Chapter 2

Laser processing of materials

Abstract

The laser has become a precious device for mankind. Science and engineering, communications, medicine, manufacturing and materials processing, art and entertainment, data processing, environmental sensing, defense, energy, astronomy, and metrology are some examples in which lasers are applied. It is difficult to imagine state-of-the-art physics, chemistry, biology, and medicine research without the use of radiation from various laser systems.

The objective of this chapter is to describe the basic principles of laser theory and operation, the characteristics of typical lasers, and how lasers are employed in a variety of applications. Special emphasis will be given to industrial applications in materials processing.

1. Introduction and brief history

Lasers are devices that generate or amplify coherent radiation at frequencies in the infrared, visible, or ultraviolet regions of the electromagnetic spectrum [1]. The general principle by which lasers operate was originally invented at microwave frequencies, where it was called microwave amplification by stimulated emission of radiation, or *maser*.

The word *laser* is an acronym for *light amplification by stimulated emission of radiation* and its concept traces back to Albert Einstein in 1917 with his paper on quantum theory of radiation [2]. The invention of the laser can be dated to 1958 with the publication of the scientific paper, *Infrared and Optical Masers*, by Arthur L. Schawlow, then a Bell Labs researcher, and Charles H. Townes, a consultant to Bell Laboratories [3]. That paper, published in *Physical Review*, the journal of the American Physical Society, exposed a theoretical basis for the laser construction and outlined some of its problematic aspects.

In May 1960, the American physicist Theodore Maiman, working at Hughes Aircraft Company, built the first laser to successfully produce a pulse of coherent light, using synthetic ruby as the laser medium [4]. The first continuously operating laser was achieved a few months later. A door to a new scientific field and to a multibillion dollar industry had been opened.

2. Generation of laser light

Radiation can be produced over a continuous range - the electromagnetic spectrum - shown in Fig. 2.1. The whole range of the spectrum can be divided into parts. Radio waves occupy the low frequency, low energy, long wavelength range, and are produced by antennae. Microwaves are generated by electrical oscillators. Infrared radiation is produced from electronic transitions and molecular vibrations in materials. Visible light (in the wavelength range of 390-780 nm) is characterized in order of increasing wavelength as violet (390-430 nm), indigo (430-455 nm), blue (455-492 nm), green (492-577 nm), yellow (577-597 nm), orange (597-622 nm), and red (622-780 nm), and is produced from transitions between energy states in the valence electrons of atoms. Ultraviolet light originates from corresponding high energy electronic transitions. X-rays result from deep electronic transitions. High frequency, high energy, short wavelength gamma rays are produced by radioactive decay.

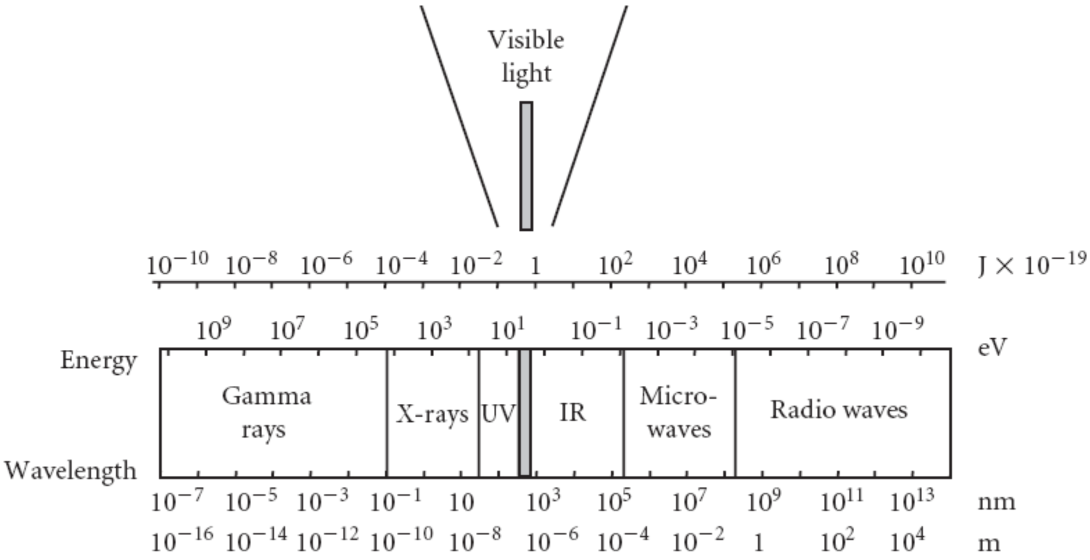


Fig. 2.1. The electromagnetic spectrum [5].

Laser light is generated by transitions between high and low states of energy in species (atoms, ions and molecules) in various media, as shown in Fig. 2.2. The wavelength of the light emitted is characteristic of the material itself, i.e. its energy levels and respective transitions. Sustainable light generation depends on a suitable combination of fundamental physical phenomena to generate the light and an appropriate mechanical design to maintain and amplify the emission.

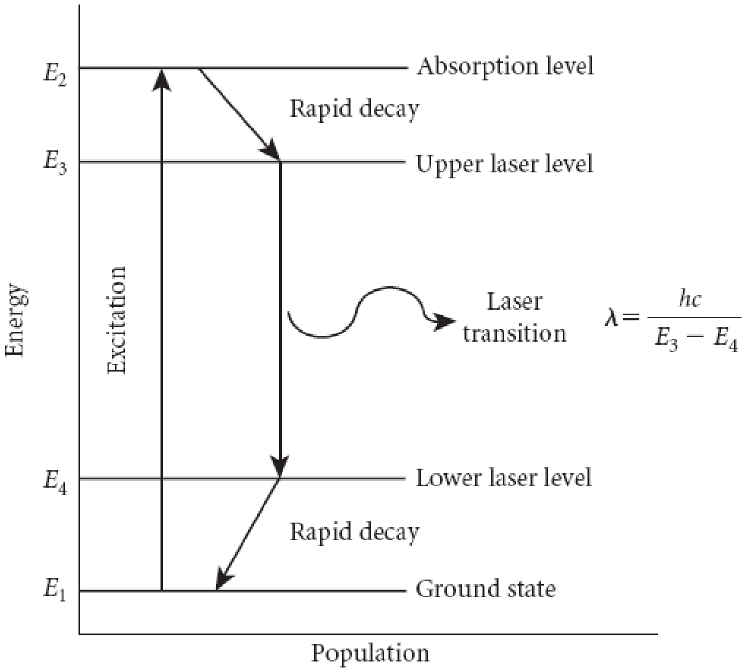


Fig. 2.2. Schematic of light emission resulting from energy transitions from higher to lower energy levels [5].

There are several active media which can be used to generate laser light such as gases, liquids, insulating solids, semiconductors, etc.

3. Basic principles and operation

A laser requires four basic components to operate: an *active medium* in which light can be amplified by stimulated emission of radiation; a means to *excite* the medium – the excitation or 'pumping' source – to maintain the population inversion; a means to provide optical *feedback* – the optical cavity; and an *output* device to enable usable amounts of beam energy to exit the laser. Additionally, a laser requires power and control systems, means of cooling the active medium and an interface for operation. Amplification of laser light can only occur if emission takes place in a suitable device – the *optical cavity*. Amplification is achieved when stimulated emission increases the number of photons circulating in the optical cavity, illustrated schematically in Fig. 2.3.

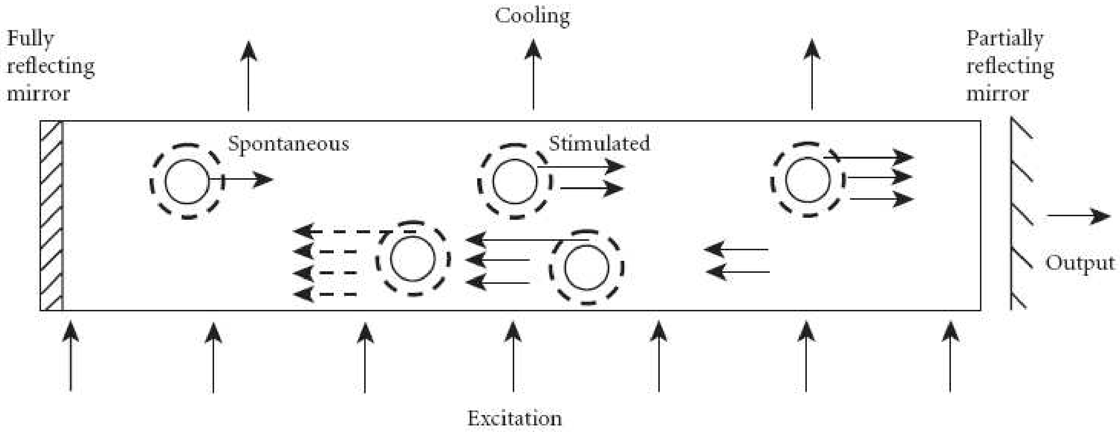


Fig. 2.3. Schematic illustration of light amplification by stimulated emission of radiation [5].

A laser generates a beam of very intense light. The major difference between laser light and light generated by white light sources (such as a light bulb) is that laser light is monochromatic, directional, and coherent. *Monochromatic* means that all of the light produced by the laser is of a single wavelength. White light is a combination of all visible wavelengths (400 to 700 nm). *Directional* means that the beam of light has very low "divergence" or spread. *Coherent* means that all the light is moving in the same direction and the waves are in "phase" with each other. A light bulb produces many wavelengths, making it incoherent. The color, or wavelength, of light being emitted depends on the type of lasing material (active medium) being used and certain materials and gases are capable of emitting more than one wavelength. In this case, the wavelength of the light emitted is dependent on the optical configuration of the laser. In material processing applications, we are mainly interested in the infrared, visible and ultraviolet portions of the electromagnetic spectrum.

4. Types of lasers

Laser action occurs in all states of matter: solids, liquids, gases, and plasmas. The spectral output ranges of solid, liquid, and gas lasers are shown in Fig. 2.4 and extend from the soft x-ray and extreme ultraviolet regions to millimeter wavelengths, thus overlapping masers. In addition to lasers operating at one or more discrete wavelengths, some are tunable over broad wavelength bands. Using various frequency conversion techniques—harmonic generation, parametric oscillation, sum- and difference-frequency mixing, and Raman shifting—the wavelength of a given laser can be extended to longer and shorter wavelengths.

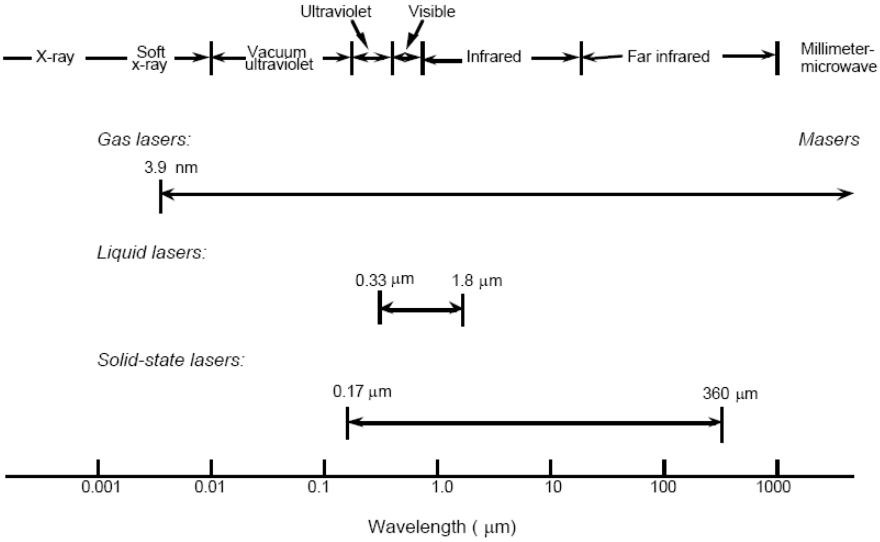


Fig. 2.4. Ranges of output wavelengths for various laser media [6].

Lasers for material processing may be classified by: active medium (gas, liquid or solid); output power (mW, W or kW); wavelength (infrared, visible and ultraviolet); operating mode (CW, pulsed, or both); and application (micromachining, macroprocessing etc.). Since the state of the active medium determines the principal characteristics of the laser beam for material processing, it is frequently used as a primary means of classification: gases (atoms, molecules, ions and excimers); liquids (principally organic dyes); and solids (insulators and semiconductors). In Fig. 2.5 is shown the categorization of lasers for materials processing.

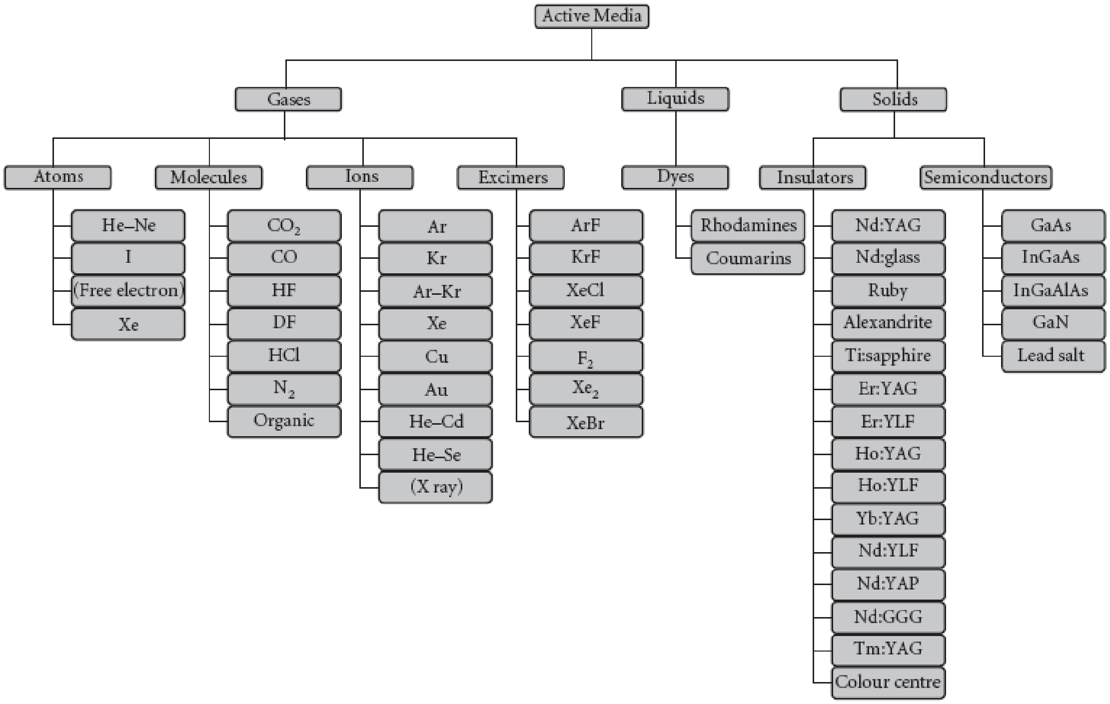


Fig. 2.5. Lasers for material processing categorized by the type of active medium [5].

5. Laser processing of materials

The type of laser is selected according to the application: an infrared wavelength for large-scale application, or a shorter wavelength for microprocessing. The laser beam is formed into a geometry that is appropriate for the area to be treated using optics modulators. The form of beam power – continuous wave (CW) or pulsed – is selected depending on the application: a traversing CW beam is suitable for treatment areas on the order of square millimetres, whereas a stationary pulsed source is appropriate for discrete processing to micrometre-scale depths.

When processing materials with laser the optical energy delivered is absorbed by the interaction of the electric field of the electromagnetic radiation with electrons [7]. If the electron is bound within the phonon structure of a solid this force will be transferred to the structure. If there is a sufficient flux of photons the force becomes enough to cause the structure to vibrate, which we detect as heat. With greater and greater photon fluxes the vibration becomes sufficient to break the solid structure and it first melts, then evaporates. The vapour may then be ionized introducing Coulomb forces to remove the material. This last effect is only achieved with the immense power that is currently available with femtosecond pulses. Beyond this power range, lasers are being used for atomic fusion.

Some of the advantages of optical energy from a laser compared with other forms of energy are [7]:

- power intensity – one of the highest available in industry today
- power shaping – this is almost uniquely possible for optical energy in both time and space
- ease of automation – there is an uncluttered interaction zone with few extraneous signals, allowing a wide open window for in-process sensing
- photolytic processing – this is unique to photons and opens a new level of chemistry
- coherence and spectral purity – this allows strange optical effects through diffraction, interference and multi-photo events.

Generally the average power determines the speed with which the process can be undertaken. The beam quality/spot size has an impact on quality and penetration. Pulsing capability allows the peak power necessary to achieve the process to be controlled independently of the process speed. Wavelength affects the efficiency of power coupling to the workpiece and process quality. The laser to workpiece beam delivery affects the flexibility and ease with which the equipment can be used.

6. Industrial applications

Lasers are reliable tools that compete on an economic and productivity basis with traditional technologies on manufacturing applications. Manufacturing processes include joining (welding, soldering and brazing), cutting, drilling and surface treating (hardening, coating appliance, etc.).
The beam spot size is typically in the rage of 10-1000μm, which permits the power to be delivered very accurately. Since absorption of laser radiation by the workpiece material is usually high, the heat is very localized with low part distortion [8]. The processing parameters and environment can be chosen in a way that the finished part quality does not require any further post processing. These advantages allow new, more cost effective, designs to be used in

manufactured products. In addition, the very localized nature of the laser beam input, with the right choice of wavelength and pulse parameters often allow new materials to be used in products that are not considered processable by conventional means, e.g. many crack sensitive materials can be machined by laser beams, and parts with dissimilar thermal characteristics reliably welded. The computer control available with most modern lasers means that they can be readily integrated into advanced automated manufacturing environments and used for a multiplicity of tasks in the production cycle. The non-contact nature of laser products means that they do not wear out and can be readily reused when the part or processing requirements change.

Table 2.1. The main laser types employed in materials processing [9, 10]

	% material processing laser market 2002	
Type of laser	Value	Number of units
CO_2 laser—flowing gas	36	12
CO_2 laser—sealed	6	29
Solid state laser, lamp pumped	33	22
Solid state laser, diode pumped	4	9
Excimer	18	2
Diode >10 W	1	0.001

The main commercial lasers for laser material processing are shown in Fig. 2.6. Operating regions of different lasers can thus be distinguished, and power levels appropriate for material processing selected. Fig. 2.7 illustates the range of industrial processes in which lasers are employed taking into account the required laser energy and interaction times for the respective processes. This makes easier a selection of a laser type for a given application considering the required amounts of energy and interation time (e.g. pulse duration).

Two types of laser dominate the applications in materials processing: the solid-state Nd:YAG laser and the gaseous CO_2 laser (Table 2.1). CO_2 laser applications are dominated by cutting. This is mainly of flat sheet using CW lasers of 500-I5OOW power. CO_2 laser welding is usually carried out with higher power lasers. In the case of Nd:YAG lasers, the main process is welding. However, there is also significant activity in cutting and drilling. This laser type has two distinct advantages, the options of pulsed operation to high peak power, and power delivery to the work area via flexible fibre optics.

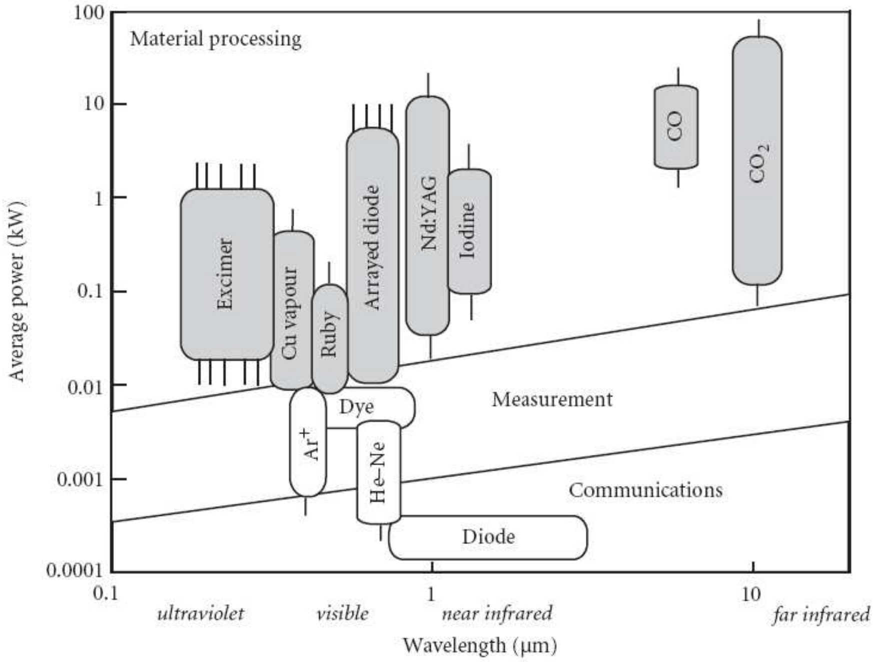


Fig. 2.6. A selection of commercial lasers characterized by wavelength and average power, shown on a background of applications (lines indicate the principal output wavelengths, and those used principally in industrial material processing are shaded) [5].

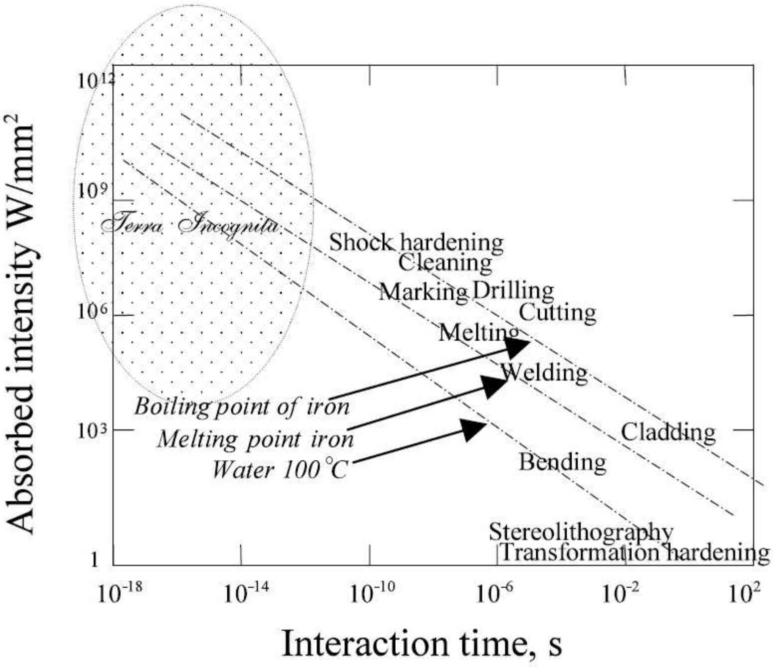
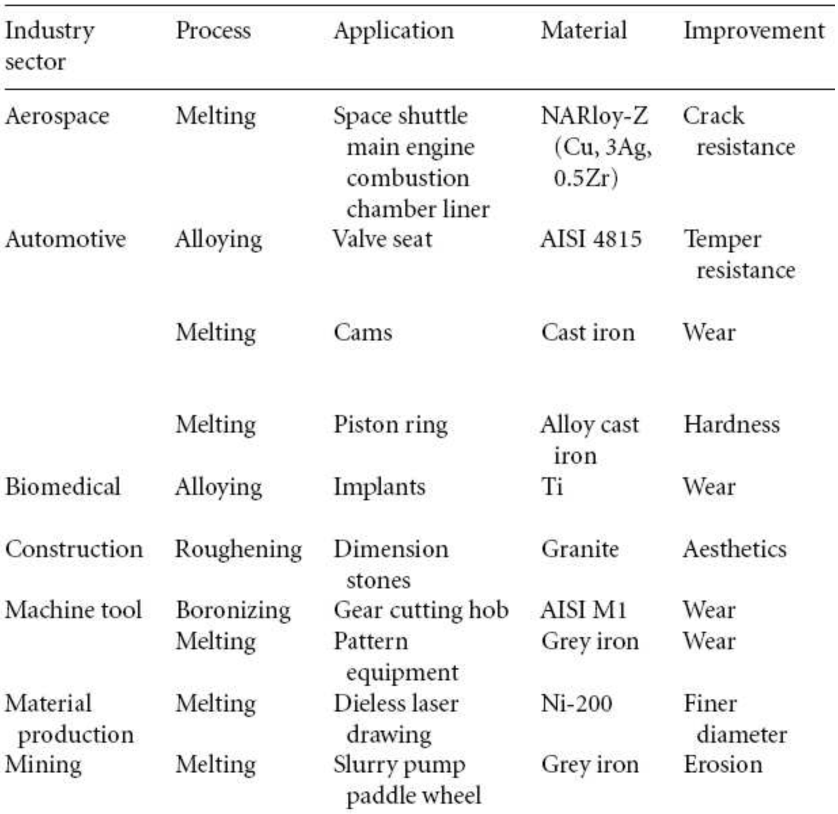


Fig. 2.7. Range of processes using lasers in industry [7].

6.1. Surface melting

Laser surface melting comprises a family of processes that includes alloying and particle injection, in which the material surface is melted, but not intentionally vaporized, by a scanning distributed laser beam. Surface melting, and subsequent rapid resolidification, is a means of producing a refined or metastable microstructure in localized areas on a component, which have improved service properties such as resistance to wear, corrosion and oxidation, particularly at high temperatures. In Table 2.2 can be found some aplications for the this treatment and the respective advantages.

Table 2.2. Industrial applications of laser surface melting and alloying



Industry sector	Process	Application	Material	Improvement
Aerospace	Melting	Space shuttle main engine combustion chamber liner	NARloy-Z (Cu, 3Ag, 0.5Zr)	Crack resistance
Automotive	Alloying	Valve seat	AISI 4815	Temper resistance
	Melting	Cams	Cast iron	Wear
	Melting	Piston ring	Alloy cast iron	Hardness
Biomedical	Alloying	Implants	Ti	Wear
Construction	Roughening	Dimension stones	Granite	Aesthetics
Machine tool	Boronizing	Gear cutting hob	AISI M1	Wear
	Melting	Pattern equipment	Grey iron	Wear
Material production	Melting	Dieless laser drawing	Ni-200	Finer diameter
Mining	Melting	Slurry pump paddle wheel	Grey iron	Erosion

The process is acomplished by the absorption of the optical energy delivered by the beam which results in the heating of the material. As a consequence, being the energy enough, a melt pool forms and then rapidly cools down and solidificate. The high cooling rate is due to a very localized heating process which gives rise to very high thermal gradients.

Ferrous alloys – notably highly alloyed steels and cast irons – respond particularly well to such treatment. Porous, inhomogeneous ceramics and ceramic-based composites are suitable candidates for laser-based glazing. Kilowatt-class infrared CO_2, Nd:YAG and diode lasers are the sources of choice for applications on the scale of millimetres, where deep melting and a relatively low solidification rate are desirable, because the power density required may be generated over a relatively large beam area.

Practical millimetre-scale surfacemelting is carried out over wide ranges of power density (10–104 Wmm^{-2}) and beam interaction time (1–10^{-4} s).

6.2. Cutting

This is possibly the best known of these applications. It currently accounts for the work being done by nearly 80% of the industrial laser equipment in service. The laser is starting to dominate this market since it can cut more swiftly and neatly than most competing tools. It was also the first application area for the laser, since there was a readymade market for cutting, particularly flat-bed profile cutting. The laser can cut in at least seven different ways [11]: evaporative, melt and blow, melt and blow in a reactive gas, thermal stress cutting for brittle materials, scribing and mechanical snapping, cold cutting—in which the photon energy is similar to the bond energy or there is such an instantaneous impact of energy that the material is ionized and hence flies apart because of Coulomb forces; in either case there is a negligible heat-affected zone (HAZ).

6.3. Drilling

Laser drilling offers an alternative to mechanical drilling and punching [12]. It is especially adaptable for small holes with large depth-to-diameter ratios. With laser drilling, a wide range of hole diameters are obtainable. Material such as steel, nickel alloys, aluminum, copper, brass, borosilicate glass, quartz, ceramic, plastic and rubber are all being successfully laser drilled. The laser is so fast and so repeatable that it is particularly ideal for high production volumes associated with fully automated or semi-automated tooling applications.

Laser drilling is the process of repeatedly pulsing focused laser energy at a material, vaporizing layer by layer until a thru-hole is created. This is what is called a “popped” or “percussion drilled” hole. Depending upon material and material thickness, a “popped” hole could be as small as .004” in diameter. If a larger hole is required, the laser, once through the material, is moved with respect to the work piece to contour the desired diameter. This is called “trepanning”. The end result is a fast, efficient way to create quality holes.

6.4. Welding

Laser welding is one of the high-quality welding techniques, being similar to electron beam welding, in which the energy is so intense that a ‘keyhole’ is developed. The high-aspect-ratio, almost parallel fusion zone of ‘keyhole’ welds leads to low distortion and a small HAZ compared to alternative processes. It is also fast and leaves a cosmetically attractive weld bead.

Further advances in laser welding may come from the renewed interest in hybrid welding with the laser and arc processes being combined [13].

6.5. Cladding

This is a relative newcomer and is having to make its own market since no comparable process has previously been available for localized precision cladding. The laser with a coaxial powder feed acts like a ‘metal pencil’. It can write metal tracks of a few micrometres to a few millimetres in width or height. When these tracks are superimposed on one another they will build into walls. When the direction of the tracks is controlled by a computer, whose programme is a sliced 3D object, then the 3D object can be built directly, without a mould, in whatever material is being fed as a powder [14].

6.6. Bending

The process of thermal bending is not new but is undergoing a revival as a precision process when used with a laser. But it is a precision bending technique with no tool contact nor any spring back [15]. The bending action is due to the formation of a compressive stress in the heated surface spot leading to plastic flow that is not fully recovered on cooling. If only the surface is heated (thermal gradient method) bending will be towards the laser; if heating occurs through the thickness, buckling may occur allowing bending either towards or away from the laser or, for fully restrained pieces, to a shortening of the part (upsetting). The bend region is thus thickened and not thinned as in normal mechanical bends. It is currently used by Phillips [16] as a method of final adjustment to the alignment of the hard disk in their miniature computers.

6.7. Cleaning

This is another novel technique whereby a blast of light can remove a surface layer of dirt [17-20]. The mechanism is thought to be by evaporative processes, as in ablation; impact processes, as in laser shock cleaning or laser steam cleaning; or vibration processes, as in transient thermal heating. In the case of marble statuary the short sharp pulse from the laser is sufficient to remove dirt and sterilize the surface at the same time, to reveal marble, whose reflectivity is higher than the dirty surface, and hence the process is almost self-correcting. For paintings, the spectrum of the material ablated can be used to control the depth of cleaning; with cleaning electronic components during manufacture, the laser cleaned surface can sometimes be soldered without the need for a flux. There is a concept that laser cleaning with a blast of light could clear an area during the manufacture of integrated circuits, such that the necessity for cleanliness in whole rooms is reduced. It is a quiet process that does not require solvents or abrasive particles; the fumes can be collected by normal vacuum technology which makes it ideal for cleaning both the inside and outside of buildings. It is currently used extensively in aircraft paint strip.

6.8. Shock hardening

After the development of high power lasers, the laser treatment of engineering materials drew a great deal of attention, which in turn causes rapid growth of fields of laser applications such as surface hardening. Surface hardening of metals and alloys can be achieved in different ways, which include heat treatment in the solid state or transition to the liquid/vapor states. Under the high power laser irradiation, a shock wave is generated due to a rapid evaporation of the surface. In this case, the high power laser absorbed energy heats a thin surface layer to a high temperature. The evaporating surface generates a compression shock wave which propagates into the substrate and a hot low density plasma expands towards the laser beam. The shock wave generated alters the surface microstructures and the state of stress levels, which improve the mechanical properties of the substrate such as hardness and fatigue strength. The increase in the fatigue strength is due to the surface compressive residual stresses resulted by the shock waves [21]. The increase in hardness is the result of dislocations and formation of other phases generated during the propagation of shock waves [22].

6.9. Marking and engraving

Laser marking uses laser light to discolor material leaving little or no tactile feel in the surface marked. This process is used to maintain the surface integrity while providing a permanent identification, be that logo, part number, serial number etc. Laser marking material coloration is dependent upon the material being marked.

Marking with a laser can be achieved by three main techniques [23]:

- Impressing a dot matrix at high rates of from 3 to 400 characters s^{-1}
- Mask marking at the rate of around 100 images s^{-1}
- Vector or bitmap marking with a steerable beam at the rate of 70 characters s^{-1}

The ease of marking with a laser has allowed industry to mark almost everything they wish for stock keeping, legal indemnity, serial identification, security or dating reasons.

Laser engraving uses laser light to ablate away material leaving a tactile depression in the surface engraved. This process is used when the material being engraved does not lend itself to the laser marking process, or when the item being engraved needs the added depth provided by a deep engraving. Laser engraving allows materials to be engraved that are not engravable by mechanical means [24].

6.10. Main industrial markets

A few examples where the laser has brought unique economic benefit to manufacturing are listed below:

- Electronics
- Jewellery

- Automotive
- Solar technology
- Tool and mouldmaking
- Aeronautics and Aerospace

7. Conclusions

The laser is a uniquely versatile tool for processing a remarkable range of metals and alloys, ceramics and glasses, and polymers and composites in both laboratory and industrial environments. Light can be produced in pulsed or continuous form, with a wavelength extending from sub-ultraviolet through the visible to beyond the infrared, at power levels that span decades between milliwatt and multi-kilowatt. Laser-based fabrication is possible on both microscopic and macroscopic scales and uses a variety of mechanisms. The beam from a single laser can be manipulated for a large number of tasks, giving a flexibility like no other technology. Laser processing provides a competitive advantage over many traditional 'heat, beat and treat' methods of industrial fabrication. It can be a profitable replacement for an existing technique, or the basis for a completely new process.

Optical energy is one of the most adaptable forms of industrial energy we have ever seen. We are likely to spend at least the next century exploring what we can do with it. So far a good start has been made. The opportunity for laser based systems to provide significant advantage in manufacturing industries via helping to improve product quality, productivity and innovation in both replacement and new applications is very real.

References

[1] A.E. Siegman, Lasers, University Science Books, Sausalito, CA, 1986.

[2] A. Einstein, Physika Zeitschrift 18 (1917) 121-128.

[3] A.L. Schawlow and C.H. Townes, Phys. Rev. 112 (1958) 1940-1949.

[4] K. Barat, Laser Safety Management, CRC Press 2006.

[5] J. Ion, Laser Processing of Engineering Materials, Butterworth-Heinemann 2005.

[6] M.J. Weber, Handbook of Laser Wavelengths, Boca Raton: CRC Press LLC 1999.

[7] W.M. Steen, Journal of Optics A: Pure and Applied Optics 5 (2003) S3-S7.

[8] C.L.M. Ireland. in Laser Applications, IEE Colloquium on, pp. 8/1-820 1993.

[9] R. Steele, Laser Focus World February (2002) 61-82.

[10] K. Kincade and S.G. Andersen, Laser Focus World January (2002) 81-105.

[11] J. Powell, CO2 Laser Cutting, Springer, Berlin, 1993.

[12] http://www.laserage.com.

[13] W.W. Dulley, Laser Welding, Wiley, New York, 1998.

[14] J. Mazumder, D. Dutta, N. Kikuchi and A. Ghosh, Optics and Lasers in Engineering 34 (2000) 397-414.

[15] J. Magee, PhD Thesis, Liverpool University (1998).

[16] W. Hoving. in Laser applications in micro-technology LANE (Geiger, M. and Vollertsen, F., eds.), Meisenbach, Germany 1997.

[17] F. Bloisi, A.C. Barone and L. Vicari, Applied Surface Science 238 (2004) 121-124.

[18] H.-T. Hsu and J. Lin, International Journal of Machine Tools and Manufacture 45 (2005) 979-985.

[19] M.P. Mateo, G. Nicolas, V. Pinon, A. Ramil and A. Yanez, Applied Surface Science 247 (2005) 333-339.

[20] T. Kim, J.M. Lee, S.H. Cho and T.H. Kim, Optics and Lasers in Engineering 43 (2005) 1010-1020.

[21] M. Gerland, M. Hallouin and H.N. Presles, Materials Science and Engineering A 156 (1992) 175-182.

[22] B.S. Yilbas, S.Z. Shuja, A. Arif and M.A. Gondal, Journal of Materials Processing Technology 135 (2003) 6-17.

[23] A.F.H. Kaplan, Marking and scribing, Chapman and Hall, London, 1998.

[24] http://www.lasermarking.com.