. All the optics must have a clear aperture twice as large as the beam diameter delivered to them. This makes optical alignment much easier and ensures that no power losses occur due to the beam missing or clipping one edge.

All the optics must be protected against moisture and fumes that could damage the optical surfaces. Putting the optical elements inside sealed tubes filled with dry nitrogen or clean dry compressed air provides this protection. In this environment the beam is less absorbed and diffused by eventual contaminants in its path. Besides protecting the optics, the tubes also have a safety function since they protect the operator by avoiding leakage of direct or scattered laser radiation.

In many systems that use Nd:YAG solid-state lasers, the manipulation of the beam is greatly simplified by the use of optical fibres. Apart from the eventual need for changes in the beam shape and size, the entire path to the workpiece is made safely by the fibre. There is no need of tubes, pressurized air, mirrors or prisms. Special connectors position the beam in and out of the optical fibre.

For aiming, a HeNe laser is frequently included in the optical system. In the case of Nd:YAG, the red beam of the HeNe utilizes the same optics of the infra-red and hence it can also be used for alignment of the optics.

Protection cabins and safety devices

Tubes protecting the optical chain prevent leakage of scattered radiation, however other sources of electromagnetic radiation are still present. The focused beam may scatter on the material surface and, in some cases, specular reflection may occur. Depending on the conditions of the process, the heated spot on the material is seen as a bright source of white radiation. It emits not only the visible spectrum but also UV and near infra-red. Even though this is not a coherent emission it can cause serious injuries to health, so shielding is essential. To protect the operator against radiation, the work volume is enclosed inside a protection cabin. The doors and walls of this cabin are constructed with materials transparent to visible radiation but which absorb unwanted emissions. For cutting with CO_2, only the far infra-red has a dangerous intensity and sheets of cheap, transparent plexiglas are used. For processes using the near infra-red radiation of the Nd:YAG laser, or even for welding with CO_2, special absorbing glasses are used.

Extra protection can be obtained by using many interlocks that interrupt the laser emission and stop all movement of axes if any door of the protection cabin is open during the processing. In many plants, these interlocks are also put in all entrance doors together with warning signs and lights.

In the case of operations that require opening the door of the protection cabin, as in the case of alignment or manual focusing, the interlocks are disabled and the operator must use special protective eyewear.

Automation, CNC and PLC

The Programmable Logic Controller (PLC) is dedicated to manage all the input/output signs coming from the system continuously controlling its status. It is integrated with the CNC (Computer Numeric Control, as mentioned) giving to it real-time information about the system situation.

The CNC is the "brain" of the machine, managing all the system's decision. It is fully compatible with the laser and motion system and directly controls the laser power supply and the axes motion. By an off-line CAD/CAM programming, it also generates the path of the tool, integrating it with process variables, hence synchronously associating for every point of the path a process status previously programmed. Thus it not only determines the path of the tool but also the velocity of the axes, the process gas type and pressure, the laser output power, repetition rate, pulselength etc. Some systems have stored in their memory numerous data related to the processing of technological parameters and selection according to material characteristics and the particular operation. Each time the type of material or thickness is changed, the system automatically determines the optimum processing parameters and reorganizes the machine set-up.

Other important characteristics of the use of programming CAD/CAM is the nesting of many parts in the same metal sheet. Equal or different pieces are arranged in the metal sheet in a way that minimizes the production of scrap.

The association of CNC with new powerful personal computers through specialized softwares brings the possibility of a nearly unmanned operation and the presence of a highly skilled operator is no longer needed. Some systems are able to automatically produce different pieces on different materials and thickness. This possibility together with the automatic loading/unloading of equipment gives to laser machining a great versatility and speed, not dependent on the constant presence of an operator. Such a feature is one of the most important characteristics in the popularization of laser processing machines.

Diagnostic system

To control material processing in a real-time basis, a series of devices are used to monitor the region affected by the laser beam. Several kinds of sensors use different techniques to monitor the processes detecting eventual changes in characteristics. Hence optical and audio properties of the process are used as a feedback control to maintain the optimized process.

The accuracy and repeatability of processing is also assured by a real-time laser beam diagnostic. Hence a series of sensors and equipment are integrated into laser processing systems for continuous, on-line monitoring of beam quality parameters such as M^2, pointing stability and power.

Many laser machines also have an incorporated observation system to inspect the quality of the final result of the processing. Frequently this system is integrated into the beam delivery system and uses an optical microscope to provide a magnified visualization of the affected area. Sometimes, the image formed in the microscope is projected in a CCD array and this image is transferred to a monitor.

Gas supply and fume exhaust systems

The gas supply system must be able to manage many different kinds of gases and supply them in a controlled and precise manner. Depending on the process, the pressures can reach up to 25 bars or be low enough to create a shroud over the hot area. The flow rates can be high, in the range of several m^3/h, so the reservoirs, the piping and the valves must be properly designed. The quality of materials used in the gas circuit must be carefully chosen to avoid contamination. It is important to ensure that the compressor is supplying pure air free of oil and moisture. These contaminants can cause a severe and rapid degradation in the optics especially in the case of CO_2 lasers that use air-cooled ZnSe focusing lens.

A fume exhaust system is fundamental both for safety and for protection of the optics. The fume produced in the process contains vapour and small particles of the processed material and gases formed in the reaction of the laser beam with the hot material and the assistance gas. Besides being dangerous to health, these fumes may be deposited on the surface of optical elements thereby decreasing their useful life. Therefore, an efficient exhaust system is necessary to maintain a clean environment inside the protection cabin. It must evacuate and filter the fumes before releasing them externally.

2

Overview of industrial laser applications

Doctor W. de Rossi

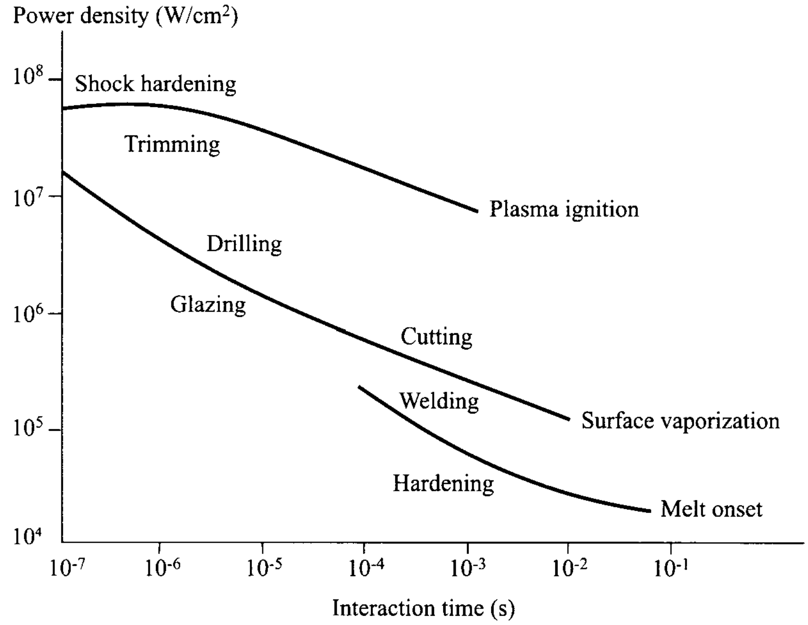
As discussed in chapter 1, the unique features of the laser have given rise to widespread recognition of its potential as a powerful tool in industry and an important and marketable asset. Spatial coherence and high light radiance are its leading advantages over traditional methods of material processing. Spatial coherence allows the laser to focus on a very small spot, providing a localized and extremely high radiation density. By controlling the thermal load supplied to a given material, virtually any temperature-time regime can be applied to the heated area. This gives the laser its incredible versatility in so many distinct applications.

The thermal load given by the laser beam causes the material to undergo transformations from one thermodynamic state to another. These transformations are observed as heating, melting and vaporization. The extent to which these transformations occur will depend upon the initial state of the material and the rate at which energy and mass transport processes occur within the system and with the environment. Understanding these processes leads to better control of the operation and is essential in the prediction of how much material is removed, fused or transformed. The magnitude to which these phenomena occur depends upon the relation between the laser parameters and the optical and thermal properties of the material. In the energy balance for laser-initiated processes, the absorbed energy is lowered in comparison with the incident energy by losses like reflection, scattering, latent energy and radiation by the heated surface. Thermal diffusion is another loss mechanism of the heated zone.

In addition to the energy balance, it is also necessary to account for the dynamic forces that give rise to the material transport which occurs. In general, the models propose that the energy absorbed by the material induces melting and vaporization at the surface and depending on the intensity of the laser beam, plasma ignition may be initiated. Below the surface, a thin layer of molten material is formed. The vapour pressure blows this molten material away from the interaction point opening a hole in this region.

With careful control of the thermal load supplied to a given material, industrial lasers can be used in material removal such as cutting, drilling, scribing and marking, in joining operations such as welding, brazing and soldering and many kinds of thermal surface modifications, among them hardening, alloying and cladding. Laser processes are clean, rapid and usually involve low overall heat input into the workpiece, minimizing distortion. No processing forces are involved and most laser techniques are ideal for automation. The particular type of laser, its wavelength and regime of operation depends on the specific application. In most cases however, the power density must be enough to induce a modification in the surface of the material, to be effective in processing and this is generally done by focusing the laser beam to a small diameter, typically in the order of 0.2 to 0.5 mm. The radiation intensity for almost all applications ranges from 10^4 to 10^9 W/cm^2. Intensities lower than 10^4 W/cm^2 are insufficient to heat the material surface and intensities higher than 10^9 W/cm^2 induce the apparition of a plasma layer near the irradiated surface that absorbs the major part of the radiation. Figure 16 shows some typical application regimes relative to incident laser beam parameters.

Figure 16. General industrial applications of lasers



Cutting

With normal free-running lasers, the power density achieved by focusing is in the range of 1 to 5 MW/cm^2. Such density of power however is not sufficient to achieve clean cutting and a jet of gas directed towards the focus position is usually used to remove molten and vaporized material from the cutting zone. Moving the workpiece relative to the focused laser beam, one can obtain a clean, sharp cut in all kinds of materials. High-speed cuts on flat and 3D surfaces leave the material relatively undisturbed so that the cut parts can be immediately used in the next assembly stage. Suitable lasers used for cutting are CO_2 and Nd:YAG, both pulsed and cw. Metal thickness ranges from 0.1 to 25 mm and cutting speeds of 6 to 250 mm/s.

Welding

Laser welding is achieved with power densities of between 10^5 and 10^7 W/cm^2 and interaction times from 1 to 0.1 ms. Under these conditions, the heat flux delivered by the laser beam to the heated zone is much higher than the natural losses. So the mechanisms of losses such as heat conductivity, convection and heated metal emission fail to compensate for such a flux. There are two laser-welding modes: conduction and penetration. The conduction mode involves power intensities high enough to cause melting but without vaporization, making the final shape of the weld (in the case of spot-welding) appear as a half-sphere modified by the fluid flow of the weld pool. In deep-penetration laser welding, the intensities are higher, generating a column of vapour in the central part of the weld pool. This vapour column, or deep penetration cavity, extends through the workpiece giving a high depth-to-width ratio to the weld.

The main advantages of laser welding are high process rate, small heat-affected zone and low warpage. Welding speeds may reach up to 90 spot welds/min. and in the case of seam welding up to 25 mm/s if pulsed or up to 200 mm/s if continuous.

Some disadvantages are the precise preparation of welding seam (where the gap must be infinitesimal) and high investment costs.

Drilling

Laser drilling is performed by pulsed lasers operating at pulselengths of between 10^{-3} and 10^{-5} s and radiation intensity of between 10^7 and 10^8 W/cm^2. At such intensities the material heats, melts and evaporates with the vapour blowing off almost all the remaining liquid material. Laser drilling can be performed in three different ways: firstly, by single shot, where the breakdown is produced by one laser pulse; secondly, by percussion, where a series of subsequent pulses are used; and finally, by trepanning, with the hole being cut according to the given contour. Hole diameters range from 100 mm to 1.5 mm with a depth to diameter ratio of 50.

Laser assisted machining

Preheating the workpiece to temperatures close to melting point, just ahead of the tool bit, causes a decrease in material hardness and an increase in cutting speeds. For this purpose, the use of a high-power laser beam in assisted lathe machining is an alternative to processes that employ heating by means of a plasma arc. The softening of the surface, apart from causing an increase in cutting rate, also generates a machined surface with improved smoothness and fatigue strength [9]. The decrease in the material resistance to the turning tool leads to an increase in the service life of the cutting tool and in an improvement of the accuracy on account of the decrease of elastic deformations involved. Many types of steels and superalloys have been machined with the aid of a laser source where a focused CO_2 laser providing a power density of 3.5 MW/cm^2 is directed to the workpiece at a distance of approximately 5 mm ahead of the cutting tool.

Directly machining with a laser beam, without the cutting tool, is also possible in some materials such as alumina and silicon nitride. In these cases, the control of the amount of removed material gives a finished surface similar to that obtained with conventional grinding.

Soldering and brazing

Laser beams can also be used as a source of heat in precision soldering or brazing of delicate materials. It is used when the parts cannot withstand soldering temperatures for long periods of time as is the case with many electronic components. The accurate control of process parameters ensures precise heat input leading to high product reliability. By controlling the energy and the number of laser pulses and keeping the repetition ratio at moderate rates, very precise soldering can take place in less than one second.

Fusion laser welding can often replace brazing of small parts. Two different materials can be joined by melting just one of the pieces thereby performing a self-brazing process. Here the parts are free from deformation and there is no need of heat treatment of adjacent material due to the precise control of the laser power delivery.

Non-metal welding

As for any other type of welding, in non-metal welding, laser energy is used to heat and melt a limited zone that bonds the materials upon solidifying [10]. The poor thermal conductivity of plastics severely restricts laser-welding applications. They are limited to thin sheets because the low coefficient of thermal conductivity reduces the depth of the melted zone into the material since the heat must be conducted from the surface. To increase the depth of the melted zone, the laser beam must move across the material at a slower rate. There is a lower limit to this rate because if it is too slow, an excess of energy absorbed at the surface will cause vaporization to occur. Another difficulty arises from the chemical instability of some plastics at liquid plastic phase, requiring that the temperature vary no more than a few degrees centigrade which is difficult to control. Owing to these limitations, not all plastics are suited for laser welding and only thin plastics with preferred thermal and absorption characteristics can be processed. Good exceptions to these rules are polyethylene and polypropylene that can be well-processed by the CO_2 laser. The reasons originate from their chemical stability at elevated temperatures and the relative transparence to the 10.6 μm wavelength that penetrates deep in these plastics.

In addition to plastics, some glasses and amorphous quartz can also be laser-welded with good results. Although these materials have low thermal conductivity like plastics, they are quite stable at high temperatures and surface vaporization tendencies are much less pronounced.

Laser hardening

Laser-induced transformation hardening employs relatively low-power densities of between 10^4 and 10^5 W/cm^2 with interaction times from 10^{-2} to 10^{-1} s. In this process the workpiece surface is laser heated and allowed to undergo rapid self-quenching by means of heat flux to the metal bulk which remains cold. The method ensures high homogeneity of heating and the thickness of the hardened layer may reach from 1 to 2.5 mm with an operating speed of 30 to 130 cm^2/min. The best results in laser hardening are obtained with high-carbon and alloyed steels and cast iron, however aluminium alloys are also treated.

Tailor welded blank

Tailor-welded blank (TWB) is a butt-welding process used in the car-body production industry. It uses blanks of different composition, thickness and coatings that are welded in a 2D plane before stamping. Such a procedure allows a design that optimizes the strength/weight ratio giving more stiffness to components such as the shock tower and the door interior. Welding in a 2D plane is easier and cheaper than in 3D because of the complex arrangement needed for fixturing the parts that must be joined without gaps. Since it is a butt-welding, the same laser machine can cut and weld the related components, improving the accuracy and saving time and money. The process was primarily used for linear (straight-line) welds, because the non-linear process is technically more difficult to produce. Recently however, some companies are offering non-linear tailored blank welding for specific applications, allowing an improvement and freedom in design, and expanding this technique to other applications.

Laser glazing

By fast scanning of a laser beam with short pulselengths, a homogeneous thin amorphous layer over the workpiece surface can be produced. This occurs when intensities of between 10^5 and 10^7 W/cm^2 and laser interaction times from $10^{\ 4}$ to $10^{\ 7}$ s are used. In this case, a fast remelting of a thin surface layer with subsequent fast cooling produces a thin layer of elevated hardness, high corrosion and abrasion resistance. The high efficiency of surface melting and the high rate of cooling (higher than 10^8 degrees/s) transforms the metal surface into a kind of metal "glass" with thicknesses that may reach from 1 to 10 μm. This method can be used with many different metals giving rise to distinct metallurgical microstructures. These include amorphous metallic solids, supersaturated solid-solution phases, metastable phases, ultrafine eutectics and refined dendritic structures [11].

Surface alloying cladding

This technique is a way to provide a separate alloy to a material surface. This is done by pre-placing or by delivering controlled amounts of the coating material to the interaction zone as the laser beam traverses the surface of the workpiece. Suitable lasers are cw CO_2 and Nd:YAG with power greater than 2,000 W.

A number of different methods have been developed for these purposes such as melting the powder coating together with a binding material on the surface of the piece; remelting of a coating pre-placed over the surface; the powder insufflation into the melting area using a rare-gas flow. The last one is becoming very popular and a variety of combinations of parent metal and powders have been used. Among some powders used are titanium carbide, zirconium oxide and chrome-carbide with nickel. Some advantages include reduction in process material cost, control of depth and development of a harder structure.

Shock hardening

If pulse duration is kept to 10^{-8} s with power densities of approximately 10^9 W/cm^2, the interaction of the laser beam with the material is limited to the surface and nearly instantaneous vaporization occurs. The vapour of the metal expands so rapidly that the effect is similar to a blast wave. As a consequence, a shock wave propagates and reflects within the material causing significant work hardening. This method of hardening has been used mainly in aluminium alloys and can be used to reharden weld and heat-affected zones in welded aluminium structures [11].

Laser marking

In many laser marking or engraving processes, extremely small quantities of material are removed from the surface of the workpiece through rapid vaporization. The resulting microscopic pores reflect incident light at a different angle, producing a visible and precise shade. Two commonly-used ways of marking are direct-write patterning and imaging.

In direct-write patterning, the laser beam is focused onto a small spot on the work surface that is moved relative to the beam to form a desired pattern. In general, neither the workpiece nor the optics are moved. The laser beam is deflected through use of a controllable mirror system and focused on the workpiece by a fixed flat-field lens assembly.

Imaging involves the use of a mask to project a pattern of laser light onto a part. The features contained in the pattern are then etched into the workpiece. High-resolution patters containing many features can be generated simultaneously over a relatively large area.

Appropriate lasers for marking are Nd:YAG cw or Q-switched, TEA CO_2 and excimer. The medium power commonly used ranges from 40 to 150 W. Typical engraving speeds may reach up to 250 mm/s with groove width between 0.012 and 1.0 mm.

Laser annealing

Laser annealing consists of irradiating the surface of ion-implanted semiconductor crystals to recover their original crystallinity. The semiconductor surface suffers an excessive damage during the ion implantation that causes an amorphization of its structure. The irradiation of the damaged surface by short laser pulses (~50 ns) with power densities in the range of 10^6 and 10^7 apart from improving the crystalline structure also activates implanted ions, lowers surface resistance and removes defects such as dislocation loops. Annealing with a laser provides more localized heating than furnace annealing and preserves the profile of implanted ions. Spatially overlapping pulsed irradiation by a Q-switched Nd:YAG laser generates a continuous single crystal layer from the initially amorphous structure.

Laser ablation

Another major application is ablation for the selective removal of coatings from an underlying material [10]. In this case, the coating to be ablated must be easily vaporized compared with the base material otherwise the base material may be damaged. Most laser ablation applications involve removing plastic or paper coatings from reflective metals such as copper, silver or smooth steels. The most widely-used application is wire or conductor stripping. ML polyamide, esterimide and other insulating coating are easily ablated from copper.

The short wavelength of excimer lasers make them excellent for ablation processes. The combination of short pulselength, high-peak power and the UV emission allows the material to be evaporated without the degree of melting and charring that is produced with Nd:YAG or CO_2 lasers. These lasers can process polymer films from non-metallic substrates and even remove very thin metals from non-metallic substrates.

Laser trimming of resistors

Resistor trimming uses the precision with which beam power and location can be controlled to evaporate resistor ink from integrated circuits without damage to the substrate. Nd:YAG cw Q-switched lasers or low-power CO_2 lasers are commonly used to burn off the print cleanly, during operation, until the desired resistance value is achieved. Precision better than 0.5% is common in this process.

A similar system can also be used for the repair of photomasks largely used in the electronics industry. The same precision that is required for resistor trimming is used to evaporate defects on photomasks such as an excess of chrome films on glass substrates.

Laser rapid prototyping

Laser rapid prototyping is an expanding technology where 3D models of CAD/CAM developed parts are produced from liquid or powdered polymer materials with the aid of a laser source. This process dramatically reduces the time to make a model by moving directly from conceptual design to a finished product, skipping many intermediate steps which exist in traditional methods. Laser prototyping is accomplished in one of two ways: stereolithography or selective laser sintering. In stereolithography a CAD/CAM program drives the translation of a 3D computer design into a stack of thin cross-sections. A UV laser beam scans the cross-sections into liquid plastic monomers, called photopolymers, which harden when exposed to UV light. Gradually, as each section is scanned, the prototype builds up. The process may be completed in minutes compared with hours or days that traditional clay or wood methods require.

The selective laser sintering method is similar to stereolithography and consists in fusing 3D objects from powdered materials. Again, a CAD/CAM program drives a laser beam to trace 3D contours layer by layer. The localized laser beam energy welds air-blown streams of metallic powder to conform objects to a programmed shape. The method allows machining to eliminate dross and imperfections in the manufacturing of custom parts and moulds.

3

Laser cutting

Doctor N. U. Wetter

For laser systems, laser cutting is the largest market worldwide and the most common industrial application. The unique properties of lasers allow for high productivity and reliable, cost-effective cutting. In comparison with competing processes, lasers also demonstrate significant advantages in cut quality and repeatability. Thus as a manufacturing tool, laser systems are successful and highly profitable. Table 1 shows how lasers compare with other technologies.

As shown in table 1 and as mentioned previously, the advantages of the laser cutting system in the manufacturing process are manifold. The small heat affected zone produced by the laser causes minimal distortion and changes of the chemical and mechanical characteristics of the workpiece. In comparison, plasma torches and oxygen flames cause large heat affected zones and punch presses tend to distort cutting edges, particularly when working with thin metal sheets. Because laser cutting is a non-contact process there is also no tool wear. Laser systems are readily integrated into an existing production line, are low-maintenance and allow easy automatization of the cutting process. Most of today's systems operate in a fully enclosed environment and are therefore very safe. Operating these systems in series production permits high processing speeds, high volume production and excellent workpiece reproducibility while maintaining consistently high standards of quality.

Table 1. A comparison of different cutting systems

Cutting system	*System cost*	*Operational costs*	*Production volume*	*Production rate*	*Flexibility of materials*	*Tool wear*	*System integration*	*Material thickness inches*	*Cut quality*	*Difficult cut shapes*	*Noise level*
Laser	High	Medium	High	High	High	No	Good	1	Good	Yes	Low
Punch press	High	Medium	High	High	Little	Yes	Good	0.5	Medium	Medium	High
EDM	Medium	High	Medium	Slow	Little	Yes	Difficult	4	Good	Medium	Medium
Milling	Medium	Medium	Medium	Slow	High	Yes	Good	—	Good	Medium	Medium
Water jet	High	High	Medium	Slow	High	Yes	Good	1-6	Good	Yes	High
Oxy flame	Cheap	Cheap	Medium	Slow	Little	No	Good	50	Bad	Medium	High
Plasma arc	Medium	High	Medium	High	Little	No	Good	2	Bad	Yes	High

3.1 The cutting process

Of the various cutting methods available, the most common are fusion cutting, where a strong gas jet ejects molten material; reactive fusion cutting, where the assist gas induces an exothermic reaction responsible for up to 90% of the total to the workpiece supplied energy; and vaporization cutting. A much less common technique is UV cutting, where photons emitted by the laser are so high in energy that they break up the bonds in organic materials. The material is cut without evaporation thus leaving no debris. This is very useful in cutting various types of plastics or whenever extreme precision or a clean cut is necessary.

Fusion cutting is a very economic method because the material need only be melted. This involves about one-tenth of the energy required for vaporization cutting. Although, depending on material type and material thickness, cutting in a pure fusion mode is sometimes impossible or inefficient and molten and vaporized phases coexist in the cut zone. It is this type of cutting process which is generally used in the industry and which will be discussed below although most of it can be applied without restriction to other cutting processes.

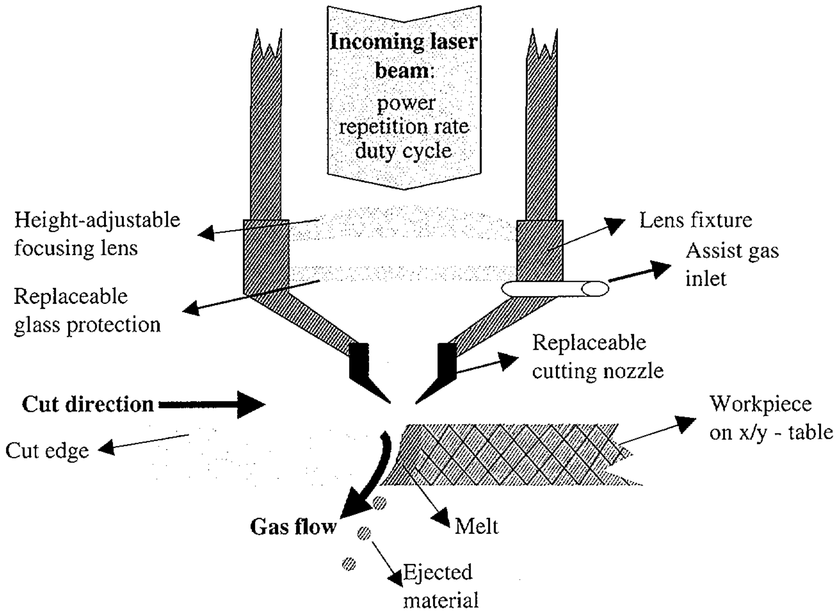
During the cutting process, the laser's principal function is that of a very intense heat source. The power density in the focus of a commercial high-power laser can achieve MW/mm^2. This is the highest power density available to industry today. The temperature in the focus can achieve values rivalled only by nuclear fusion. If the beam is absorbed by the work surface it can evaporate any known material. The usual cutting processes do not require this high-power density to cut material and high laser power is converted into high speed and high volume production. For metals the absorption of the focused laser beam by the material surface is only a problem at the beginning of the cutting process, when the workpiece is still at room temperature. CO_2 laser light (10.6 μm) is 93% reflected by steel surfaces and Nd:YAG (1.06 μm) is 70% reflected. Once the material is molten, the laser light is absorbed much better and more than 50% of the laser's energy is coupled to the workpiece, evaporating the material. A hole with molten walls is produced. Movement of the workpiece perpendicular to the laser focus will propagate this hole producing a narrow cut with a width (kerf) of the focal spot size of the laser beam (see also figure 17).

The process of producing the initial hole is called piercing and can become quite complex depending on the type of material to be processed. The difficulty is that, unless there is a hole through which the molten or evaporated material can be ejected, the only way for the debris to move is in the direction of the incoming laser beam. This represents a hazard to the laser focusing optics and leaves a border of resolidified material on top of the workpiece. Therefore the laser focusing lens needs to be protected by an anti-reflection coated glass sheet. This must be replaced periodically because the resolidified deposits on its surface blur the laser focus, making cutting impossible. If the absorbed energy in the workpiece builds up too much, a metallic vapour bubble inside the material may form. If the bubble then explodes, a crater is left behind which renders the workpiece useless. For this reason most laser cutting systems have special software routines for the piercing process, which are a function of material type. These software routines adjust the deposed power density (energy per area) during the piercing process into quantities which the work material can handle without explosive evaporation. This is generally done either by sharply defocusing the laser beam during the piercing process, called fast piercing because it takes only a very short time, or by using a smaller energy density by lowering the repetition rate, pulse energy or pulse duration. Fast piercing has the advantage that the same laser parameters can be used for both processes, piercing and cutting, whereas other piercing methods require the laser parameters to be readjusted for subsequent cutting. The complexity of the piercing process depends also on the laser's wavelength. A smaller wavelength requires little or no adjustment of the laser cutting parameters. A variety of materials exist, mostly non-metallic, which require no piercing at all. Thus the cutting process can start at once since the first pulse of the cutting sequence is sufficient to pierce the material.

Cutting parameters

Many parameters must be adjusted to optimize the cutting process and have a strong influence on cut quality and efficiency. Laser parameters are output power, operation mode (cw or pulsed) and beam quality. In pulsed operation, other parameters must be added such as peak power, duty cycle and frequency. Very important for a good laser system is also the focusing optics and mechanics. The beam must be stable and precisely centred with respect to the focusing lens and the clear aperture of the beam delivery system. Smooth motion of the beam with respect to the material is necessary for good cut quality. Parameters include focal length of the lens, position of the focal spot with respect to the material surface, cutting speed and acceleration, assist gas pressure, type and purity, gas nozzle diameter and distance from the work surface.

Figure 17. Laser processing head and cutting mechanism



As a rule of thumb the speed of the process is inversely proportional to the material thickness. Quality of the cut is strongly affected by the nozzle geometry and alignment relative to the laser beam. Generally the nozzle's diameter is only slightly larger than the beam diameter to force all gas into the kerf. The highest gas pressure is achieved with the nozzle as close as possible to the workpiece which in practice means a distance of about 0.55 mm in order to avoid accidental contact. In some cases it is an advantage to have the gas jet somewhat behind the laser focus to better clear the waste material (dross), but this poses difficulties for the steering mechanics of the processing head and gas nozzle. Some commercial processing heads come with two concentric gas nozzles where the inner gas nozzle, which delivers the laser beam, operates at low pressure whereas the outer ring nozzle operates at high pressure in order to produce striation-free and burr-free cuts [12]. Other processing heads use a fine water spray in the outer ring nozzle to minimize the HAZ of the workpiece [12]. The gas nozzles are generally made of high fusion-point material to avoid deformation by stray light and they handle high pressures (up to 20 bar). They are also replaceable because dross might stick to them during the piercing process and accidental misalignment of the laser beam with respect to the nozzle destroys the geometry of the nozzle orifice which immediately deteriorates the quality of the cut.

Once the piercing process is completed, a hole with molten walls exists. Movement of the workpiece perpendicular to the laser beam will initiate the cutting process. The dynamics of laser energy absorption and ejection of molten material is quite complex. Part of the laser beam arrives at the material surface, becoming partially absorbed and initiating fusion while most of it goes into the kerf to become absorbed and reflected by the molten walls. If the cutting speed is too low, some parts of the laser beam may go through the kerf without being absorbed. There are two major mechanisms for absorption: direct interaction of the laser beam with the material; and plasma absorption by evaporated material. Because of the high gas pressure that expels the plasma, the second kind of absorption is not very significant and it is therefore reasonable to assume that the major absorption in the kerf will occur by direct absorption, generally in a very thin layer of molten material with much less than 1 μm thickness. The melt front (see figure 18), which is the boundary between molten and solid material, has a somewhat semi-cylindrical shape and its propagation direction depends upon the energy flow distribution. The propagation velocity of the front is therefore highest in the cutting direction and always normal to the melt front.

The propagation direction of the melt through the kerf is downwards (see figure 19) due to the drag forces generated by the gas jet. Because gas pressure decreases down the kerf and heat flow decreases so much at the bottom of the workpiece that the melt front curves backwards and lowers its propagation velocity, the melt flow decelerates, increases its thickness and also its surface tension. The backwards bending of the cutting front can easily be verified during the process of laser cutting by observing the spark shower (the molten and ejected droplets) emerging from the kerf whose angle increases with higher cutting rates.

Figure 18. Relative position of melt front with laser beam and kerf

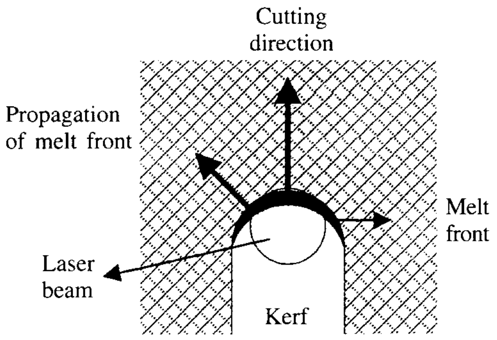
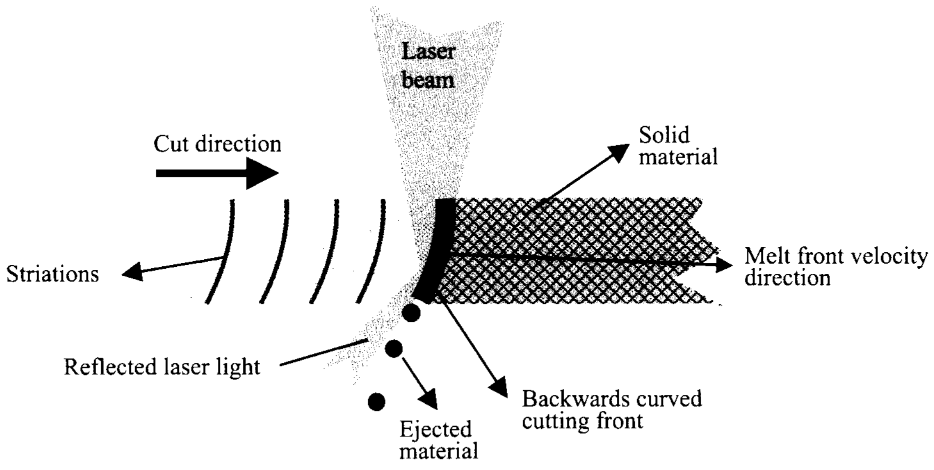


Figure 19. Cross-sectional diagram of workpiece during the cutting process

Shown are the overlap of the laser beam with the molten material inside the kerf and on top of the workpiece, backward bending of the cutting front and reflected laser beam.



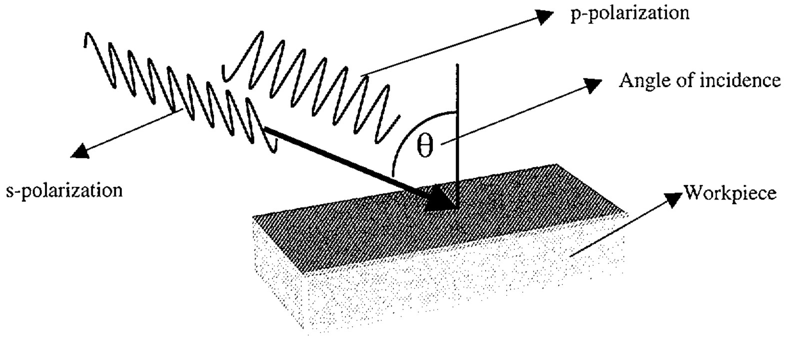
This effect is also a very useful tool to measure the efficiency of the cutting process. Experimentally an optimum compromise is found between efficiency and cut quality when the angle between the spark shower and the vertical is between 20° and 40° depending mainly on assist gas and workpiece material. After the cutting process, in most cases vertical lines on the cut edge, called striations, can be observed. The exact phenomenon that creates these striations is not well known. One theory, the critical droplet size theory, explains that the molten droplets have to attain a certain size before they can be blown out of the kerf [13]; other theories argue that the lateral heat conduction dynamics are responsible for the existence of striations. This theory, called sideways burning theory, is very effective with oxygen assisted cutting and will be dealt with in more detail in the next section.

Under certain operating conditions the ejected material might resolidify on the lower side of the workpiece around the cut area. This material (dross) must be removed which is sometimes a difficult task requiring mechanical treatment of the workpiece. As a general rule, utilizing inert gas assisted cutting, dross is easily removed by passing a piece of cloth whereas oxygen-assisted cutting may produce very hard dross particularly with alloyed steels.

3.2 Material absorption mechanism

As discussed, the laser light reflected from the molten surface depends upon angle of incidence of the laser beam, optical properties of the molten material and plane of polarization of the laser light. There are two polarization directions for linear polarized laser light: oscillation of light parallel (p) and perpendicular (s) to the plane of incidence.

Figure 20. Schematic diagram of a linearly-polarized laser beam hitting the workpiece



The reflection coefficients of parallel polarized light and perpendicularly polarized light can be easily calculated. Other polarizations are always a combination of s- and p-polarization. Very important for cutting applications is circularly polarized light whose reflection coefficient, Rc, is given by:

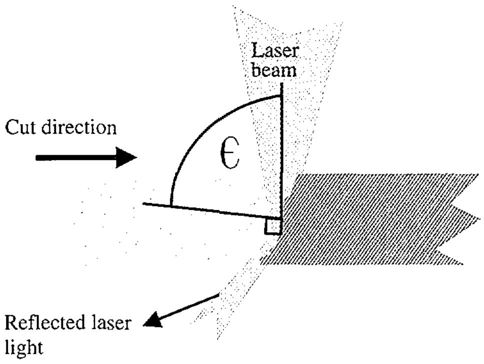
$$R_c = \frac{R_p + R_s}{2}$$

When a laser beam arrives at the surface of a metal it is predominantly absorbed by the free electrons inside the metal, leaving the solid metal structure initially undisturbed. The oscillation of the free electrons, induced by the incoming light, generates a beam whose angle of reflection is equal to the incoming beam's angle and which composes the reflected laser beam. The free electrons shield the metal and the radiation penetrates only a short way into the workpiece (about 1 μm). Therefore the metal appears "shiny" to the laser's radiation. Shorter wavelength beams have more energetic photons that have a higher probability of becoming absorbed by the electrons that are not free. Therefore these beams have better material absorption. Once the material has absorbed enough photons in order to raise its temperature significantly, the electrons can interact with lattice vibrations (phonons) and the absorption is increased. The absorption is given by:

$$A = 1 - R,$$

where R is reflectivity, which is equal to the square modulus of the reflection coefficient. During the cutting process the laser beam is always perpendicular to the workpiece surface. Thus it is easy to assume erroneously that only the absorption for normal incidence (0° of incidence angle) is important for the cutting process. However inside the kerf the situation is completely different and the angle is closer to 90°.

Figure 21. Angle of incidence during laser cutting



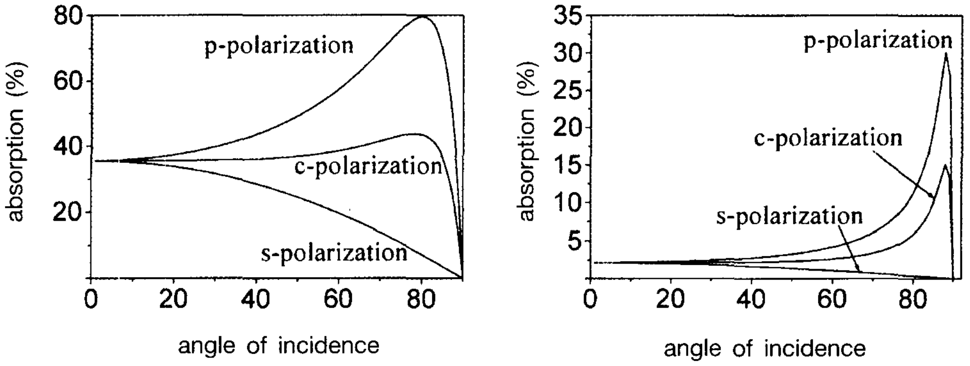
In the following figures the absorption of various materials as a function of incidence angle for different wavelength and material temperature is compared. It must be noted that these values are true only for material surfaces with little roughness (below 1 μm) and no surface films on the workpiece. A sandblasted carbon steel with roughness of 20 μm will have a typical reflectivity of 30% for 10.6 μm light and vertical incidence, an oxidized surface of only 10% and if dispersion paint is used, of only 3%.

From the figures below it can be noted that the p-polarization is always better absorbed than the s-polarization. This is owing to the electrons oscillating in the p-direction which interfere with the material surface trying to leave it and disturb the metallic structure which leads to absorption of the photon. On the other hand, electrons oscillating in the s-direction are completely free and can therefore efficiently reflect the laser light.

Figure 22 shows how important the laser wavelength is to absorption. As already seen, another important factor is the polarization of the beam. Inside the kerf, where the angle of incidence is close to 90°, the ratio of absorption of p-polarization to s-polarization of a CO_2, 10.6 mm beam is much higher than for YAG lasers. This is one of the reasons why CO_2 lasers should use circularly polarized beams. The other reason is that during lamination of the metal sheet, the metal grains become strongly elongated in the lamination direction. This generates a large difference in the absorption coefficient perpendicular and parallel to the direction of elongation of the grains for linearly-polarized light. This effect deteriorates the cut quality, generating different kerf width and non-parallel cutting edges when working with CO_2 lasers, depending on the angle between the cutting direction and the lamination direction of the workpiece. In order to eliminate all these effects, most of the commercial CO_2 laser systems come with circularly-polarized beams. The second effect is much less pronounced in YAG lasers because of the shorter wavelength.

Figure 22. Absorption of iron at YAG and CO_2 laser wavelengths

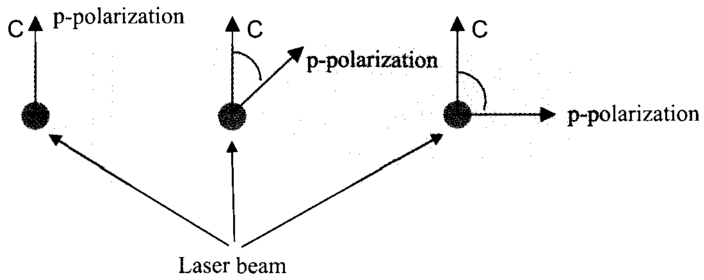
Absorption of iron at YAG laser wavelength (left) and CO_2 laser wavelength (right) as a function of angle of incidence for different laser beam polarizations at room temperature



In figure 23 the top view of a workpiece is shown. When the cutting direction is in the plane of polarization (left scheme) the strongest absorption takes place in the central part of the cut front and the smallest kerf width and highest cutting rate are attained. When the strongest absorption (p-polarization) is perpendicular to the cut front (right scheme), very large kerfs and lower cutting rates result. For intermediate angles between cut direction and p-polarization (centre scheme) the absorption is asymmetric and the kerf bends in the strongest absorption direction. The result would be a kerf that bends to the right when looking down the kerf.

Absorption as a function of angle of incidence has different characteristics at the melting temperature of iron. The 10.6 μm radiation shows a stronger dependence at melting temperature than at room temperature whereas the 1.06 μm radiation shows a less pronounced dependence under the same conditions. Both have absorption values at 0° incidence comparable to its values at room temperature but the 10.6 μm, p-polarized beam increases from 30% absorption to 80% at melting temperature for about 86° incidence angle whereas the 1.06 μm, p-polarized light remains at 80% absorption, independent of temperature, for this specific angle. Therefore the CO_2 laser light is better absorbed inside the kerf than on top of the work surface. Thus it is the laser of choice for thick metal cutting.

Figure 23. Absorption of linearly-polarized light, p, as a function of the cutting direction C



Comparing YAG and CO_2 laser systems

Absorption is often the limiting factor for a laser system's range of applications. As a general rule, the smaller the wavelength, the higher the absorption. Therefore YAG systems are generally preferred over CO_2 systems when cutting high reflectivity materials such as aluminium and copper. Other important parameters are focal spot size (beam quality) and laser operation mode (cw, pulsed, Q-switched).

Table 2. Behaviour of different materials to laser cutting

Material	*Material property*	*Preferred or most efficient laser system*
Aluminium, copper, brass, platinum, gold, silver	High reflectivity	YAG
Hastelloy, silicon nitrides, aluminium oxides, boron nitrides, nitrides, polycrystalline diamond, pyrographite, Ti, Ta, Zr, Mo, W, Cr	Medium to high reflectivity/high melting point	YAG
Mild steel, stainless steel, Fe, Ni, Sn, Pb	Medium reflectivity/ low melting point	CO_2
Die boards, PVC, epoxy, leather, wood, rubber, wool, cotton, acrylics, polyethylene, polycarbonate	Low reflectivity	CO_2
Glass, quartz, asbestos, mica, natural stones	Low reflectivity/ tendency to crack	YAG

In most cases the distinguishing parameters are material absorption of the laser's specific wavelength and heat affected zone induced by laser radiation. The higher the beam quality of the laser, the bigger the application range of the system. In some cases pulsed or Q-switched operation mode is preferred to cw radiation.

3.3 Heat affected zone

The heat diffusion through the walls of the cut edge affects the material properties within dimensions which depend upon several factors: the thermal diffusivity of the material; the laser radiation parameters; material thickness; and assist gas type and pressure. The extent of the Heat Affected Zone (HAZ) can be easily seen on most materials in the form of a discolouration or alteration of the surface reflectivity which accompanies the cut edge. The alterations of the material properties can have small effects but also embrittlement, porosity, distortion, charring and cracks. This is why the HAZ should be kept as small as possible in most cases. When the dimension of the HAZ becomes a problem, the general approach is to cool the workpiece more efficiently by pulsing the laser radiation, choosing a smaller laser spot size or pulse duration or accompanying the laser beam with a fine water spray. For example, cutting 3 mm mild steel with a cw CO_2 laser will produce a HAZ of 0.5 mm whereas a pulsed CO_2 laser produces a HAZ of only 0.15 mm. Smaller HAZ is also achieved by choosing a laser system emitting shorter wavelength. Therefore HAZ is much less of a problem with YAG lasers than with CO_2 lasers, and is virtually absent with excimer (UV) lasers.

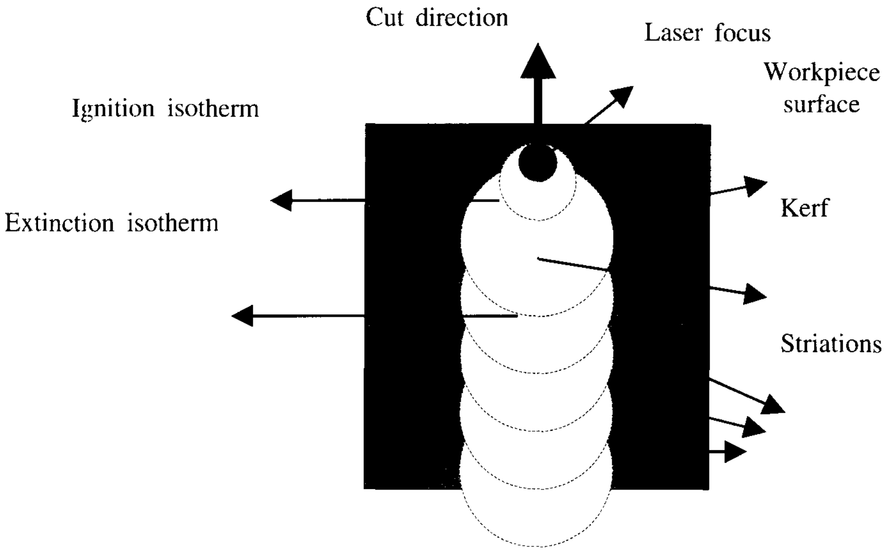
3.4 Oxygen assisted cutting

The oxygen assisted cutting process, also called reactive fusion cutting, is exothermal. This improves the energy coupling into the material and can therefore achieve much higher cutting rates with cut qualities regarded as good. The laser ignites the workpiece which, inside the pure oxygen atmosphere, is capable of burning almost on its own. The process is mainly applied to mild steel cutting but also works well in most aluminium alloys, especially when low and medium-power CO_2 lasers are used where the cutting rates can be considerably increased. Some alloyed steels and other materials should not be cut with gases containing oxygen at all because the oxidized material that has been expelled from the kerf (dross) may cling to the lower side of the workpiece and become extremely difficult to remove. In fact, this oxidized material may be much harder than the steel itself, requiring a further processing step for its removal. Furthermore, materials such as titanium ignite in the presence of oxygen because 90% of the energy supplied to the cutting process comes from the burning reaction.

In order to obtain a significant reduction in processing time, the purity of the oxygen should be better than 99.995%. A drawback of oxygen assisted cutting is that a thin oxide layer is formed on the cut surface which is not acceptable if the edges of the workpiece need to be welded afterwards. Another drawback is the higher roughness of the cut kerf. Particularly in the case of mild steel, care must be taken when using high oxygen gas pressures in order to avoid self-burning effects. These considerably increase the roughness of the cut. The problem increases with increasing material thickness and therefore low gas pressures must be applied.

The increased roughness of the kerf can be explained by the exothermic reaction that the material experiences (see figure 24). The burning reaction starts at the ignition isotherm. When ignition temperature is reached, the isotherm travels in all directions and ends at the extinction isotherm. The coarseness of the striations increases with material thickness and depends on material, assist gas and laser parameters.

Figure 24. Increased coarseness of striations with oxygen assisted cutting



4

Laser welding

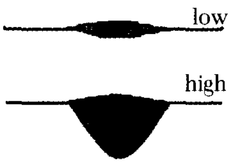
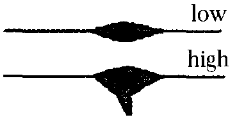
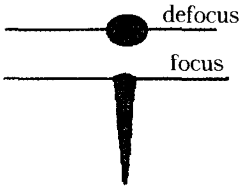
Professor W. Steen

(The following is an extract from a lecture given by Professor Steen at the ICS/ UNIDO workshop held at Buenos Aires, Argentina in October 1988.)

Introduction

The focused laser beam is one of the highest power density sources available to industry today. It is similar in power density to an electron beam. Together these two processes represent part of the new technology of high energy density processing. Table 3 compares the power density of various welding processes.

Table 3. Relative power densities of different welding processes

Process	*Heat source intensity W/m^2*	*Fusion zone profile*
Flux shielded arc welding	$5 \times 10^6 - 10^8$	
Gas shielded arc welding	$5 \times 10^6 - 10^8$	
Plasma	$5 \times 10^6 - 10^{10}$	
Laser or electron beam	$10^{10} - 10^{12}$	

At these high-power densities all materials will evaporate if the energy can be absorbed. Thus, when welding in this way a hole is usually formed by evaporation. This hole is then traversed through the material with the molten walls sealing up behind it. The result is what is known as a keyhole weld. This is characterized by its parallel-sided fusion zone and narrow width (see figure 25).

Since the weld is rarely wide compared with the penetration, it can be seen that the energy is being used where it is needed in melting the interface to be joined and not most of the surrounding area as well. The term defining this concept is joining efficiency. The joining efficiency is not a true efficiency in that it has units of mm^2 joined/kJ supplied. It is defined as [Vt/P], the reciprocal of the specific energy, where V = traverse speed in mm/s; t = thickness welded in mm; P = incident power in kW. Table 4 gives some typical values of the joining efficiency of various welding processes.

Figure 25. Micrograph of the transverse section through a laser weld
The figure shows fusion and heat affected zones

Table 4. Relative joining efficiencies of different welding processes

Process	*Approximate joining efficiency* mm²/kJ
Oxy acetylene flame	0.2-0.5
Manual Metal Arc (MMA)	2-3
Tungsten Inert Gas (TIG)	0.8-2
Submerged Arc Welding (SAW)	4-10
High frequency resistance welding	65-100
Electron Beam (EB)	20-30
Laser	15-25

The higher the value of the joining efficiency, the less energy spent in unnecessary heating – that is, generating a HAZ or distortion. Resistance welding is by far the best in this respect because the energy is only generated at the high resistance interface to be welded. But it can be seen that the EB and laser are again in a class by themselves. So how do they compare with other processes in their performance characteristics and can they be distinguished from each other? What sort of market expectation can be foreseen for laser welding? Is it a gimmick or a gift? The main characteristics of the laser and the ways in which these characteristics compare for alternative processes are listed in tables 5 and 6.

It can be seen from tables 4 and 5 that the laser offers a high-speed, high-quality welding tool. However, figures 26 and 27 show that, at only 17% of applications for Nd-YAG and 14% for CO_2 lasers, it has been slow to penetrate the TIG market for high-speed welding processes such as tube welding. This is mainly because of uncertainty about the use and reliability of lasers compared with the TIG process. The main market for laser welding processes is usually found in areas requiring the welding of heat- sensitive components such as heart pacemakers, pistons assembled with washers *in situ*, diaphragms with sealed gas or electronic components. Another application area is in welding magnetic or potentially magnetic material such as gears for cars. The speed and neatness of the weld is, however, a challenge for the future. Much research is currently being applied to welding cars, cans, domestic equipment and aircraft. The process has many superior qualities; so possibly the only obstacle is waiting for the market to be educated in the use of lasers before they are more widely used.

Table 5. Main characteristics of laser welding

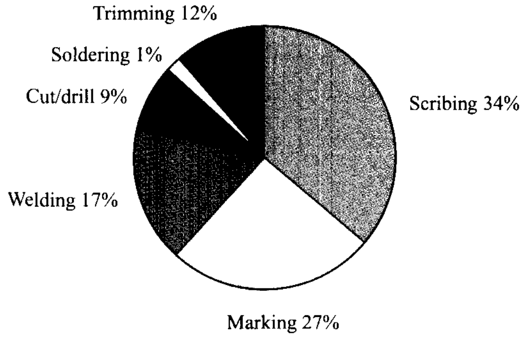
Characteristic	*Comment*
High energy density – keyhole weld	Less distortion
High processing speed	Cost effective (if fully employed)
Rapid start/stop	Unlike arc processes
Welds at atmospheric pressure	Unlike EB welding
No X-rays generated	Unlike EB
No filler required (autogeneous weld)	No flux cleaning
Narrow weld	Less distortion
Relatively little Heat Affected Zone (HAZ)	Can weld close to heat sensitive materials
Very accurate welding possible	Can weld thin to thick materials
Good weld heat profile	No clean up necessary
No beam wander in magnetic field	Unlike EB
Little or no contamination	Depends only on gas shrouding
Relatively little evaporation loss of volatile components	
Difficult materials can sometimes be welded	
Relatively easy to automate	General feature of laser processing
Lasers can be time shared	General feature of laser processing

Table 6. Comparison of welding processes

	Processes				
Characteristic	*Laser*	*EB*	*TIG*	*Resistance*	*Ultrasonic*
Rate	V	V	X	V	X
Low heat input	V	V	X	V	V
Narrow HAZ	V	V	X		V
Weld bead appearance	V	V	X		V
Simple fixturing	V	X	X		
Equipment reliability	V		V	V	
Deep penetration	X	V		X	
Welding in air	V	X		V	
Weld magnetic materials	V	X	V	V	V
Weld reflective materials	X	V	V	V	V
Weld heat sensitive materials	V	V	X	X	V
Joint access	V			X	X
Environment, noise, fume	V	V	X	X	X
Equipment costs	X	X	V		
Operating costs	—	—	—	—	—

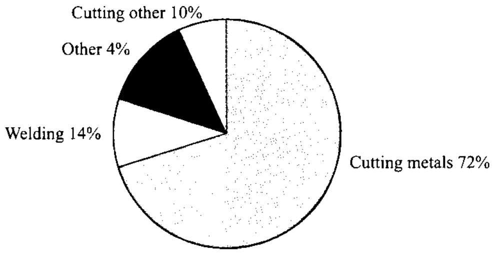
Note: V indicates point of merit; X indicates point of disadvantage.

Figure 26. Industrial applications of Nd:YAG lasers in 1986



As with laser cutting, welding relies on a finely-focused beam to achieve the penetration. The only exception would be if the seam to be welded is difficult to track or of variable gap, in which case a wider beam would be easier and more reliable to use. But, in this case, once the beam is defocused the competition from plasma processes should then be considered.

Figure 27. Industrial applications of CO_2 lasers in 1986



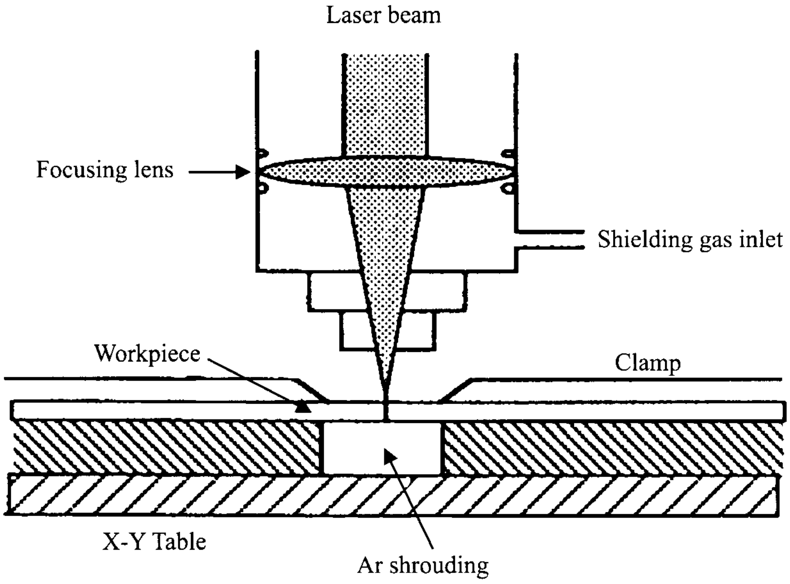
Process arrangement

The general arrangement for laser welding is illustrated in figure 28; figure 29 illustrates the flexibility of the use of optical energy. It is in this area that laser users need to gain maturity.

The advantages in welding, for example, a tube from the inside outward is that inspection becomes straightforward, thus considerable quality control costs might be saved. Shrouding is a feature of all welding and the laser is no exception; however, shrouding is not difficult and coincides with the need to protect the optics from spatter.

When welding high reflectivity material it is customary to tilt the workpiece by about 5°, in order to avoid back reflections from entering the optics train and damaging "O" rings or being reflected back into the laser cavity and thus affecting the beam, the instant it is to be used. Such feedback has an air of lack of control and is a threat to the output window of the laser. It might, however, be a good thing if properly controlled in that greater power might be expected when the reflectivity is high.

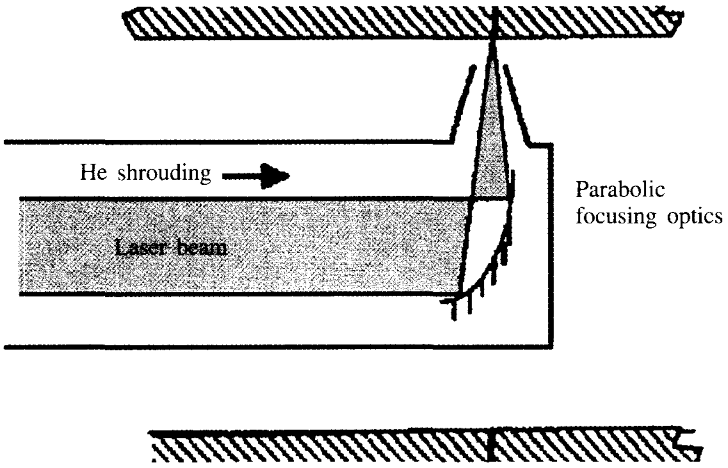
Figure 28. General arrangement for laser welding



Process mechanisms–keyholes and plasmas

There are two modes of welding with the laser illustrated in figure 30. Conduction-limited welding occurs when the power density is insufficient to cause boiling–and therefore generate a keyhole–at the given welding speed. The weld pool has strong stirring forces driven by Marangoni-type forces resulting from the variation in surface tension with temperature. Most surface treatments in which melting occurs employ an out-of-focus beam that results in conduction-limited weld beads. The alternative mode is keyhole welding in which there is sufficient energy per unit length to cause evaporation

Figure 29. Arrangement for welding pipe from the inside using metal optics



and hence a hole in the melt pool. This hole is stabilized by the pressure from the vapour being generated. In some high-powered plasma welds there is an apparent hole, but this is mainly due to gas pressures from the plasma or cathode jet rather than from evaporation. The keyhole behaves like an optical black body in that the radiation enters the hole and is subject to multiple reflections before being able to escape (see figure 31). In consequence nearly all the beam is absorbed. This can be both a blessing and a nuisance when welding high reflectivity materials since much power is needed to start the keyhole, but as soon as it has started the absorptivity jumps from 3% to 98% with possible damage to the weld structure.

Some ingenious experiments were done by the laser group at Osaka who photographed the keyhole during the laser welding of quartz and aluminium [14]. In both it was seen that the keyhole has an approximate shape as shown in figure 31 and a flow pattern, illustrated in figure 32. The flow pattern was followed by inserting high melting point particles and watching them with X-rays. The downward flow in this last example may be part gravitational since the particles were of tungsten. Nevertheless the twin vortices occur in some keyholes of sufficient depth. The location of the collision of counter rotating vortices is a region susceptible to trapping bubbles and hence vulnerable to porosity.

Figure 30. Conduction-limited and keyhole-type welds

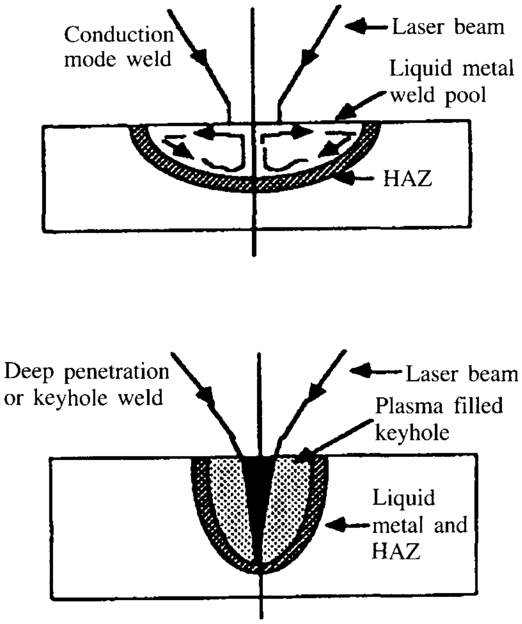
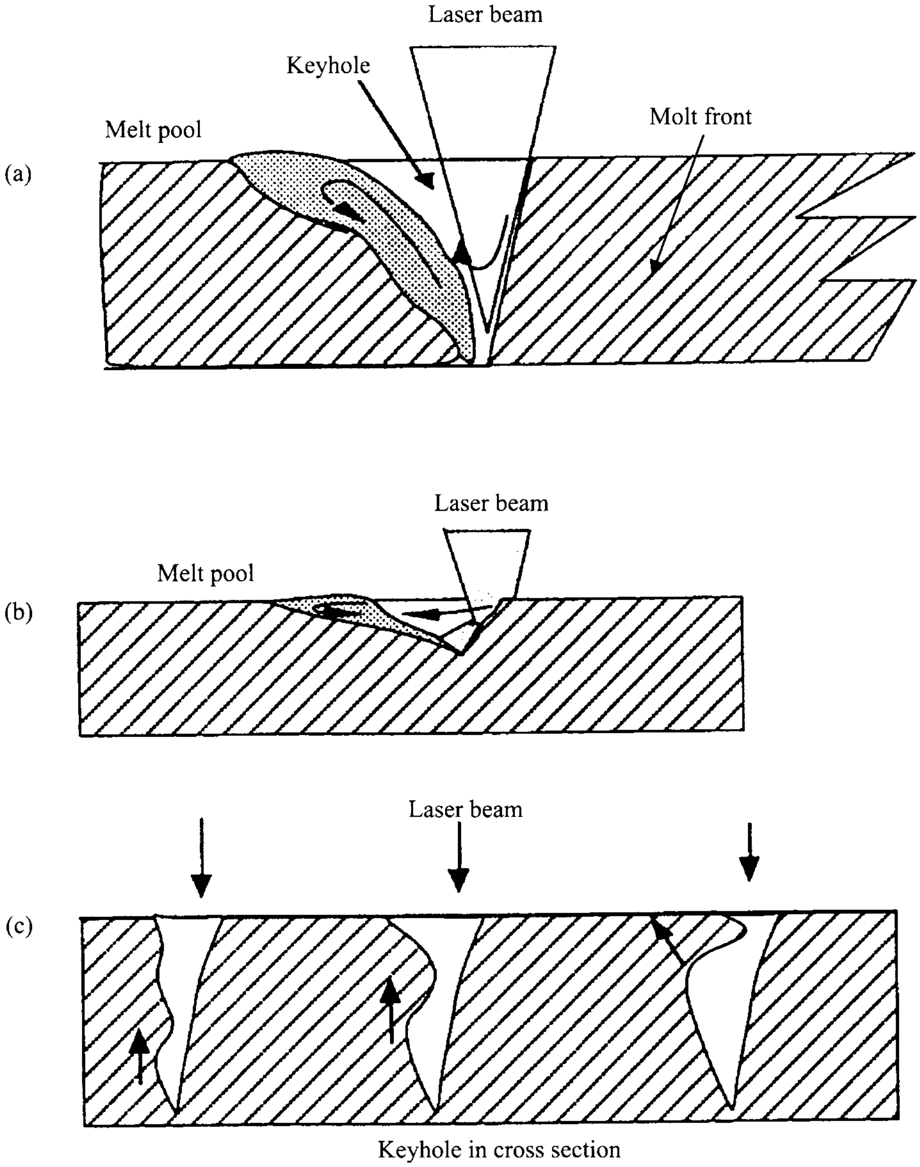


Figure 31. Shape and flow pattern in laser welds



Inside the keyhole there is considerable metal vapour which is partially absorbing and hence capable of becoming hotter and forming a plasma. This hot plasma vapour emerging from the keyhole may ionize the shroud gas. Ionized gas has free electrons and is thus capable of absorbing or even blocking the beam. Figure 33 shows what happens if there is no gas to blow the plasma away when welding with 10 kW of laser power. The plasma forms intermittently due to the "blocking" of the beam. There is some discussion on whether the plasma is opaque enough at the temperatures measured to block the beam or whether the effect just noted is due to the plasma scattering the beam by variations in refractive index.

There are two principal areas of interest in the mechanism of keyhole welding. The first is flow structures since this directly affects the wave formation on the weld pool and hence the final frozen weld bead geometry. This geometry is a measure of weld quality. The second is the mechanism for absorption within the keyhole which may affect both this flow and entrapped porosity. The absorption of the beam is by Fresnel absorption (absorption during reflection from a surface) and plasma reradiation. The Fresnel absorption can be calculated for a given shape of the leading edge of the keyhole to be non-uniform [15]. The calculation must allow for the slope of the face, mode structure of original incident beam, polarization effects and focal position. The plasma effects

Figure 32. Flow in a keyhole weld mapped by tungsten pellet [14]

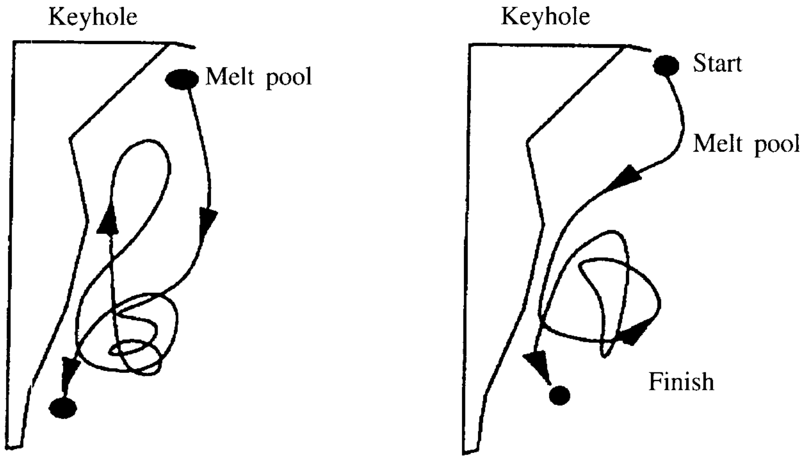
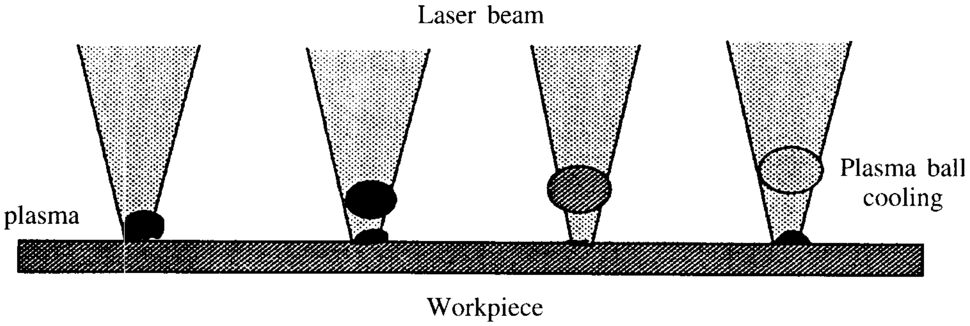


Figure 33. Blocking effect of plasma if there is no side jet removing it



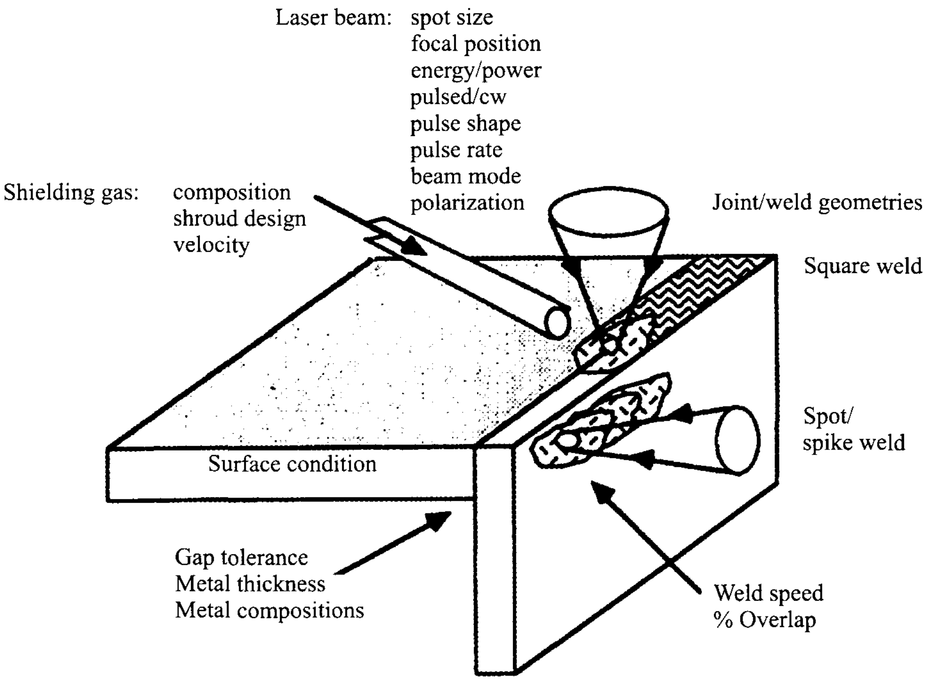
vary with polarization and speed. The Arata film [14] showed that ripples in the leading edge of the keyhole (see figure 31), on which nearly all the power first falls, may act as sites for explosive vaporization sending a vapour cloud into the melt pool. Under certain conditions this may freeze as regular porosity at the root of the weld. There is a neck at the top of the keyhole which may again trap vapour.

4.1 Operating characteristics

The main process parameters are illustrated in figure 34. They are:

Beam properties:	Power, pulsed or continuous Spot size and mode Polarization Wavelength
Transport properties	Speed Focal position Joint geometries Gap tolerance
Shroud gas properties	Composition Shroud design Pressure/velocity
Material properties	Composition Surface condition

Figure 34. The main process parameters



Effect of continuous power

There are two main problems in welding: lack of penetration or the inverse, "drop out". These are the boundaries for a good weld for a given power, as illustrated in figure 35 [16]. The maximum welding speed for a given thickness rises with increase in power.

The fall off shown at the higher power levels of 2 kW is almost certainly due to the poorer mode structure given by most lasers when working at their peak power. However, for the results in figure 36, for higher power levels up to 5 kW, the fall off may now be due to the same cause and also plasma effects. The main point to note from these two graphs is that for more power the operating window is larger. For high speeds, the effects of sideways conduction during melting is slight, hence the Bessel functions (discussed in the Swifthook and Gick model) become soluble and an equation similar to that derived for cutting results. That is:

$$Y = 0.483\ X \qquad (1)$$

In which:

$2R$ = weld width = w (m)
g = thickness (m)
P = power = $P(1\text{-}r_f)$ (W)
r_f = reflectivity
$Y = 2vR/\alpha$ and $X = P/kgT$
α = thermal diffusivity = $k/\rho C_p$ (m^2/s)
T = temperature (K)
T_m = melting point for width (K)

Thus we have:

$$0.483\ P(1 - r_f) = Vwg\ \rho\ C_pT_m \qquad (2)$$

Figure 35. Welding speed vs power for Ti-6Al-4V [16]

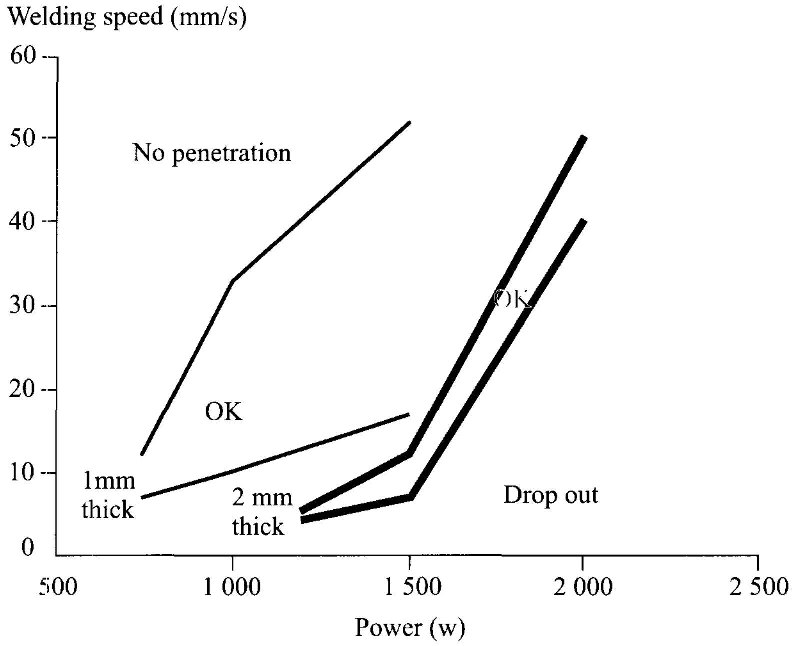
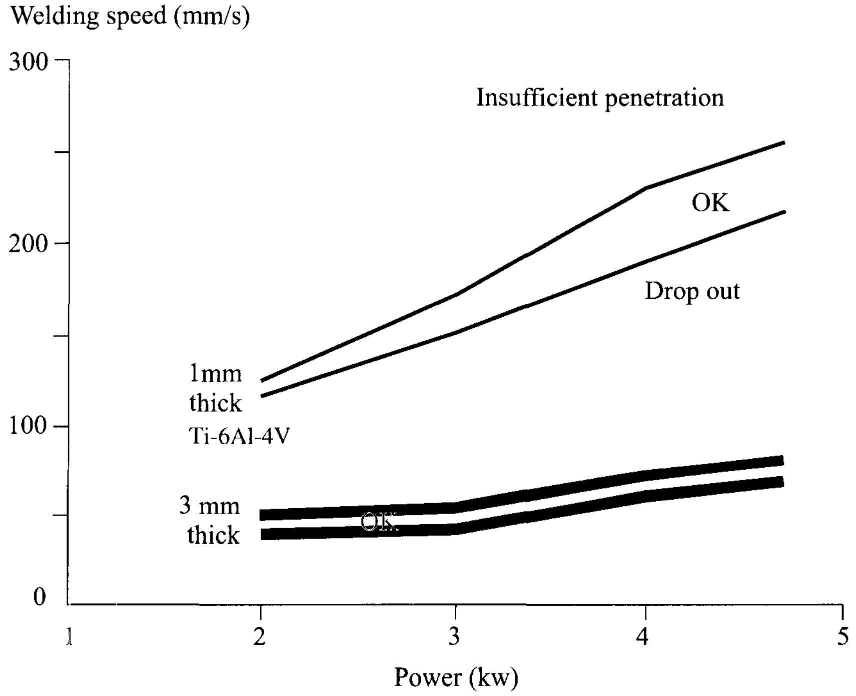


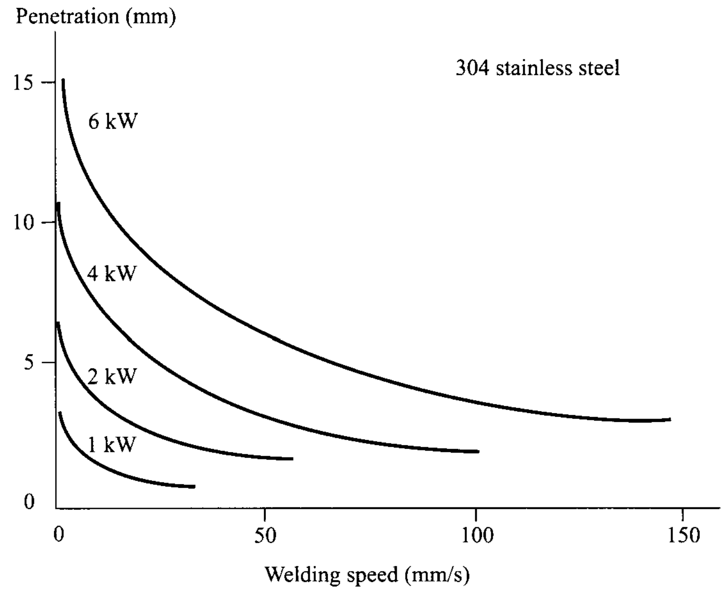
Figure 36. Welding speed vs power for Laser Ecosse model CL5 laser



This is a form of the lumped heat capacity model seen previously for cutting. This simple model for the maximum welding speed has neglected latent heat and so it must be a high value. It has also assumed that the power is distributed as a line source along the beam axis, the ultimate in fine focusing. However, the parametric relationships are enshrined in it. This formula would act as a useful rule of thumb to find out what welding speed should be possible for a given laser power, if very finely focused. It is usually high by around 30%.

Penetration is inversely proportional to the speed for a given mode, focal spot size and power as shown in figure 37 [17].

Figure 37. Welding speed vs penetration for a fast axial flow CO_2 laser



Effect of pulsed power

The use of pulsed power allows two more variables: pulse repetition frequency (PRF) and percentage overlap to be considered. The welding speed is decided by the spot size x PRF x (1 -% overlap). In fact speed is independent of power. Penetration is a function of both power and the weld bead quality. Too much power causes vaporization and material ejection as in drilling [18]. Thus for welding the pulse is usually longer than for drilling and shaped to have a smaller initial peak.

Spot size and mode

The joining efficiency is greatly affected by the mode as illustrated in the results from Akhter [19], figure 38, on the welding of zinc coated steel using a variety of lasers. A similar study made by the Fraunhofer Institute at Aachen comparing many lasers has shown that the superior mode structure of the Laser Ecosse AF5 laser gives the best penetration available today [20]. This laser is fitted with flexible mirrors that allow accurate mode tuning to true TEM_{00} modes.

Polarization

At first sight it may seem that polarization will have no effect on laser welding since the beam is absorbed inside a keyhole hence it will be absorbed regardless of the plane of polarization. In fact, this is quite unlike cutting where all the absorption had to take place on a steeply-sloped cut front. This supposition would be correct in essence but some second order events have been noted by Beyer et al. [15]. Figure 39 shows the slight variation in penetration thought to be due to polarization effects. The resulting weld fusion zones are also wider for the case of s-polarization (perpendicular to the plane of incidence) as expected since in this case the main absorption would be at the sides. The argument suggested for this phenomenon is that there are two absorption mechanisms. At slow speeds, the plasma absorption dominates and the beam is absorbed by inverse Bremsstrahlung effects in the keyhole generating a plasma that appears blue in argon shrouded systems. As the speed increases, the Fresnel absorption (absorption by reflection on front face) gains in importance due to the cooler plasma being less absorbing. However, no polarization effects were noted with aluminium. This is still a puzzle and throws some questions on the whole theory.

Figure 38. Joining efficiencies comparing various lasers ([19], BRITE1339)

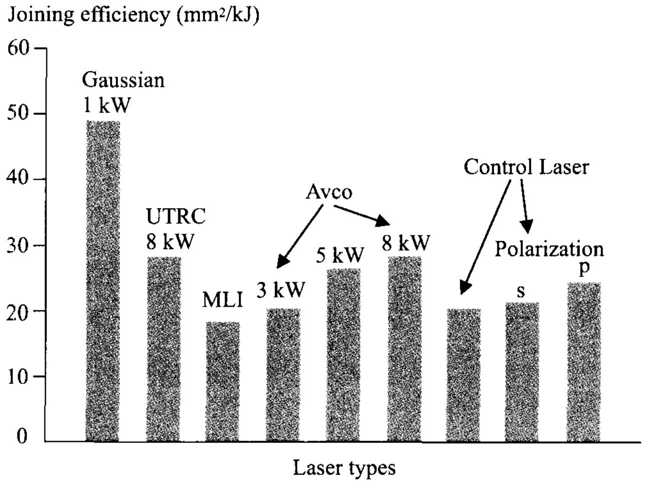
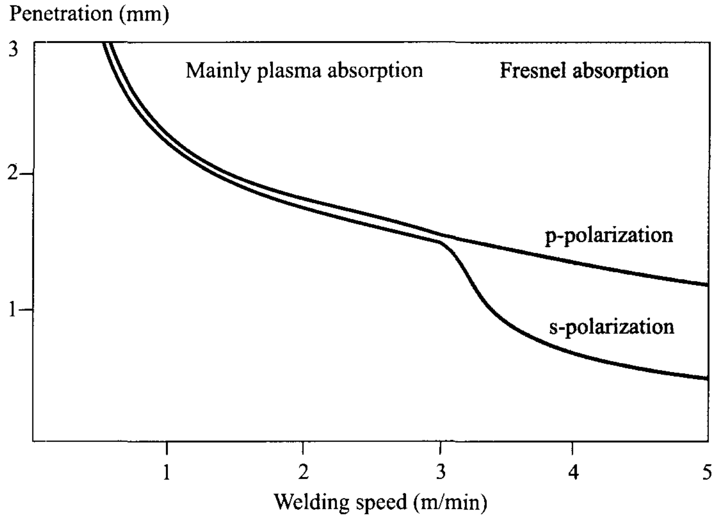


Figure 39. Influence of beam polarization on welding performance



Wavelength

Due to the high absorptivity within the keyhole there is little operational difference when welding with long or short wavelengths. When welding with a conduction-limited weld then the surface reflectivity becomes paramount and the lower reflectivity with the shorter wavelength gives a distinct advantage to excimer, YAG or CO lasers over the CO_2 laser.

Speed

The effect of speed on the welding process is principally described by the overall heat balance equation. However, in addition to these main effects there are some others. Firstly, there is the effect of speed on the weld bead and secondly, there is the problem of shrouding high-speed welds.

Effect of speed on the weld pool and weld bead shape

As the speed increases so will the pool flow pattern and size change. In general, the flow in a laser keyhole weld pool is shown in figures 30, 31 and 32. At slow speeds the pool is large and wide and may result in drop out (see figure 40(d)). In this case the ferrostatic head is too large for the surface tension to keep the pool in place and so it drops out of the weld, leaving a hole or depression. This is described in detail by Matsunawa [21]. At higher speeds, the strong flow towards the centre of the weld in the wake of the keyhole has no time to redistribute and is hence frozen as an undercut at the sides of the weld, diagrammatically shown in figure 40(b). If the power is high enough and the pool large enough then the same undercut proceeds and edge freezing occurs, leaving a slight undercut but the thread of the pool in the centre has a pressure that is a function of the surface tension and the curvature [21]. This leads to pressure instability causing the "pinch" effect in which those regions of high curvature flow to regions of lower curvature resulting in large humps (see figure 40(c)). The pressure, p, in these regions would vary by:

$$p = \gamma/r^2 \qquad (3)$$

where γ = surface tension and r = radius of curvature.

There is an intermediate region in which there is a partial undercutting and central string. All this has been mapped for certain alloys by Albright [22] as shown in figure 41 (a) and (b).

Figure 40. Range of weld shapes usually varying with speed

(a) Normal/good

(b) Undercut

(c) Humping
(Longitudinal section)

(d) Drop out

Figure 41. Map of weld bead profiles

As functions of welding speed and laser power (a) 0.12 mm thick stainless steel; (b) 0.12 and 0.25 mm thick mild steel

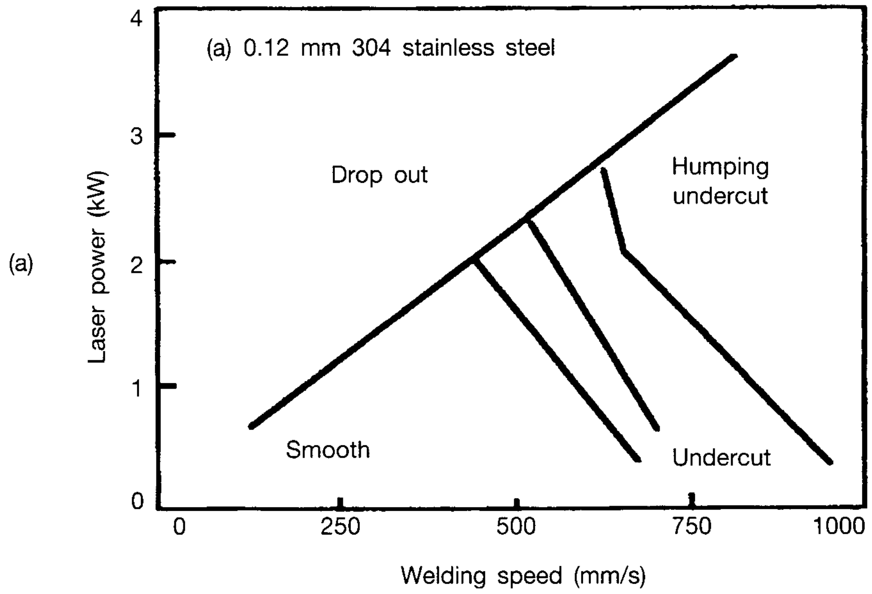
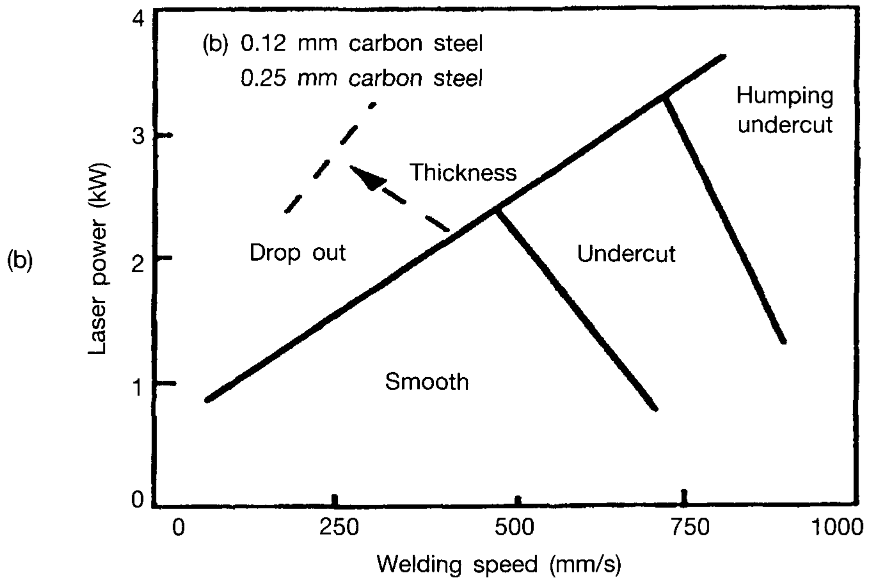


Figure 41. *(continued)*



Effect of speed on shroud arrangements

The faster the welding process, the longer the weld pool. A theoretical prediction of Gratzke et al. [23] gives the relationship: pool length, L = (3r2u)/2oc for a moving Gaussian source, but the results of marker experiments from Takeda [24] indicate the opposite. So there is room for discussion here! However, with increased speed the hot metal extends further beyond the welding point thus trailing shrouds are usually needed to avoid atmospheric contamination.

Focal position

There are suggestions [16, 24, 25, 26] that the focal point should be located within the workpiece to a depth of around 1 mm for maximum penetration. It is important to consider the need to have sufficient power density to generate a keyhole and then for that power to stay together within the keyhole to increase the penetration. Thus the main parameters to consider would be the depth of focus and the minimum spot size. It has been shown that the depth of focus, z_f is given by:

$$z_f = 15.7\,F^2\ \mu\text{m for } 10.6\ \mu\text{m radiation} \quad (4)$$

and the minimum spot size, d_{min} for a multi-mode CO_2 beam is given by:

$$d_{min} = 2.4(2p + 1 + 1)\,(F\lambda) \quad (5)$$

$$\therefore d_{min} = 80\,F\ \mu\text{m} \quad (6)$$

Figure 42 shows the beam diameter versus the distance from the lens for various F numbers. The shaded area shows the parabolic relationship between the depth of focus, z_f, and the minimum beam diameter, d_{min}. A certain power density, P/d_{min} or P/d_{min}^2 is required to form a keyhole for a given traversed speed. This is marked in figure 42 by the horizontal line. From this analysis it can be seen that the optimal position of the focus for maximum penetration varies as shown in figure 43; a result in agreement with Seaman's work is shown in figure 44 [26].

Figure 42. Beam diameter vs distance from the focus

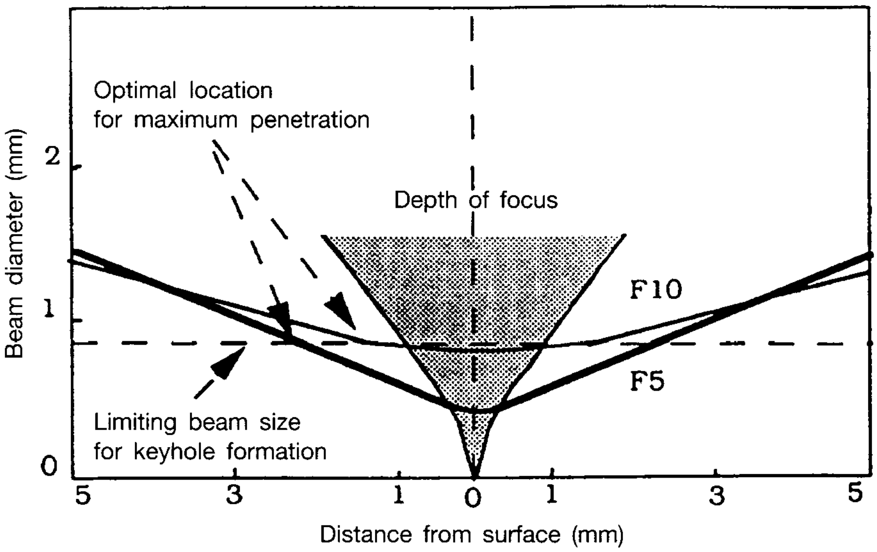


Figure 43. Theoretical variation in the optimal position of the focus within the workpiece for maximum penetration for a given power

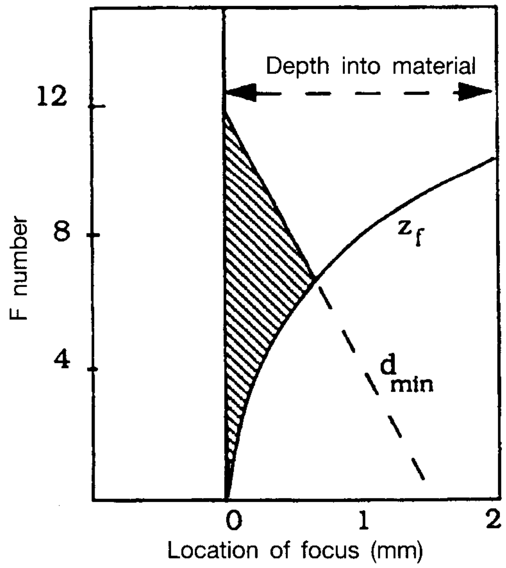
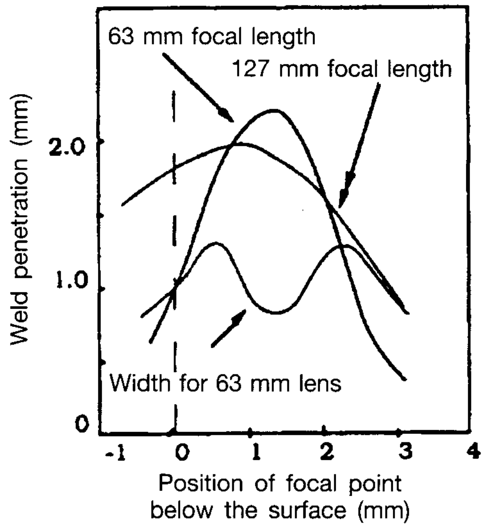


Figure 44. Effect of focal position on weld penetration for 1018 steel [26]



Joint geometries

Laser beams causing keyhole-type welds prefer a joint which helps the absorption and hence the formation of the keyhole. High-intensity welding processes are not sensitive to different thicknesses of the pieces to be joined. This allows some new types of joint to be considered.

Figure 45 shows some of the variations that can be considered. The flare weld was used by Sepold [27] for very high speed welding of two strips at speeds up to 4 m/s. It is currently used for making seam welds in thick section pipe. The plane of polarization must be correct in this mode of welding or the beam will be absorbed before being reflected down to the point of the joint. It is, of course, a very efficient joining technique. The T-weld geometry has a surprise attached to it, in that as the keyhole penetrates at an angle into the workpiece it tends to turn upwards to allow full penetration around the base of the T. This very convenient event is the result of the reduced thermal load on the T side of the keyhole which encourages the melting isotherm that way.

Figure 45. Various welding joint arrangements

(a) Butt joint

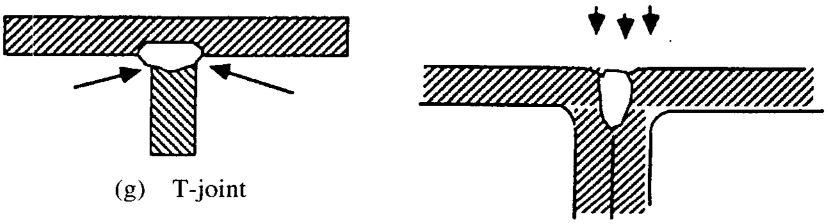
(b) Fillet or lap joint

(c) Spot or lap weld

(d) Spike or spot weld

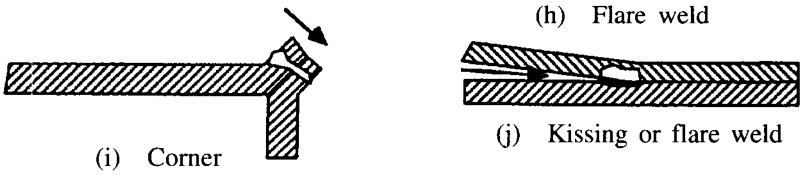
(e) Flange joint

(f) Edge joint



(g) T-joint

(h) Flare weld



(i) Corner

(j) Kissing or flare weld

In butt joints the gap must be small enough that the beam can not pass straight through the joint. That is to suggest that the gap should be smaller than half the beam diameter (< 200 μm). For welds where there is a large gap, the beam is sometimes rotated by rotating the lens off axis from the beam. However in these cases there is a chance of some drop out or a lower level in the weld. This can be corrected by adding filler material as a wire [28] or as a powder [19]. On the whole the welds do not require filler material as they are autogenous. One might question how this is possible when the conservation of mass suggests that if there is a gap there will be a fall in the level of the weld. In practice there is usually a rise in the level! This is due to the stresses in the cooling weldment drawing the workpieces together and so squashing the melt pool. Thus a small gap can be tolerated.

The extent of the squeeze is proportional to the forces which are in turn proportional to the contraction of the cooling weld. Thus the gap which can be tolerated, g, is approximately given by the relationship:

For butt welds: $A\beta\Delta Twt_p = gt_p$

$$\therefore g = A\beta\Delta Tw \qquad (7)$$

where: β = coefficient of thermal expansion (m/°C)
ΔT = temperature change, approx: melting point (°C)
w = weld width (m)
t_p = sheet thickness (m)
g = gap width (m)
A = constant
B = constant

For lap welds (gap between plates): $B\beta\Delta Tw\ 2t_p = gw$

$$\therefore g = B\beta\Delta T\ 2t_p \qquad (8)$$

Welding with a gap in lap welding is essential if zinc coated steel is being welded or another material with a volatile coating. In this case there must be some way to vent the high-pressure zinc vapour. Zinc boils at 906 °C and steel melts at around 1,500 °C; the keyhole is even hotter. So as the keyhole enters the interlayer of zinc there is a sudden evolution of vapour that will destroy the weld continuity. Akhter [29] has calculated the required size of the gap from the volume of the zinc vapour to be exhausted. The situation, which is modelled, is shown in figure 46 (a) and (b). The volume of vapour generated per second at the interface is:

$$2(w + 2b)Vt_{zn}\rho_s)\rho_v \quad m^3/s \qquad (9)$$

The vapour escapes as it is formed around the melt pool at a velocity v_2. Thus the rate of escape of the vapour through the gap is:

$$= \frac{v_2\pi(w + 2b)g}{2} \qquad (10)$$

For a balance between the generation and exhaust of vapour we have from equations (9) and (10):

$$v_2 = \frac{4t_{zn}V\rho_S}{\pi.\rho_V} \qquad (11)$$

This escape velocity can only be achieved with an acceleration pressure. This pressure must not exceed the ferrostatic head in the weld pool $(\rho_L g_c t_p)$ or the vapour will be expelled through the pool and destroy the weld quality. Thus:

$$v_2 = \sqrt{\frac{2\Delta P_{12}}{\rho_V}} = \sqrt{\frac{2\rho_L g t_p a}{\rho_V}} \qquad (12)$$

By eliminating v_2 between equations (11) and (12), a relationship is given for the limiting value of the gap required for sound welding of zinc coated steel:

$$g_{limit} = \frac{4t_{zn}V\rho_s}{\pi\sqrt{2\rho_V\rho_L g t_p}} \qquad (13)$$

If the gap is smaller than this value then some blow out in the weld is to be expected. Akhter suggests a method for controlling the gap in production by dimpling [29]. The model also suggests that there is a value of the laser power above which it is impossible to weld zinc coated steel. The value is expected to be around 5 kW. This is the result of a balance between the exhaust of high-pressure vapour, requiring a gap and the mass balance on the weld pool to avoid drop out, not requiring a gap. The map of the process is shown in figure 47.

Figure 46. Welding zinc coated steel with a gap between the sheets for exhausting the zinc vapour

Diagrams (a) and (b) show the welding of zinc coated steel with a small gap between the sheets for exhausting the high-pressure zinc vapour generated during welding [28]. (a) side view, (b) plan view.

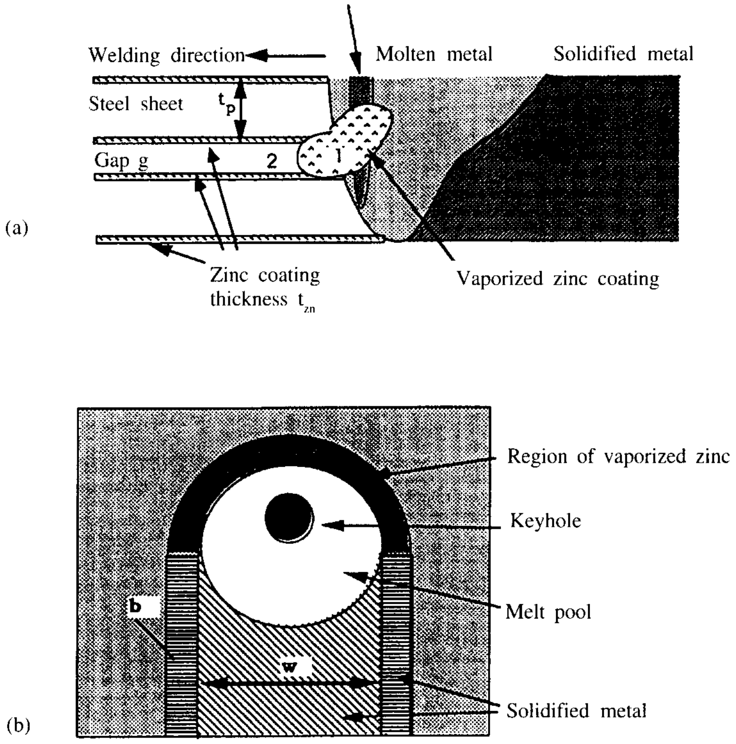
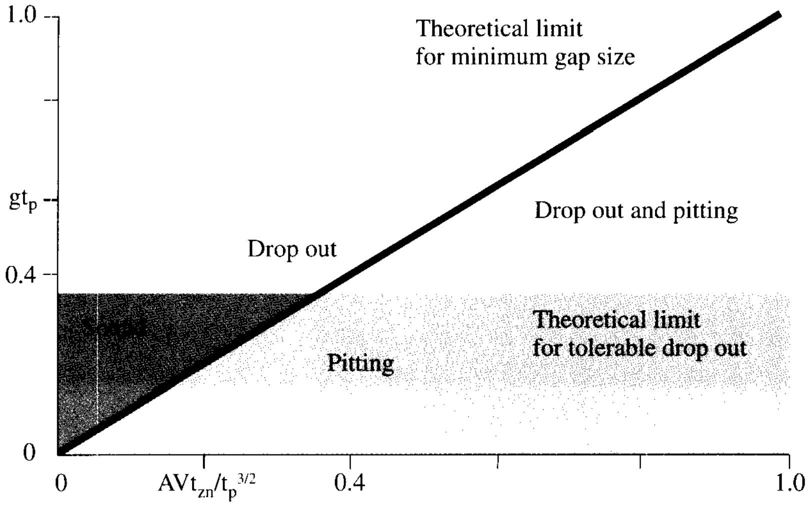


Figure 47. Operational diagram for the welding of zinc coated mild steel with a gap



Gas shroud and gas pressure

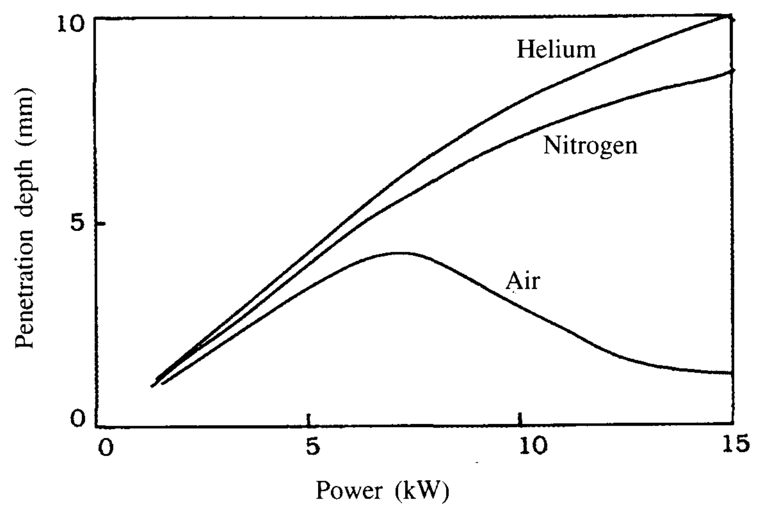
The gas shroud can affect the formation of plasma that may block the beam and thus the absorption of the beam into the workpiece. The formation of plasma is thought to occur through the reaction of the hot metal vapours from the keyhole with the shroud gas. It is unlikely, in view of the fast emission of vapour from the keyhole, that the shroud gas enters the keyhole. The plasma formed above the keyhole with the shroud gas will be absorbing to an extent determined by the temperature and the ionization potential of the gases involved. Table 7 lists the ionization potential of the gases often encountered in laser processing.

Table 7. Operational diagram for the welding of zinc coated mild steel with a gap

Material	*First ionizaiton potential, eV*	*Material*	*First ionization potential, eV*
Helium	24.46	Aluminium	5.96
Argon	15.68	Chromium	6.74
Neon	15.54	Nickel	7.61
Carbon dioxide	14.41	Iron	7.83
Water vapour	12.56	Magnesium	7.61
Oxygen	12.50	Manganese	7.41

The plasma-blocking effect will be less for those gases having a high ionization potential. Thus helium is favoured, in spite of its price, as the top shroud gas in laser welding. The shroud underneath the weld would be of a cheaper gas such as argon, N or CO. The difference in penetration can be significant as shown in figure 48. The plasma blocking is higher with higher powers. Alexander and Steen's results, shown in figure 49, give this data a new slant [30]. At slow speeds there is an advantage for helium but at high speeds there is an advantage for argon. The explanation is that the plasma is both good and bad in aiding absorption. If the plasma is near the workpiece surface or in the keyhole it is beneficial (as in Alexander and Steen's high-speed results). If, however, it is allowed to become thick or leave the surface, its effect is to block or disperse the beam. This effect of speed on the preferred gas compositor is also noted by Seaman [26]. Because of this plasma effect it is usual to weld with a side blown jet to help blow the plasma away.

Figure 48. Variation in penetration with shroud gas composition and laser power (results from RIM, BRITE 1339, 1991)



If the shroud gas is slightly reactive with the weld metal then a thin film of, say, oxide may form which will enhance the optical coupling. The work of Jorgensen [31] shows greater penetration when the shroud gas contained 10% oxygen (see figure 50). This may, of course, be unacceptable for some welds but is worth noting.

Figure 49. Penetration vs speed for helium and argon shroud gases [30]

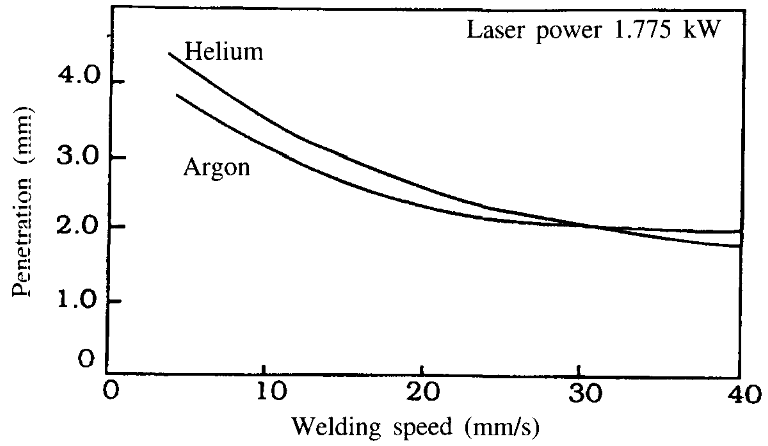
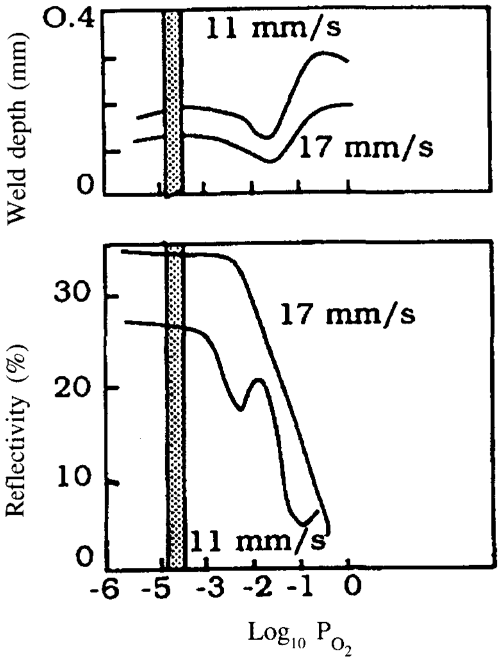


Figure 50. Weld depth as a function of partial pressure of oxygen, related to reflectivity (after 33)



$\mathrm{Log}_{10}\ P_{O_2}$

(P = pressure; O_2 is oxygen)

Effect of shroud design

The shroud design must give total coverage of the melt and the reactive hot region of the weld. It must do so without having flow rates that may cause waves on the weld pool. As just noted, in welding, a side jet is often added to blow the plasma away. In the case of welding zinc coated steel, the side jet may blow backward along the new weldment in which case the zinc vapour will condense on the weldment and so enhance the corrosion protection [32]. The side jet can also be used to feed powder filler into the weld. For high-speed welds, the shroud will need to have a trailing section. An interesting design invented by the Welding Institute [33] was a plasma disruption jet. It is illustrated in figure 51. The concept is that if the fine 45° jet is correctly located it will blow the plasma back into the keyhole and hence enhance the absorption. The welding performance is shown in figure 52. The main benefits are for thicker section welding. The weld fusion zone is altered to be more nearly parallel and the "nailhead" can be eliminated by this process.

Figure 51. The design of a plasma disruption jet with trailing shroud [33]

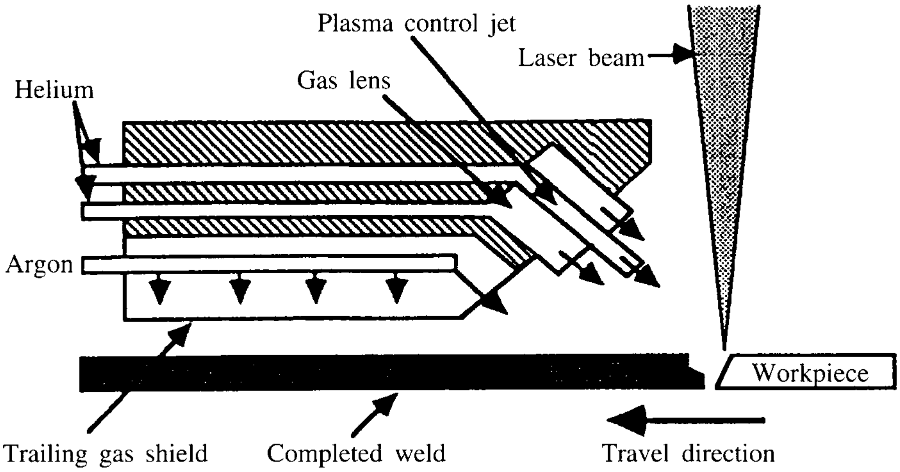
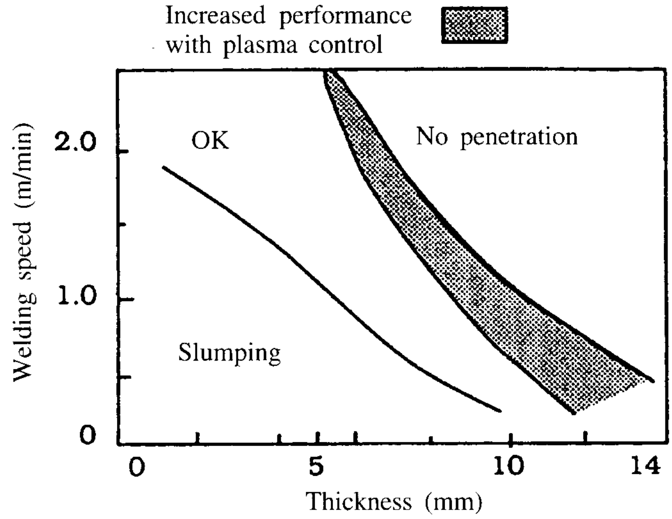


Figure 52. The effect of a plasma control jet for a 6 kW laser welding 18.8 stainless steel



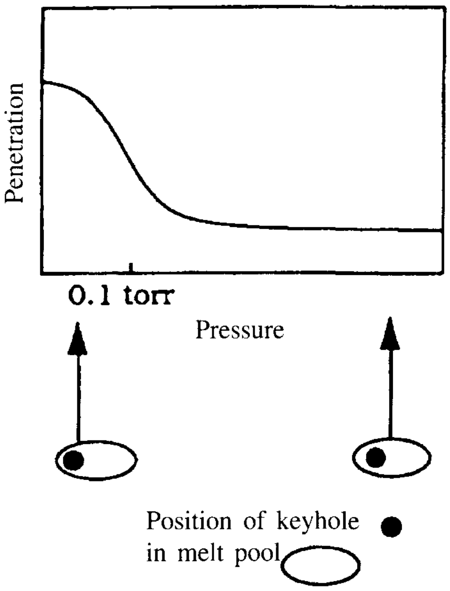
Effect of gas pressure — as shroud velocity and environment

The nozzle pressure affects the gas flow rate and hence the ability of the gas either to blow the plasma away or correctly protect the weld. There is a minimum flow rate for adequate protection and also one for the removal of the plasma. There is a maximum rate above which the weld pool flow is affected and the melt pool ruffled, causing a poor bead.

Variation in environmental pressure has a dramatic effect on penetration, particularly at very low pressures. The results are shown schematically in figure 53 [14]. This means that the penetration of the laser and the electron beam are not too dissimilar. The EB is by necessity working in a high vacuum and hence enjoys the high penetration. There are two theories as to why this increase in penetration occurs. The first is that the lower pressure reduces the plasma density and hence the plasma is no longer blocking the beam. The second is that at the lower pressures, the boiling point is reduced in a manner predicted by the Clapeyron-Clausius equation [34].

$$dp/dT = \Delta H/T\Delta V \qquad (14)$$

Figure 53. Relationship between penetration and pressure for electron beams and lasers



Since the change in volume with the change in phase, ΔV, is negligible with melting as opposed to boiling there is not a similar effect on the melting point. The melting point and boiling points become closer together at the lower pressures hence the wall thickness of the keyhole will be thinner. A thinner liquid wall is easier to maintain and hence the keyhole is more easily stabilized. It is this stability that allows greater penetration. Arata made a film illustrating the reduced plasma: this also shows the keyhole moving forward as illustrated in figure 53. Separating these two theories is very difficult and will test people's imagination for some time yet.

Effect of material properties

The main material problems with laser welding, in common with most welding methods, are crack sensitivity, porosity, HAZ-embrittlement and poor absorption of radiation. For welds of dissimilar metals there is the additional problem of the possible formation of brittle intermetallics.

Crack sensitivity refers to centreline cracking, hot cracking or liquation cracking. It is due to the shrinkage and stress building up before the weld is fully solidified and strong enough to take the stress. It is thus most likely in metal alloys having a wide temperature range over which solidification occurs e.g. those with high C, S, P contents. Some alloys listed in order of crack sensitivity are given in table 8. Cracking can be reduced or eliminated by using a high pulse rate, adding a filler or using preheat.

Table 8. Crack sensitivity rating of certain metals [17]

		Composition								
Material	*Crack intensity*	*C*	*Si*	*Mn*	*Cu*	*Fe*	*Ni*	*Cr*	*Mo*	*Other*
Hastelloy B2	High	0.12	1.0	1.0		4-6	Rem	1.0	26	V, Co
Hastelloy C4		0.12	1.0	1.0		4.5-7	Rem	15	16	V, Co
Inconel 600		0.08	0.25	0.5	0.25	8.0	Rem	15.5	—	Al
Inconel 718		<0.08	—	—	0.15	18.5	52.5	19	3	Nb,Ti,Al
316 Stainless		0.08	1.5-3	2.0		Rem	19-22	23-26		
310 Stainless		0.25	1.5	2.0		Rem	19-22	24-26		
Hastelloy X		0.15				15.8	49	22	9	Co,W,Al
330 Stainless		0.08	0.7-1.5	2.0	1.0	Rem	34-37	17-20		
Aluminium	Low			0.6	4.4	Mg	Al			
2024						1.5	Rem			

Porosity often results when welding material subject to volatilization such as brass, zinc coated steel or magnesium alloys. It may also be caused by a chemical reaction in the melt pool as with welding rimming steel or melting with inadequate shrouding such metals as SG cast iron. It may also be present in metals having a high dissolved gas content such as some aluminium alloys. Control may be achieved with proper attention to the shrouding system, adding a "killing" agent such as aluminium to rimming steel or controlling the pulse rate or spot size.

The main advantages of laser welding are that it is a process having a very low hydrogen potential (which may cause hydrogen embrittlement); it gives less tendency to liquation cracking due to the reduced time for segregation and it causes less distortion due to the smaller pool size. Table 9 is a summary of some of the laser welding characteristics for the main alloy systems.

The welding of dissimilar metals is only possible for certain combinations as shown in table 10. Due to the small fusion zone and relatively rapid solidification of the weld there is a greater range of welds possible with the laser than with slower processes. There is also a greater tendency to form metastable solid solutions.

Table 9. Laser welding characteristics for different alloy systems

Alloy	*Notes*
Al Alloys	Problems with: (a) reflectivity — requires at least 1 kW, (b) porosity, (c) excessive fluidity — leads to drop out
Steels	OK
Heat Resistant Alloys: e.g. Inco 718, Jetehet M152, Hastelloy	OK but (a) weld is more brittle, (b) segregation problems, (c) cracking
Ti Alloys	Better than slower processes due to less grain growth Iridium
Alloys	Problem with hot cracking

Table 10. Laser weldability of dissimilar metal combinations [17]

	W	*Ta*	*Mo*	*Cr*	*Co*	*Ti*	*Be*	*Fe*	*Pt*	*Ni*	*Pd*	*Cu*	*Au*	*Ag*	*Mg*	*Al*	*Zn*	*Cd*	*Pb*	*Sn*
W																				
Ta	E																			
Mo	E	E																		
Cr	E	P	E																	
Co	F	P	F	G																
Ti	F	E	E	G	F															
Be	P	P	P	P	F	P														
Fe	F	F	G	E	E	F	F													
Pt	G	F	G	G	E	F	P	G												
Ni	F	G	F	G	E	F	F	G	E											
Pd	F	G	G	G	E	F	F	G	E	E										
Cu	P	P	P	P	F	F	F	F	E	E	E									
Au	—	—	P	F	P	F	F	F	E	E	E	E								
Ag	P	P	P	P	P	F	P	P	F	P	E	F	E							
Mg	P	—	P	P	P	P	P	P	P	P	P	F	F	F						
Al	P	P	P	P	F	F	P	F	P	F	P	F	F	F	F					
Zn	P	—	P	P	F	P	P	F	P	F	F	G	F	G	P	F				
Cd	—	—	—	P	P	P	—	P	F	F	F	P	F	G	E	P	P			
Pb	P	—	P	P	P	P	—	P	P	P	P	P	P	P	P	P	P	P		
Sn	P	P	P	P	P	P	P	P	P	P	F	P	F	F	P	P	P	P	F	

E Excellent
G Good
F Fair
P Poor

Gravity

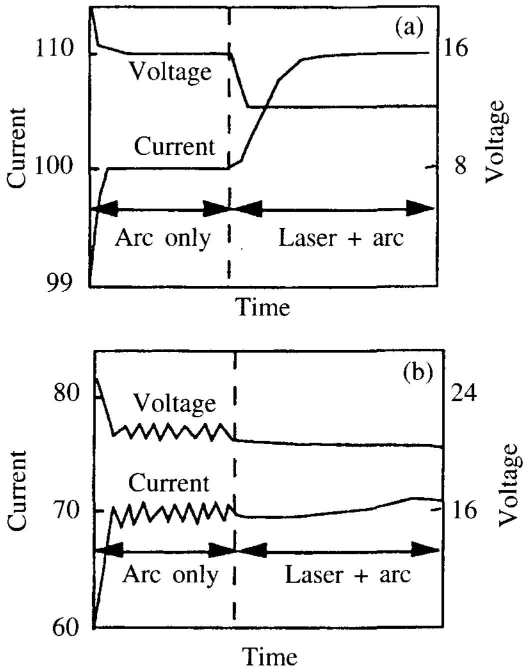
Duley's experiments [35] in the NASA KC-135 microgravity aircraft using a 25 W cw CO_2 laser to "weld" PMMA (acrylic), polypropylene and polythene showed that for hypo- and hypergravity there was no change in the penetration depth but there may be a reduction in the sheer strength with reduced gravity. In these experiments there was a notable change in the wave structure on the trailing edge of the keyhole. There were larger and faster waves with higher gravity.

4.2 Process variations

Arc-augmented laser welding

It has been found that the arc from a TIG torch mounted close to the laser beam interaction point will automatically lock onto the laser generated hot spot [36]. Eboo found that the temperature only had to be around 300 °C above the surrounding temperature for this to happen [37]. The effect is either to stabilize an arc that is unstable due to its traverse speed or to reduce the resistance of an arc that is stable (see figure 54). The locking only happens for arcs with a low current and therefore slow cathode jet; that is, for currents less than 80 A. The beauty of this process is that the arc is on the same side of the workpiece as the laser. The process allows a doubling of the welding speed for a modest increase in the capital cost. It does not enhance the penetration to any great extent. At very high speeds there may be some problems with the weld bead profile since the weld pool is larger than with the laser alone. The increased pool size is however not as much as expected. Eboo showed by mathematical modelling the heat flow from the laser and the arc separately that the combined effect of the two was not the expected addition of two effects [35, 36]. His results fitted the data only when the arc radius was decreased by the hot core from the laser event, shown in figure 55. Thus arc-augmented laser welding results in the arc rooting in the same location as the laser and doing so with a finer radius than usual—a true form of adding energy to the laser event. If augmenting the laser is not appealing, then the process has another advantage in that it is a method for guiding an arc.

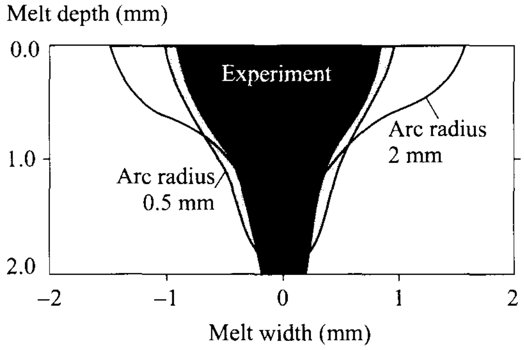
Figure 54. The coupling of an arc and a laser beam results in (a) the reduced resistance of the arc or (b) the stabilization of the arc for high-speed welding [36]



Twin beam laser welding

If two laser beams are used simultaneously then there is the possibility of controlling the weld pool geometry and hence the weld bead shape. Arata using two electron beams demonstrated that the keyhole could be stabilized causing fewer waves on the weld pool and giving a better penetration and bead shape [14]. O'Neill using both an

Figure 55. Comparison of experiment with theory for various theoretical arc radii during arc-augmented laser welding [37]



excimer and CO2 beams simultaneously, showed that improved coupling for the welding of high reflectivity materials such as aluminium or copper could be attained this way [38]. The enhanced coupling was considered principally due to altering the reflectivity by surface rippling caused by the excimer blast (35 MW for 20 ns at 100 Hz) with a secondary effect coming from coupling through the excimer generated plasma.

Walking beams

Arata suggested a method for avoiding the plasma by allowing the beam to dwell on a spot just long enough for the plasma to start forming and then to kick the beam forward to dwell on the next spot [14]. He showed an improved penetration capability. The process is more efficient than pulsed welding.

Applications

The laser has a certain thickness range over which it competes as shown in figure 56. Within this range if the productivity of the laser can be used then it will usually compete successfully as in the costed example below.

Some current welding applications:

transmission systems for cars—taking advantage of the low distortion and the possibility of focusing near potentially magnetic material

hermetically sealing electronic capsules

the end plate on a piston assembly for a car while a nylon washer is nearby

transformer laminates to reduce hum—smaller weld zone reduces eddy losses

bimetallic saw blades

stamped mufflers

cooker tops

car doors, floor panels (laser seam welding gives greater stiffness compared with spot welding and hence could lead to quieter cars)

flare welding of thick pipes

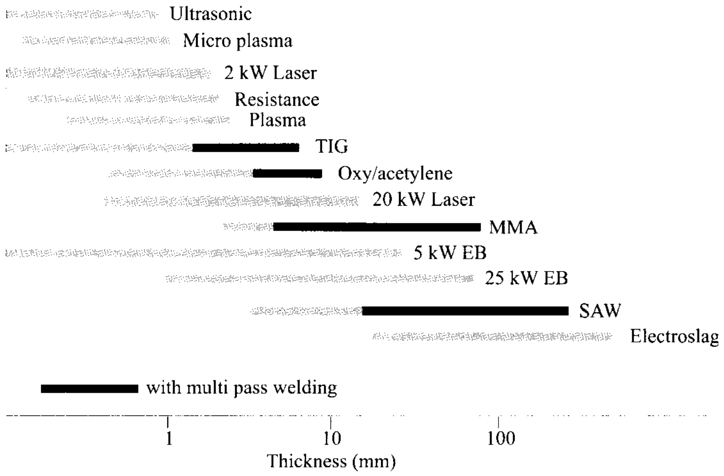
complex shapes prior to pressing [39]

repair of nuclear boiler tubes from the inside (there were nine internal welding units working in Japan in 1991) [39].

Laser soldering is fast becoming a major process in the electronics industry.

The applications are too numerous to list. Roessler [40] gives a useful review of applications in the car industry.

Figure 56. Comparison of operating range for different welding processes



4.3 Costed example

The cost of processing is made up of capital and operating elements. The relative capital cost of a laser facility is listed in table 11. If, for the sake of this example, the capital is costed as an operating cost at 10% per annum for 1,800 hours per year we can then compare the approximate cost of a metre weld in 3 mm mild steel made by Manual Metal Arc (MMA) or laser as shown in table 12. The actual numbers are debatable but the difference is striking—it turns upon keeping the laser working. The capital depreciation is a fairly sensitive figure to the fraction of the year that the equipment is working. Therefore much of this work is done by job-shops or in plants with a need for all-year operation. A similar conclusion is drawn by the cost analysis of Fiat and Comau [41].

Table 11. Relative capital cost of a laser facility

Process	*Capital cost in relative units (MMA = 1)*
Manual Metal Arc (MMA)	1
Submerged Arc (SAW)	10
Electroslag	20+
TIG	2
Microplasma	20+
MIG	2
Resistance (Butt)	0.5-10
Oxy/fuel	0.2
Electron Beam (EB)	10 450
Friction	4-100
Laser	100+

Table 12. Comparison of the welding costs for a metre of weld by manual metal arc and laser

	Manual Metal Arc (MMA)	
Capital Cost	300A set – £850	2kW CO_2 laser plus workstation £150,000
Consumables	1 m of 4mm flux coated mild steel rod	gases at £4ftr
Welding speed	1 mm/s	10 mm/s
Process time for 1m of weld	1000 s	100 s
	£	£
Capital depreciation at 10 %/yr for 1,800 h/yr	0.013	0.23

Table 12 *(continued)*

	Manual Metal Arc (MMA)	
Consumables: 1 m of 4 mm rod—£4/h gases	0.5	0.11
Labour £20/h MMA; £15/h laser	5.50	0.41
Power at £0.06/kW/h at 4 kW—MMA and 10 kW laser	0.066	0.016
Clean up time at 40 % arc time	2.20	—
Total	£8.28	0.77

As a general rule:

"A laser working for one shift per day is just paying for itself; if working for two shifts per day, it is distinctly profitable; if it is working three shifts per day you will probably find the owner in the Bahamas or some such place."

An interesting thought with which to finish this chapter!

5

Laser drilling

Doctor W. de Rossi

Laser drilling can be carried out on a number of materials. It is particularly useful when the holes to be drilled are very small, are in very hard materials or, by contrast, in very fragile substances such as ceramic substrates for printed circuits used in microelectronics.

Some examples of laser drilling include:

cooling holes into nickel base alloy turbine components of aircraft engine; these holes are 57° tilted 600 μm diameter into 1.6 mm Hastelloy X sheet [47]

drilling lubrication and air-bleed holes in automotive components

holes 9.5 mm deep and 1.5 mm in diameter drilled into a curved surface at an angle of 35°. Three of these holes are needed in transmission internal gear components made of a hot-forged, powder-metal alloy with a Rockwell C hardness of 60 [42]

0.2 mm diameter bleeder holes in fuel pump covers

gas tank pressure-reducers with calibration orifice of 250 mm diameter [43]

stainless steel cups with holes 110 μm ± 5 μm diameter

Only a pulsed laser operation is used in laser drilling. When a very short pulse of laser light is focused on a small spot, any material will melt and/or vaporize almost instantly. The resultant gases and vapour pressures generated blow away vaporized and molten substances, leaving a hole in the material. Laser drilling is performed at power densities from 10^7 to 10^8 W/cm^2 and an operation time from 10^{-3} to 10^{-5} s. The diameter of a drilled hole is controlled by varying the amount of laser power and the degree of defocus of the lens. The maximum hole diameter is limited by energy per pulse and the wavelength of the laser, the focusing optics, the quality of the beam and the material itself determine the minimum hole diameter.

Although excimer and copper vapour lasers have been widely used for small hole drilling, solid-state Nd:YAG and Nd:glass are dominant in metal processing whereas CO_2 lasers maintain an advantage in most non-metal applications. A CO_2 laser produces a minimum hole diameter of about 70 μm in thin material sheets while the Nd:YAG laser can produce holes as small as 5 μm in thin foils. One of the early applications of solid-state lasers for drilling used a ruby laser for hole-making in clock jewels and diamond draw plates, while the CO_2 laser was used for perforating teats in baby's bottles. Today laser boring is commonly utilized whenever non-laser processes are expensive or not practical.

These non-laser processes comprise mechanical and electrophysical methods. The latter include EDM (electrodischarge machining), ECM (electrochemical machining) and ES (electrostream) drilling. While they produce clean, straight, accurate holes with minimal recast, no delamination and no cracking into the material, the cost can be very high in many applications. In these cases the laser drilling has proved to be an effective alternative. Although the quality of a hole drilled by laser is inferior by comparison with the other methods, it has proved to be adequate in many cases. Its high productivity can lead to dramatic economic benefits, mainly in the increase of effective labour. Laser drilling can also be justified whenever its unique advantages are significant. It is more advantageous than mechanical methods in the treatment of large-size complex-shape details, when working under different angles to its surface. Laser boring is especially employed in composite materials. It is also preferable when drilling high aspect ratio (depth/diameter) holes with diameters smaller than 0.25 mm.

The advantages of using lasers for drilling include:

no tool wear, breakage and overheating, the hardness of the workpiece is not critical

hard materials such as diamond and alumina can easily be drilled

low distortion, even in very fragile components

easy access to reach into complex geometry and at difficult entrance angles

ability to drill into curved surfaces or at low angles with no walk-off problems

high precision in diameter and circularity with very tight tolerances

high accuracy in positioning of laser drilled holes

a wide range of holes, diameters and depths can be selected and drilled instantly

absence of chips and burrs

diameters of hole sizes in the micron range

ease of automation

combined operations in a single set-up

ease of optical inspection

elimination of secondary operations

no need of expensive or hazardous consumables

high productivity (more than 10 holes/s) because of high duty cycles

aspect ratio up to 50:1

Frequently laser drilling involves a mechanism that removes material in liquid or vapour form, the ratio between them depending on the level of the power density. Higher intensity leads to a greater amount of material held in a vaporous state. In the extreme case, when a Q-switched laser is used, the liquid-vapour ratio is very small and a direct transformation from solid to vapour occurs in almost all the affected volume. However, most of the drilling process utilizes longer pulse duration where the liquid-vapour ratio is quite high. This method of drilling is more efficient and the almost instantaneous temperature rise plus the small amount of material that reaches the vaporization temperature causes nearly complete expulsion of the liquid material from the crater. This is a consequence of the high pressure caused by the expansion of the vapour in the central part of the affected area being much higher than the adhesion forces between the liquid phase and solid wall. The liquid material that is not expelled is removed by direct vaporization or remains as a smooth and thin coating (less than 50 μm) on the side wall of the hole. This material is commonly called recast. The recast has been melted and resolidified in such a short time that the hardened metal has a different structure than the parent material. Depending on the alloy, the recast is often quite hard and prone to develop microcracks induced by stresses during the solidification process. If the microcracks propagate into the parent material at the grain boundaries, the entire affected zone will be weakened. To reduce this problem, it is necessary to choose adequate laser parameters and decrease its average power in order to minimize heating of the surrounding parent material.

The explosive nature of the expulsion of the molten material causes tapering in the entrance side of the hole, with an uncontrollable but repeatable hole-to-hole diameter variation of ±10%. The best approach in controlling the quality of the drilled hole is to induce direct sublimation of the parent material by the use of very high intensity levels (10^8 W/cm^2). This leads to an ablation process with a reduced amount of molten material resulting in a better contour of the hole. Figure 57 shows a typical cross-section of a laser-drilled hole.

The formation of a vapour plasma layer also has a drawback in laser drilling. Its high absorption of laser radiation blinds the material from the trailing edge of the pulse reducing the efficiency of the process. The use of assist gas is a way of circumventing the problem and prevents the formation of debris and dross that tend to interrupt penetration.

Figure 57. Typical cross-section of a laser-drilled hole

The quality of laser-drilled holes is a function of complex interactions between a large number of variables such as:

- Material dependent variables
  - type of material
  - thickness of material
  - surface reflectivity
- Laser variables
  - wavelength
  - pulse energy
  - pulse duration
  - mode structure
  - pulse repetition rate
- Assist gas variables
  - type of gas
  - nozzle design
  - gas pressure
- Focusing lens variables
  - focal lens
  - focal position.

The complex nature of the interaction between the laser beam and the material means that a precision hole is very difficult in materials more than 100 μm thick. The best results are possible only with high-peak power lasers operating in a low-order transversal mode where the energy and the time pulselength can be continuously controlled preferably by the CNC control. The most important quality parameter criteria are: hole dimensions (diameter, tolerance and degree of parallelism); surfaces in the hole (thickness and structure of recast layer, oxidation); microcracks; deposits of splashes and bars.

Holes from 10 μm to 1.5 mm can be efficiently drilled with traditional laser drilling systems. Diameters larger than 1.5 mm demand a method of drilling similar to cutting. Holes with smaller diameters are possible but require more complex systems, where the wavelength is shortened to UV and/or an effective and accurate control of the depth of focus is maintained.

Holes with a depth in the order of 20 mm are possible in some alloys with systems that employ Nd:YAG lasers. This depth is increased to 25 mm when the Nd:glass laser is used. The maximum aspect ratio routinely obtained is in the order of 1:50. The degree of taper depends on many factors including the laser parameters, the material and the particular focusing system used. For depths smaller than 250 μm the taper can be neglected, for deeper holes, the typical laser-drilling taper is between 3° degrees and 20°.

One of the advantages of using lasers for drilling is the ability to make holes at small entrance angles with respect to the material surface. Although the volume of debris toward the lens decreases for smaller angles, other difficulties may appear. These include the decrease of power density on the surface of the material; another is the geometry of the optical focusing system that becomes more complex and renders difficult the use of a short focal lens and gas nozzles.

Non-metal drilling

Drilling non-metal material is somewhat different from drilling metals. In this case, the material plays a more important role and the laser characteristics must be more carefully matched to the specific material. The wavelength and the power density are the most critical factors as they determine the kind of interaction that takes place during the process. Hence evaporation, bond breaking or chemical degradation may drill non-metals, depending on the combination of material and laser parameters.

Laser parameters

The following are descriptions of how the quality of the hole varies according to the influences of laser parameters [44].

Pulse energy
The combination of pulse energy, time pulselength and focus diameter must be enough to reach the threshold of vaporization. Above this level, an increase of pulse energy leads to an increase of penetration and greater depth can be achieved. The formation of cratering on the top surface however is more evident with higher pulse energy.

Pulse duration
Again, this parameter is connected to the mechanism of material removal. Once the diameter of the hole is fixed, the energy and the pulselength determine the intensity upon the material. As an increase in the pulse energy can lead to a degradation of the hole quality, a decrease in pulse duration takes the intensity to a level beyond the threshold of vaporization improving the hole quality. The typical duration of laser drilling pulses is 0.4 to 2.0 ms, the choice being a compromise between efficiency and quality. Shorter laser pulses produce higher quality holes but with less efficiency, requiring more pulses to drill through. Pulses of 1.0 ms and more are more commonly used and give high removal of material whereas pulses shorter than 0.5 ms result in holes with less distortion and tapering.

Number of pulses
The number of pulses used to drill a hole can have a decisive influence on its quality. For holes with a high aspect ratio, for instance, a better result is obtained by reducing

pulse energy and increasing the number of pulses needed to perforate the material. On the other hand, low aspect ratio holes drilled with just one laser shot generally exhibit less taper.

Focal length of lens

Shorter focal lengths are used in drilling small diameter holes. As the depth of focus is directly proportional to the focal lengths, the thickness of the material being processed is limited by the focal length of the lens. To further increase the penetration depth with the same lens, it is necessary to increase the quality of the beam i.e. to decrease the value of the beam quality factor M^2. A beam with small M^2 can be focused in a smaller spot size over a longer depth of focus when compared with a beam with higher M^2. Hence in order to drill high aspect ratio holes with reduced taper, it is essential that the beam have a quality as close to one as possible.

Types of laser drilling

Three different ways in which laser drilling can be performed are described below.

Single pulse drilling

The breakdown produced by one laser pulse is known as single pulse drilling and is performed, as its name suggests, with just one laser pulse. The diameter range attainable is between 20 and 250 μm and the aspect ratio is from 2:1 to 6:1, the maximum being limited to the formation of slag, wall cave-in and uneven contour. The quality of the hole and the efficiency of the process depend almost exclusively on the beam characteristics, so frequently a fundamental mode laser is used in this type of drilling. Low repetition rate Nd:YAG or Nd:glass are the most common lasers employed for single pulse drilling. With energy up to 10 J and an intensity of 50 MW/cm^2, a depth of 1.5 mm can be obtained.

Percussion mode drilling

Secondly, the breakdown produced by a series of succeeding laser pulses is known as percussion mode drilling. This method requires a series of laser pulses delivered to the same area. The diameter and depth attainable depends on the energy and the number of pulses. Multi-pulse drilling results in holes with improved quality when compared to a single pulse and makes possible deeper holes with higher aspect ratio. The holes are generally less tapered and better defined. Consequently, for drilling a deep hole, it is more efficient to use a series of high repetition rate lasers with low energy pulses. In percussion mode drilling, the aspect ratio can be improved to more than 50:1, with diameters from a few microns up to 1.0 mm and a depth of 15 mm.

Trepanning mode drilling

In this method, the drilled hole is produced according to a given contour. This is called trepanning mode drilling. The beam is moved in relation to the workpiece, overlapping drilling pulses in a continuous way. Two methods for trepanning are possible, one where the beam is moved according to a desired contour while the workpiece is fixed; and the other where the beam is fixed and the workpiece is moved under the CNC control (also called cutting mode). One way of moving the beam is by using an off-centre rotating lens or a scanner. Larger diameter holes with good quality can be attained by rotating the beam along the hole contour. The trepanning mode drilling is generally used to drill large holes with diameters greater than 0.5 mm and requires a laser with a high repetition rate and a good spatial mode control. Frequently a gas jet is used to assist in the removal of molten metal from the cut zone, especially in thick materials. The pressure of the gas prevents the molten metal from flowing into and refilling the area cut by the laser. This method offers the following three important advantages over percussion drilling [45]: an improved hole diameter accuracy and repeatability; an improved hole straightness; and a thinner recast layer on the hole side walls. In trepanning drilling, the formation of craters may be minimized by first moving the beam to the centre of the hole and allowing it to burn through the part. The beam is further moved, cutting a kerf to the edge of the hole.

Laser systems for drilling

ND:glass laser drilling

The Nd:YAG is the more common laser used for drilling in applications requiring high pulse repetition rates. However, in processes where high productivity is not the main objective, Nd:glass lasers have a demonstrated ability to drill superior quality holes at large aspect ratios. This ability comes from the temporal behaviour of its output pulse. While the overall pulse shape is determined by the power supply, the spectroscopic properties of the laser medium gain and the laser cavity determine the manner in which the output occurs within the envelope pulse. In the case of Nd:glass, the temporal aspect of the output power is more highly spiked than in the case of Nd:YAG and the overall laser pulse behaves as a collection of much higher peak power laser pulses in the microsecond scale. This characteristic is very important when drilling because the higher peak power pulses vaporize a higher amount of the material. It is thus more effective in blowing away molten material, leaving a hole almost free of recast metal. Although the wavelength of the two lasers is almost the same, one pulse of the Nd:glass laser can penetrate more deeply than a pulse of the Nd:YAG laser with the same energy, spatial profile and pulselength. Apart from the better hole quality, reliability and cost are two other aspects favouring Nd:glass lasers over Nd:YAG. The Nd:glass system is more simple and consequently cheaper owing to lower maintenance costs. The possibility of making quite long rods allows very high energies in one laser pulse, making possible holes of grater thickness with just one single shot laser pulse. Typically the Nd:glass laser is used to produce holes in the range of 0.5 mm to 100 μm with a diameter tolerance of ± 5 μm and productivity close to 1 hole/s.

Short pulse Nd:YAG drilling

A line of lamp-pumped Nd:YAG lasers has recently been developed specifically to improve the quality and efficiency of precision drilling processes [46]. Its enhanced ability to drill thin metal sheets is due to the temporal profile of the laser pulse. The total pulse length is considerably shorter than that of conventional lasers, in the range of 50 μs, with a very fast rise time and a concentration of energy in the beginning of the pulse. Such a combination, apart from an improvement in the cosmetic quality of the hole, minimizes the thickness of the recast layer and the occurrence of microcracks.

The pure Q-switched Nd:YAG laser with a pulsewidth in the range of 15 ns and a pulse energy of 150 mJ has also been used to percussion drill [47] turbine components of aircraft engines. The lesser energy input and the short duration of the laser pulse minimize heating of the workpiece even in materials with high heat conduction.

Slab laser drilling

The Nd:YAG slab laser system is a new technology that has been used successfully in drilling processes. Its advantage comes from the better quality of the laser beam that can reach close to diffraction limit even at a high level of average power. This system has demonstrated improvements in drilling taper and aspect ratios. Angles of drilling taper can be as low as 1.5° and an aspect ratio of 60 has been obtained. The complexity of a slab laser system makes its cost more elevated than a conventional rod laser assemblage and therefore is justified only when quality is of prime importance.

Excimer drilling

Excimer lasers produce short high average, peak power pulses in the UV. Because of these characteristics, the mechanism of drilling (or machining) is almost entirely ablation, where material is removed through chemical bond breaking. In this case, the pulses vaporize surface layers of material selectively without the degree of melting and charring that is produced with Nd:YAG or CO_2 lasers, resulting in a high precision material removal with much better edge quality and definition. The HAZ and bulk material distortion are minimal. The short wavelength of the excimer allows the production of holes of minimum diameters in the range of a few micron, giving much higher hole densities. With excimers, patterns are better defined by mask-imaging rather than focused-spot translation.

One of the disadvantages of UV radiation is its strong absorption in most metals. This leads to a typical penetration depth of less than 0.5 μm, limiting the depth of material removal by a single laser shot. This fact, the low repetition rate and the high-pulse energy of the excimer laser favours ablations over large areas or small shallow holes but is not suitable for drilling high aspect ratio holes. Its wavelength is therefore better suited to processing non-metal materials such as polymers amd ceramics.

Copper vapour laser drilling

The copper vapour laser (CVL) operates in a range of parameters localized between the high-power infra-red Nd:YAG and CO_2 lasers and the UV excimer laser. Its high power in the visible spectrum combined with excellent beam quality allows some drilling processes to be more efficiently performed by the CVL. The absorption depth of visible light is usually longer than that of the UV, in the range of 10 μm. The ability to remove a higher amount of material per shot associated with the high repetition rate gives the CVL a high productivity in either obtaining a high density of drilled holes or producing single deep holes. Like the excimer laser, the CVL can be focused in a very small spot size, being capable of drilling holes of 10 μm diameter with an aspect ratio of 10, the HAZ is also almost negligible ($\sim$ 0.5 μm) and the dross is minimal.

The use of the CVL is particularly advantageous when processing difficult materials like ceramic, copper and aluminium. It is also used routinely in a wide range of materials like titanium, stainless steel, mild steel, tungsten, gold, zirconium, kapton, silicon, diamond and glass fibre composites. Typical drilling applications include trepanning of large diameter holes, in the range of 100 μm, with tight tolerances in diameter and circularity. Although the CVL can process in thicknesses of up to 5 mm, it is more effective with sheets thinner than 0.5 mm.

It has been shown that the mechanism of material removal using CVL depends on the thermal properties of the material [48]. For material with high thermal diffusivity and low melting point, the formation of a thick melt layer causes a more significant melt expulsion by the vapour recoil force than by evaporation. For material with lower thermal diffusivity and higher melting point such as carbon steel, the melt layer is thinner and evaporation is a more significant mechanism of material removal.

Laser drilling with ultrafast pulses

The next-generation laser machine tool is based upon diode pumped solid-state laser technology capable of delivering several kW of average power running either continuously or pulsed with a beam of high quality spatial profile. With the aid of fibre-optic beam delivery and a beam clean-up, this brand new system is not yet commercial, but in the laboratory has shown high accuracy on the micron scale. As is known, in the picosecond range of pulse width, the threshold of laser induced breakdown (LIB) is well-defined and the fluence (i.e. density of energy) needed to initiate breakdown is much lower than with pulses of longer duration. This high accuracy in predicting the LIB has been used to generate holes with very small diameters. By controlling the input intensity profile, a situation can be obtained where only a small portion of the central part of the focused beam is above the ablation threshold. The ultrafast pulse duration prevents a spreading of the affected zone, so a drilled hole with a diameter smaller than the spot size is possible. Therefore, with this technology the minimum diameter possible is no longer limited by the focusing optics or the wavelength of the laser. X. Lin et al. obtained holes in diamond with a diameter of less than 1 μm using a focused spot size of 5 μm and 0.3 μm holes in silver films using 200 fs Ti-sapphire laser pulses focused to a 3 μm diameter [49].

CO_2 laser drilling

The characteristics of the CO_2 laser are such that this laser is better suited to drill plastic, ceramics or glass materials. Its 10.6 μm wavelength is absorbed well by these materials and the laser is used in pulsed mode generally with a pulse length of 200 μs. These materials are poor heat conductors, amorphous and some are brittle. Such physical characteristics may complicate the laser process; cracking, microcracking and glassing may arise mainly in ceramic processing. The interaction of the laser beam with solid ceramics is of a very complex nature because these materials are formed by two different components: the powered alumina and a binding agent that is an organic polymer with a low temperature of evaporation. The absorption of laser radiation causes microexplosions that expel material in the form of vapour mixed with particles. These fumes are very detrimental to the subsequent part of the beam for the following reasons: the ejected particles scatter the radiation while the vapour refracts and defocuses the beam.

6 Marking and scribing

Doctor W. de Rossi

Laser marking is a less spectacular application than welding or cutting but it is by far the largest application of industrial lasers. This method was introduced in the production line in the late 1960s and was used for scribing of ceramic substrates for electronic components.

Some examples of laser engraving applications are:

marking of bar code and alphanumeric data on vehicle identification number tags

marking parts by burning off paint previously baked on

ceramic component marking

engraving of ITO conductive coatings layers [50]

marking very narrow line widths for indicator lines in pressure gauges

The principle involves heating the irradiated area in order to produce a change in the surface of the material that is visible to the naked eye. The process can be performed either by material ablation or photochemically-induced colour changes. In the photochemically-induced process, a permanent colour change is the simplest, caused by simply bringing the material to its molten temperature. Depending on the material, the colour contrast can be sufficiently readable to constitute a finished product. If not, additional power can be delivered to engrave the work surface. In general, this results in enough contrast for easy readability especially in light-coloured plastics. For darker colours, it is sometimes necessary to fill the engraving with ink of a contrasting colour. Two and three colour marking is also possible using combinations of precoating and backlighting techniques. In the material ablation process or photoablation, the laser beam is focused onto a small spot on the work surface to produce a fluence that is above the ablation threshold of the material to be ablated. In this case, almost all the material is removed in the vapour state and the ratio of liquid material removed to vapour material removed is minimal. The absence of a remelted layer in the affected zone leads to a very high-resolution pattern. By the use of these two techniques, almost any material can be engraved with the highest flexibility.

Nd:YAG lasers are best for marking metals and dark plastics, CO_2 systems mark ceramics and transparent materials whereas excimer lasers are widely used for marking organic materials. Pulsed CO_2 lasers are common for stencil or mask applications where the same information is put on a large number of items. The Nd:YAG laser is more common when successive items are labelled differently. Although the process requires a high peak-power pulse, the most common systems use low average power lasers with power ranging from 5 to 150 W. A 150 W CO_2 laser, for instance, can scribe 0.6 alumina substrate at 200 mm/s, and 1 mm substrates at 100 mm/s. More sophisticated systems employing Q-switched Nd:YAG lasers allow speeds as high as 2,000 mm/s. Engraving can be from just a surface mark to depths of 1.2 mm. The ability of these lasers to maintain high peak power despite the repetition rate assures constant scribe depths over a wide speed variation. The combination of operating software and computer speed allows a wide variety of orientation, fonts and graphics capability to generate intricate marking design. The use of systems with fully programmable laser power allows versatility and a notable increase in productivity. All this is accompanied by decreases in system size and price. The non-contact, low-heat input nature of laser marking allows it to be used for delicate materials where alternative methods are difficult.

Laser marking is preferable to alternative processes when high marking throughput is required, when mechanical stresses on the objects need to be avoided or when a material is particularly hard or valuable. The fields of application include the automobile industry, aeronautics, consumer goods, electronics and tools.

Among the main three systems employed for marking, the Nd:YAG laser is the most popular. This is due to its flexibility: it can be employed in a wide variety of operation modes and output characteristics, giving to the Nd:YAG system a wide spectrum of laser-material interaction. This versatility allows laser marking of characters, bar codes, logos and graphics with permanent, high-quality marks at high speed and high resolution. Another system being used with success is the UV waveguide laser operating in the far-UV. Despite its modest energy, it is suited to applications involving photoablation with focused beams. These lasers are small and air-cooled, their emission shows near-diffraction-limited divergence and the beam aperture is small. As a consequence, the output can be easily focused to very small spot size (in the 1 to 50 micron range) giving a high level of fluence over the substrate.

Direct write patterning

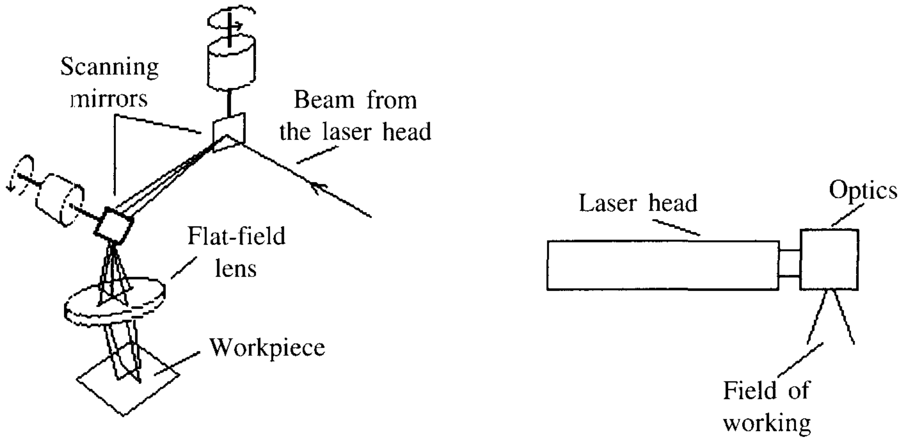
Direct write patterning or beam-steered laser marking requires focusing the laser light onto a small spot on the work surface to produce fluence that is above the ablation threshold of the material to be ablated. The surface is then moved relative to the beam to form arrays of holes, channels, marks or other features. This can be done in dot matrix mode using raster scan (i.e. a system where the image is formed by lines) to form alphanumeric characters or in engrave mode with a vector technique that scribes alphanumeric characters or other figures with a lower speed but excellent mark contrast.

Ablation of organic materials typically requires a surface fluence of 0.02 to 1 J/cm^2; whereas ceramic and metal surfaces often require fluence of 1 to 20 J/cm^2. On small spatial scales, the total amount of laser energy required to produce ablation is also small. For example, 1 nanojoule of laser energy in a 1-μ spot is often adequate for polymer ablation. A high-energy laser is not needed and can not be efficiently utilized for direct-write ablation with small focal spots. A UV laser of tens of μJ can be efficiently focused to spots approximately 10 μ in diameter [51]. The corresponding fluence in these small focal spots is tens of J/cm^2, more than adequate for ablation of almost any UV-absorbing material.

Figure 58 is a simplified illustration of the operation of a typical, modern beam-steered laser marking system. The collimated laser beam is positioned in X and Y by means of two computer-controlled galvanometer-driven flat mirrors and focused on the workpiece by a flat-field lens assembly. In this system, neither the workpiece nor the optics is moved during the marking process. In order to develop enough power at the workpiece, it is usually necessary to focus the laser spot down to 0.25 mm or smaller. Typically, the combination of a 75 mm focal length lens and a 50 W laser will produce a 75-μ spot with a marking power of 55 MW/cm^2 and a total marking field 75 mm in diameter [52].

All operating parameters are under computer control so that the operator can generate the desired results by means of programming. The peak output power and the resulting work surface temperature are determined by the selection of pulse repetition rate. The beam travel speed is determined by the rate of change of signals to the

Figure 58. Typical beam-steered laser marking system



steering mechanism. The travel rate in conjunction with the pulse rate determines the degree of penetration and actual work performed on the surface. Modern scanners permit very high accuracy and throughput, with beam focus being located with a precision of one part in one thousand.

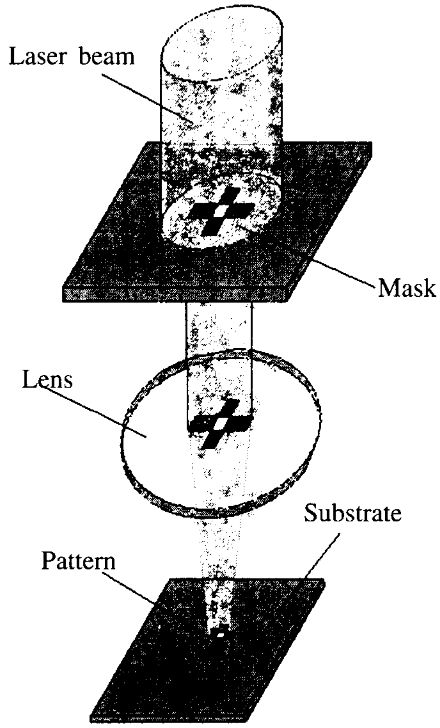
Imaging

Near-field imaging involves the use of a mask to project a pattern of laser light onto a part. The features contained in the pattern are then etched into the workpiece. High-resolution patterns containing many features can be generated simultaneously over a relatively large area. In many cases, special corrected lenses are actually used in place of the focusing lens to retain image resolution over these large areas. Furthermore, using conventional imaging techniques, the size of the pattern is limited by the size and shape of the laser beam and by the demagnification required to achieve proper material removal. Advanced imaging techniques allow processing that is independent of the demagnified laser beam area. The beam-utilization factor (BUF) is the fundamental measure of how well an imaging process is optimized for high-duty-cycle operation. Unlike Gaussian-beam use, near-field imaging transfers flat-top profile to uniform ablation in the imaging plane. Optical losses are also an important factor in BUF and in general it is preferable to minimize the total number of elements.

Imaging is the primary technique used to deliver excimer beams. Imaging techniques are preferred for excimer processing because of the high divergence and poor far-field quality of the beam. In addition, optimum processing using excimer laser light requires lower power densities than those found at the focal point of a lens. Lower power density means correspondingly larger processing areas in contrast to IR laser focal point processing. High-power excimer lasers can be application-flexible with low BUF or they can be application-inflexible with high BUF. The optical tooling required for high-efficiency processing is usually quite involved. This is why most flexible processing systems use the beam delivery shown in figure 59 and waste laser power at the mask. The challenge is to find techniques that allow both flexibility and efficiency.

Parallel processing and premask beam conditioning are among the techniques available to increase production rates or reduce part costs. These techniques involve the geometrically splitting or reshaping of the beam in order to increase the BUF. Simultaneous processing of two or more parts can be achieved by breaking the single beam into two or more sections and irradiating each part separately. Premask conditioning involves the use of beam homogenizers to increase the usable fraction of the beam (BUF) or condenser optics which help match the laser beam size to the area of the mask.

Figure 59. Near-field imaging system



In general, the advantages of laser marking include:

- the process is non-contact so no special clamping or fixturing is necessary
- marking is possible in very fragile parts
- it can be applied on smooth and rough workpieces
- the image does not wear off in normal use, it is resistant to abrasion and burr-free
- marking speed is high, so that throughput is optimized
- it is virtually immune to subsequent cleaning and finishing processes
- its flexibility allows free programming of design permitting easy changes in the pattern
- it has the ability to mark difficult-to-reach parts
- it has high legibility and low distortion
- it has operating simplicity
- it eliminates the use of chlorofluorocarbons because there is no ink to clean
- the operating costs are low

The disadvantages include relatively high capital costs and contrast that is dependent on the material. A given type of laser can not mark all surfaces. However, the overall versatility of lasers gives them a substantial edge over alternatives such as ink-jet marking, electromechanical etching, vibromachining, and mechanical stamping.

7 The laser market

Professor F. Grassi

(The following is an extract from a lecture by Professor F. Grassi [53] at the ICS/ UNIDO workshop held in Fortaleza, Brazil in October 1998.)

As described previously, lasers are used today in a broad range of applications. They are used not only in industry but also in almost all fields of activity. A few examples of these applications follow.

In measurement, where commonly used lasers include He-Ne, argon and diode, applications comprise measurement of length and angles; Doppler effect in laser spectroscopy; holography; velocimetry; combustion analysis; anemometry; surfaces digitizing; length and time standard samples; time of flight; vibration; 3D sensing and placement.

In production, CO_2, Nd:YAG, excimer and copper vapour are almost exclusively used as the laser source. Main applications include quality control, material synthesis, welding, cutting, drilling, surface modifications, hardening, cladding, soldering and brazing.

In transport, He-Ne, diode, Nd:YAG and CO_2 lasers are used in ring giros, distance radar, aircraft signalling systems, emission control, fog signalling, guidance and orientation systems.

In training and entertainment, diode, argon and He-Ne lasers are used in musical compact discs, teaching programs, laser display and video techniques.

In the field of energy and environment, commonly used lasers include CO_2, Nd:YAG and excimer. Main applications involve Lidar, pollution control, nuclear fusion, plasma spectroscopy, air and water analysis.

In medicine and dentistry CO_2, Nd:YAG, He-Ne and Er:YAG lasers have been used in dermatology, cardiology, laser surgery, oculistics, eye surgery, calculus removal, digital imaging, hard tissue dental drills and cut of soft gum tissue.

Main biomedical applications use argon, Nd:YAG and He-Ne lasers. Some examples include biodynamics, micromanipulation, analysis, optical tomography and two-photon microscopy.

In the military field, lasers have been used largely in rangefinding, target designation, guidance, weapons simulation and surveillance. Commonly used lasers are CO_2, Nd:YAG, diode and He-Ne.

For information processing, diode, He-Ne and argon lasers find applications in laser printers, displays, signal processing, optical character recognition and bar code scanning.

7.1 General laser market share

The distribution of market shares considering all laser applications are as follows [54]: 30% in material processing; 15% in medicine; 10% in R & D; 25% in compact discs, memories and communications, and 5% in the fields of measurements, tracking and environment. Considering only the industrial material processing applications, 75% of the market is for cutting, 20% for welding and 5% for surface treatments. In this case, 45% of the market is for electronics, 20% for mechanical engineering and machining, 15% for job shops, 10% for automobile industry, 5% for white goods industry and 5% for other applications.

7.2 High-power laser machining market

The laser market [53] is considered here mainly in relation to mechanical machining performed with the aid of lasers with power greater than 1,000 W as well as the strongly correlated systems market where a laser generator is always integrated.

Micromachining applications, mainly in the electronics and electrical fields, are not considered here since their applications are quite different compared with the macromachining of metals with high-power lasers.

As a gross figure, the systems market world-turnover is four times greater than the laser generators market. This market can be divided into different categories depending on: dimensions of the workpiece (2D or 3D); size and thickness of the workpiece; relevant accuracy (macromachining and micromachining); technology and laser powers (cutting, welding, heat-treatment, drilling etc.) and different main groups related to cutting and welding of metals with CO_2 or Nd:YAG lasers.

Considering the most common and important sector (macromachining of metals by high-power lasers for cutting and welding), the 2D market turnover covers between 80 and 85% of the total and consequently, the 3D market covers no more than 15 to 20% in terms of money.

System prices and diffusion

The unitary value [53] of a 3D system (ranging from $US 550,000 to $US 850,000) is substantially more than that of the 2D one (ranging from $US 300,000 to $US 450,000) and consequently the total market for the 3D system is from 8 to 10% of the total in terms of installed systems. During 1996, 2D systems numbering 1,720 and 3D systems numbering 165 where installed around the world. In 1997, the overall market growth was between 15 and 20% and the same is forecast for the next ten years.

The following discussion is limited to CO_2 and Nd:YAG systems with lasers powered by more than 1,000 W used only for macromachining of metals (in practical terms for the job-shop 2D and automotive 3D markets). Compared with 1995, the market growth has been about 30% for the number of installed units and 25% for the value. The same increment was observed in 1993 and 1994 after a recession in 1991 to 1992 and in 1993, mainly in Japan. In Europe and the United States of America, over the same periods, the total laser market increased or remained constant; by contrast, in Japan the same period exhibited a decrement due to saturation of the internal domestic market. Effective increments for Japanese production of laser systems found their target in 1994 and in the following years in Australia, China, the Republic of Korea, Taiwan Province of China and in the United States but there was reduced growth in Europe. European production compensated its domestic recession (1991-1993), increasing its sales in the United States. In Germany, where sales showed a reduction, the effect was not as remarkable as in Japan since the European market was not as saturated at that time as the Japanese one. In any case, the market share in Europe stayed almost constant from the point that it decreased in Germany (from 40% in 1990 to 33% in 1993). This was counterbalanced by an increase in Italy (16% in 1993), France and Spain. In effect, in 1990 the German to Italian market share proportion was nearly 4 and in 1994 it reduced to nearly 2.

Comparing the traditional machine tool and the laser system market

It is interesting to note the difference between the laser machining systems market and the analogue market of the more traditional machine tools. The general behaviour of the global economy has a greater effect on the traditional machine tools market, since relevant investments are reduced and old equipment is not frequently replaced with more productive and modern machine tools when production decreases. The opposite applies to laser systems because during recessions, production shifts from standard mass production to more selective and smaller batches typical of niche markets. For this reason, the more versatile and flexible laser machine becomes competitive in comparison with the rigid machines for mass production. It is a typical practice during recessions to outsource portions of manufacturing operations and to reduce inventory build-up, averaging and filtering the peaks versus valley production requirements. Since the laser system is capital-intensive (although the earnings can be up to $US 150,000 per shift per year), the big companies prefer to shift capital investments to external job-shops. Job-shops, on the other hand, are innovation-driven by their need to compete with other job-shops and they are facilitated by the flexibility and versatility of laser machines, as well as by the financial facilities of governments or by tax reductions in their capital investments.

Note that the total market value ratio between machine tools and laser systems is about 15 but is forecast to decrease as lasers become more widely accepted. The laser system market is forecast to double its turnover in the next four or five years. Other important reasons for this change are that the laser systems emulate established processes of traditional machine tools, reducing further the traditional market share, for example, the punch-press traditional machines. New applications ideally suited to laser machines are discovered every day.

Market shares

As shown above, lasers have wide applications over many different disciplines other than mechanics including electronics, packaging and micromechanics. They are all differently affected by macroeconomic time phases. The job-shop has the capability to be activated on demand in a short time to produce small batches ("just-in-time") with higher quality and lower hourly costs with respect to big companies. A tendency in some parts of Europe (namely France and northern Italy) is for job-shops to predominate (i.e. outsourcing) while in northern Europe the big companies prefer to manage in-house laser innovations and related investments in R & D and systems.

From 1994 on, the major percentage of installations shifted from Japan to the United States, mainly because of a strong increment in sales of Japanese and European systems in the United States but not because of an increase in domestic production of United States manufactured systems. At present the total market share is about 35% in the United States and 25% in Japan but in 1990 it was nearly the opposite.

The different power lasers used are CO_2 and Nd:YAG. For cutting, the CO_2 laser still takes the lead (90%) but 10% of the systems use cw Nd:YAG at powers up to 4 kW. This laser source is mainly integrated with articulated robots since they can exploit the fibre beam delivery and, being less expensive, they remain competitive despite the higher cost of the Nd:YAG laser. The Nd:YAGs are more common in micromachining and accurate drilling applications. In the welding applications the market share is nearly 50/50 between CO_2 and Nd:YAG (pulsed) but CO_2 still leads. The new Nd:YAG diode pumping shows promising developments, as does the high-power CO_2 (up to 20 kW) for welding with high penetration of ship fabrications and heavy carpentry.

If we consider the total picture of lasers used for processing applications (macro and micro machining), the CO_2 share is 60% and the Nd:YAG (cw and pulsed) is 27%.

The CO_2 turnover is double compared with the Nd:YAG. The total market value in 1996 of laser generators was $US 600 million. Of that, the CO_2 is $US 330 million and the Nd:YAG is $US 162 million.

Considering the distribution of the entire laser processing systems by user industries, the single predominant sector is electrical electronics which retains over 40%. Metal processing, automotive and mechanical engineering together is another 40%. Aerospace, packaging and non-metal processing is represented by the residual 20%.

The total market turnover of the entire laser processing system is nearly $US 2 billion.

Lasers—their advantages and disadvantages

The following discussion focuses on examples of the extreme flexibility in using laser light in a variety of applications.

The advantages of the laser are a result of its unique properties. Among them the most important are the monocromaticity, the coherence and the collimation. Hence, its radiation has a relatively fixed and constant frequency, it is generated in the form of very long continuous wave trains (all in phase) and it has a small beam divergence, where the radiated energy propagates without dispersion, remaining confined in a "cylinder" (high radiance).

The above unique properties provide the following practical advantages.

The beam can be focused to small spots (0.1 to 0.2 mm). As a consequence high-power density (between 10^5 and 10^8 W/cm^2), high-pulse energy (up to tens of J) and very short pulses (so very high peak powers) are available on the "knife edge" for high accuracy cutting (e.g. of intricate pieces).

The beam can be directed over long distances with low dispersion losses and with acceptable divergence which allows for "flying optics" machines up to 12 m long (total length X+Y+Z axes).

No inertia or force is exerted by the tool on the workpiece. In order to move and orient such a "weightless" tool, it is now possible to design and build lighter machines with higher speed and acceleration. Furthermore, laser light is not affected by the noise of electromagnetic fields, it can be easily polarized and there is no wear.

Laser beam generation is no longer a laboratory process but an industrial process under development. It can be rendered safe by taking relatively simple precautions and often using cheap and simple materials.

The laser beam propagates through most gases and can be transmitted and focused through transparent materials (lenses). It can also be transmitted by optical fibres and deviated by reflective simple materials like copper and aluminium (mirrors). It propagates and reacts at the speed of light (it *is* light).

The heat affected zone (HAZ) in processed materials is small and as there is no contact tool, there is no induced deformations on the workpiece.

Laser systems can be easily adapted to electronic control, computer software and automation and are capable of generating process feedback signals by themselves because photons are easily integrated with electrons (such as photodiodes and diode lasers). They can respond rapidly to changes in power, frequency and duty cycle as well as in power modulation. The power supply can operate in a wide range of levels (from mW to tens of kW), pulse energy (from micro J to tens of J) and pulse repetition rates. Pulse lengths and temporal shapes can also be readily changed.

The parts generated are fully finished and further operations are not required. Many types of materials can be processed with the same laser (as CO_2) such as mild and stainless steel, brass, aluminium, wood, plastics.

In high-power applications with CO_2 and Nd:YAG lasers, high radiance is crucial because it enables the beam to focus to small spots, long distance propagation, large energy, large power density and small HAZ.

To be cost-effective, an application must make use of the unique characteristics of lasers. When these types of applications are identified, the disadvantages become incidental.

The major disadvantages of using lasers are its high capital cost and its low efficiency. The high capital cost (a 2,200 W CO_2 laser costs about $US 132,000 or $US 60 per W) is balanced by the fast return of the investment (between 1.5 and 2 years). Today some advanced laser systems can work unmanned and unattended for many hours (up to 48 hours continuously) before the need of unloading the finished parts and loading the raw metal sheets. In some cases they are also able to unload automatically the cut pane, stack them in order and load the new raw metal sheet.

The efficiency is low, between 10% and 15% for CO_2 laser generators. Considering the whole system with the cooling power, CNC and electromechanical power of the system, the overall ratio between power available onto the workpiece and the total input power ranges from 5% (for systems using slow-flow lasers) to 9% (for systems using fast or transverse-flow lasers). Considering the electrical power costs and the relevant added value of the laser manufactured workpiece (just-in-time production style, shape material and thickness flexibility, high quality, accuracy and best finishing) the profitability is still very high, in spite of the low efficiency.

A further disadvantage is the fact that the technology is still in progress and needs to be consolidated. Too many parameters to be managed and laborious processes to be controlled are examples of difficulties with this technology. Such drawbacks however are being overcome by the development of modern user-friendly laser systems where off-line PC programming and CNC manage automatically all the process parameters and their stability. The operator has just to input the material type, its thickness and the workpiece shape and nesting. The machine fixturing and tooling (as change in focal position or its length) is now simple, fast or fully automatic.

Adapted materials for laser processing

Sheet metal fabricators are producing metals particularly adapted for smooth laser cutting, with the best thermal properties and homogeneous and stable composition (laser steel). This kind of production is growing together with laser applications and systems. In the past years, two of the most important sources of process instability were the quality and homogeneity of materials – since the assumption was that the laser was capable of cutting everything.

The prudent job-shop owner will always try to use good laser steel in order to avoid queries both from customers about the quality of the parts produced and from system manufacturers about system performance. The same holds for gases and pipes used both for the laser and for the process: the higher the gas purity, the better the final quality.

In terms of lasers and system manufacturers, much effort is invested in producing machines that are reliable, stable and which have high repeatability. These factors contribute to a smoother learning process for the user that in turn makes more accessible the fascinating field of laser applications. Normally speaking, after a few months of intensive use, a capable user will know more about the system, the laser and the related cutting parameters than the manufacturer.

7.3 Examples and general aspects of the management of laser technology

Another more general aspect of technology management, for those now entering the industrial laser business, is the following classification of advantages and disadvantages.

Among the advantages the most outstanding aspects are the high productivity, the improved quality, the high flexibility, the just-in-time production styles and the reduction in manpower, scrap and re-work. The very high profitability obtained with these aspects is also reinforced by the possibility of using on-line processing and by the improvements in work process planning, logistics and procedures with substantial reduction in material and processing costs (20% to 30%).

Other aspects contributing to the growth of laser technology in industry is its capability of being adapted and applied to similar firms and processes as well as its capability of being diffused in many localities. It is also complementary and frequently superior than alternative technologies and contributes to the development of all technologies, being present in more than one scientific and economic sector.

A further aspect that can not be disregarded is the safety of the laser processing and the environmental effects that can be readily controlled such as noise, vibrations, fumes, chips, lubricating and refrigerating fluids.

As already mentioned, the laser technology also has some drawbacks. Although the most important is the high capital cost, others must be considered. These include the necessity of skilled operators, the difficulty of maintenance and the fact that it is not yet a stabilized technology. Another aspect that adversely affects the laser market is its incapacity of using recycled waste and the difficulty of using local resources.

Financial and economic aspects

The opportunity this field presents to new business interests has both an economic basis as well as a technological one.

From an economic point of view, laser manufacturing has a high capital cost but a fast investment return because of its high profitability. Financing the initial investment necessary to buy the equipment is often facilitated by special national laws on particular forms of credit, or is encouraged by the supplier by means of special payment conditions, or both. Because of its characteristics (high capital, fast return of investment) it is particularly adapted to the leasing form of financing.

Typically the market price of a basic 2D system with three or four-axis machine and cabin, (without loading/unloading automation but with a simple bed manually loaded) ranges from $US 300,000 to $US 450,000. The added price of the automation (automatic sheet loader and automatic double pallet exchanger that enables the machine to cut all the shift time, practically with the same raw sheets load), is between 20% and 35% of the basic price. As far as the 3D systems are concerned, the market price of a basic five-axis cutter, with cabin and a fixed table to load the piece and the fixture, ranges from $US 550,000 to $US 50,000. The added price of the automation (typically an automatic double carriage for loading/unloading the pieces) is between 15% and 25% of the basic price. Consequently, there are two possibilities to choose between when purchasing a laser system. The most common possibility is that a well-established carpentry activity already exists. The owner needs to improve its capability, quality, flexibility and consequently the profit margins and/or enlarge the market and the product range, or be able to produce the actual products better and faster. The second possibility is that a fully new plant will be created and the most natural way will be to install the most modern and innovative equipment available.

In terms of technological reasons for using lasers, the advantages have been mentioned above. From a practical point of view, it is useful to point out the following: that the demand for accuracy, edge finishing, fast delivery time, variable types of shape, materials or thickness may increase; that the owner may wish to improve profit margins by cutting mild steel as well as stainless steel and aluminium. The profit on stainless steel cutting is nearly double that of mild steel and the profit on aluminium cutting between 6 and 8 mm of thickness can be determined by the owner. The same holds for very large pieces (e.g. of several metres) cut in stainless steel for big heat exchangers, chemical or power plants, nuclear plants, turbine and similar.

Technology before the laser required highly skilled manual labour thus a single piece could cost a fortune. Nevertheless, the market was prepared to pay a high price. With the laser, many of the same pieces can be made after the initial investment in fixture and programming and the overall cost is certainly lower. This is typical in car-body prototyping.

Profitability

A 3D fixture for a car-body piece can cost $US 8,000; 2D pieces cost considerably less. In 3D, one minute of cutting time costs between $US 3 and $US 5. Total cutting time for a single piece can be 6 to 10 minutes. The average batches are from 50 to 500 pieces. The machine cost can range from $US 60 to $US 150 per hour. Consequently in 1 hour, 6 to 10 pieces are produced with an added value of between $US 180 and $US 300. For a batch of say 300 pieces, the total cutting time will be 40 hours (on average). The total machine cost is $US 4,000, the total batch price is $US 9,600 ($US 32 each) plus the fixture cost ($US 11,000) and plus the part programming cost (about 4 to 8 hours' labour), say, $US 120. The cut batch of 300 pieces can be sold for $US 20,000 (this refers to the cutting only and does not include the material and stamping). So a single piece-cutting cost is between $US 65 to 70. The profit in this case will be $US 6,000 per week. Note that all the fixture costs are paid and that the fixture themselves can be used for successive productions of the same piece.

In the case of a 2D-piece production, the difference between a laser system (i.e. a sequential process) and a punch press (i.e. a parallel process in cutting) is in the break-even number of pieces produced. The optimal production range will be between 5,000 and 10,000 pieces for the punch press and lower than 2,000 for the laser system. For a punch press there is a significant investment in tooling and a short time required per piece. For a laser, the tooling is only the cost of a lens but it requires more time per piece. The former has a long delivery time and the latter a very short one. To produce a complex stainless steel flange of 6 mm thickness with overall dimensions of about 100 mm, the tooling cost of a press can be around $US 8,000. The required time per piece can be 6 seconds and the delivery time one or two weeks. For laser machines the tooling cost can be $US 300, the time required per piece 120 seconds and the delivery time from a few hours to a couple of days. Systems working on two shifts (3,345 h/y) at 80% of maximum electrical power and a machine efficiency of 95%, gives an idea of related costs. It is assumed that most of the maintenance and programming is performed off-line or on the third shift.

The set-up and routine maintenance are made on working time. The machine has a low level of automation so that its running time will be equal to the hourly cost of labour (one operator will manage one machine). The main parameters to be considered are electrical consumption; compressed air; process and laser gases; spare parts and consumables; labour and machine depreciation.

If the job-shop has two installed machines with a good level of automation, the same operator will be able to work on two machines and the operator cost can be estimated as 1,672 h/y (half of the machine running time). This is roughly equal to half of the total labour cost. Machine depreciation can be estimated at 20% per year. Financial costs, covered room and programming time are not considered. There is a significant difference between cutting with O_2 at low pressure and with N_2 (clean cut) at high pressure (much more expensive). In fact, if mild steel is cut with O_2, the average consumption is 5 m^3/h and $US 4/h. If stainless steel is cut with N_2 at high pressure (clean cut) the average consumption can be 30 m^3/h and $US 45/h. Laser gas consumption, for a fast axial flow, is about $US 0.5/h or less. The compressed air used by the system can consume 60 m^3/h and $US 1/h. Electrical consumption can be 60 kW/h and $US 5/h.

In summary:

	$/hour
electrical consumption	5
compressed air	1
laser gases	0.5
assist gas—O_2	4
assist gas—N_2	45
spare parts and consumable	1
Depreciation	30
Labour	20
Total (with O_2)	61.6
Total (with N_2)	102.5

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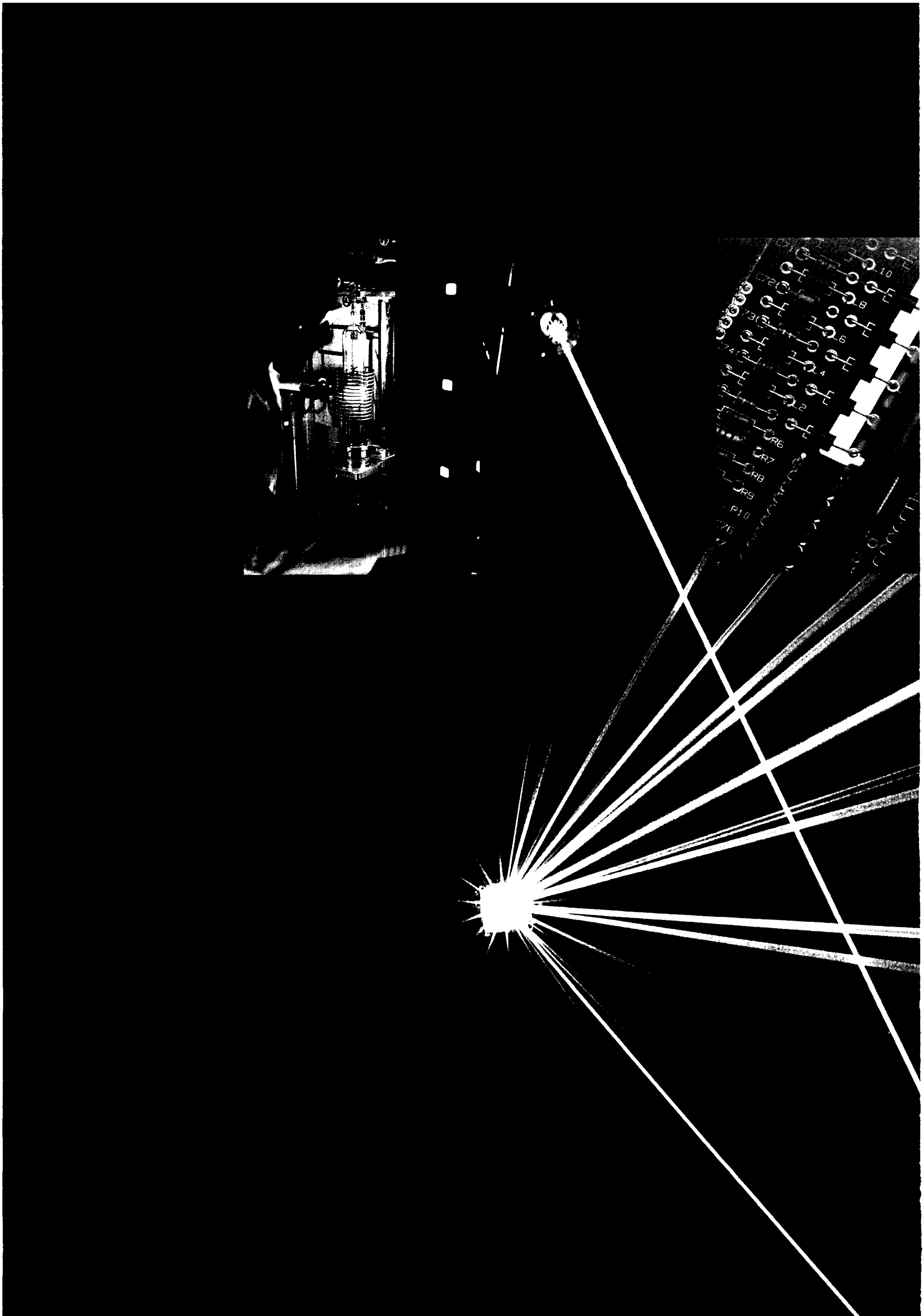
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