

J. Paulo Davim *Editor*

Nontraditional Machining Processes

Research Advances

 Springer

Nontraditional Machining Processes

J. Paulo Davim
Editor

Nontraditional Machining Processes

Research Advances

 Springer

Editor

J. Paulo Davim
Department of Mechanical Engineering
University of Aveiro
Aveiro
Portugal

ISBN 978-1-4471-5178-4 ISBN 978-1-4471-5179-1 (eBook)

DOI 10.1007/978-1-4471-5179-1

Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2013940292

© Springer-Verlag London 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law. The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The designation “*nontraditional machining*” refers to a group of processes that removes material by various methods involving electrical, thermal, chemical and mechanical energy (or combinations of these energies). Currently, typical applications of nontraditional machining methods include high accuracies, good surface finish and complex geometries, parts machined without burrs or residual stresses as well as work materials that cannot be machined by conventional methods. In general, the nontraditional processes are characterized by high specific energies and low removal rates when compared to conventional machining processes. Today, nontraditional macro and micromachining processes present great importance to automotive, aircraft, moulds and dies and other advanced industries placed in all industrialized or emerging countries.

Chapter 1 of the book describes *Laser-Assisted Manufacturing: Fundamentals, Current Scenario and Future Applications*. Chapter 2 is dedicated to *Laser Beam Machining*. Chapter 3 describes *Laser Cutting of Triangular Geometry in Aluminum Foam*. Chapter 4 contains information on *Micro-Electrical Discharge Machining*. Chapter 5 describes *Prototype Machine for Micro-EDM*. Chapter 6 contains information on *Abrasive Water Jet Milling*. Finally, Chap.7 is dedicated to *A New Approach for the Production of Blades by Hybrid Processes*.

The present book can be used as a research book for final undergraduate engineering course or as a topic on manufacturing at the postgraduate level. Also, this book can serve as a useful reference for academics, researchers, manufacturing, industrial, materials and mechanical engineers, professionals in nontraditional machining and related industries. The scientific interest in this book is evident for many important centers of research, laboratories and universities as well as industry. Therefore, it is hoped this book will inspire and enthuse others to undertake research in this field of nontraditional machining processes.

The Editor acknowledges Springer for this opportunity and for their enthusiastic and professional support. Finally, I would like to thank all the chapter authors for their availability for this work.

Aveiro, Portugal, February 2013

J. Paulo Davim

Contents

1 Laser-Assisted Manufacturing: Fundamentals, Current Scenario, and Future Applications	1
C. P. Paul, Atul Kumar, P. Bhargava and L. M. Kukreja	
2 Laser Beam Machining	35
Shoujin Sun and Milan Brandt	
3 CO₂ Laser Cutting of Triangular Geometry in Aluminum Foam	97
B. S. Yilbas, S. S. Akhtar and O. Keles	
4 Micro-Electrical Discharge Machining	111
Muhammad P. Jahan	
5 Prototype Machine for Micro-EDM	153
Ivo M. F. Bragança, Gabriel R. Ribeiro, Pedro A. R. Rosa and Paulo A. F. Martins	
6 Abrasive Water Jet Milling	177
Mukul Shukla	
7 A New Approach for the Production of Blades by Hybrid Processes.	205
A. Calleja, A. Fernández, A. Rodriguez, L. N. López de Lacalle and A. Lamikiz	
Index	231

Contributors

S. S. Akhtar Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

P. Bhargava Laser Material Processing Division, Raja Ramanna Centre for Advanced Technology, PO: RRCAT, Indore, Madhya Pradesh 452 013, India

Ivo M. F. Bragança IDMEC, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, Lisbon 1049-001, Portugal

Milan Brandt School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora, VIC 3083, Australia

A. Calleja Department of Mechanical Engineering, Escuela Técnica Superior de Ingeniería Industrial, University of the Basque Country, Alameda de Urquijo s/n, Bilbao 48013, Spain, e-mail: amaia_calleja@ehu.es

A. Fernandez Department of Mechanical Engineering, Escuela Técnica Superior de Ingeniería Industrial, University of the Basque Country, Alameda de Urquijo s/n, Bilbao 48013, Spain

Muhammad P. Jahan Department of Architectural and Manufacturing Sciences, Western Kentucky University, Bowling Green, KY 42101, USA, e-mail: muhammad.jahan@wku.edu

O. Keles Mechanical Engineering Department, Gazi University, Ankara, Turkey

L. M. Kukreja Laser Material Processing Division, Raja Ramanna Centre for Advanced Technology, PO: RRCAT, Indore, Madhya Pradesh 452 013, India

Atul Kumar Laser Material Processing Division, Raja Ramanna Centre for Advanced Technology, PO: RRCAT, Indore, Madhya Pradesh 452 013, India

A. Lamikiz Department of Mechanical Engineering, Escuela Técnica Superior de Ingeniería Industrial, University of the Basque Country, Alameda de Urquijo s/n, Bilbao 48013, Spain

L. N. Lopéz de Lacalle Department of Mechanical Engineering, Escuela Técnica Superior de Ingeniería Industrial, University of the Basque Country, Alameda de Urquijo s/n, Bilbao 48013, Spain

Paulo A. F. Martins IDMEC, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, Lisbon 1049-001, Portugal, e-mail: pmartins@ist.utl.pt

C. P. Paul Laser Material Processing Division, Raja Ramanna Centre for Advanced Technology, PO: RRCAT, Indore, Madhya Pradesh 452 013, India, e-mail: paulcp@rrcat.gov.in

Gabriel R. Ribeiro IDMEC, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, Lisbon 1049-001, Portugal

A. Rodriguez Department of Mechanical Engineering, Escuela Técnica Superior de Ingeniería Industrial, University of the Basque Country, Alameda de Urquijo s/n, Bilbao 48013, Spain

Pedro A. R. Rosa IDMEC, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, Lisbon 1049-001, Portugal

Mukul Shukla Department of Mechanical Engineering Technology, University of Johannesburg, Johannesburg, South Africa ; Department of Mechanical Engineering, MNNIT, Allahabad, Uttar Pradesh, India, e-mail: mshukla@uj.ac.za; mukulshukla@mnnit.ac.in

Shoujin Sun School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora, VIC 3083, Australia, e-mail: shoujin.sun@rmit.edu.au

B. S. Yilbas Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, e-mail: bsyilbas@kfupm.edu.sa

Chapter 1

Laser-Assisted Manufacturing: Fundamentals, Current Scenario, and Future Applications

C. P. Paul, Atul Kumar, P. Bhargava and L. M. Kukreja

Abstract This chapter presents the basic principles, applications, and future prospects of various laser-assisted manufacturing techniques used for material removal, joining, and additive manufacturing. The laser hazard and safety aspect is also briefly included.

1.1 Introduction

The principle of the laser was first known in 1917, when physicist Albert Einstein described the theory of stimulated emission. However, the first laser was practically demonstrated by Theodore Maiman of Hughes Research Laboratories on May 16, 1960 in the form of ruby laser [1]. But this technical break through was dubbed as “solution looking for problems” during early years after the invention. Following the invention of the ruby laser, many other materials were found that could be used as the basis of laser action, such as sapphire, neodymium, and organic dyes such as rhodamine 6G. There were also different ways to excite various compounds to the point of lasing, such as certain chemical reactions, or the acceleration of free electrons to very high energy levels. Today, the laser’s presence in the world is ubiquitous [2]. The lasers can heat and vaporize any material, drill holes in the hardest materials—diamond, it can create conditions similar to those on the surface of sun in the laboratory, it can cool the atoms to temperatures almost close to absolute zero, it can measure various parameters with exceptional accuracy, and it can detect impurity. Its continual expansion of the boundaries of science, medicine, industry, and entertainment has resulted in many wonderful applications. Smart bombs, supermarket bar code readers, fiber-optic

C. P. Paul (✉) · A. Kumar · P. Bhargava · L. M. Kukreja
Laser Material Processing Division, Raja Ramanna Centre
for Advanced Technology, PO: RRCAT, Indore, MP 452013, India
e-mail: paulcp@rrcat.gov.in

communication, CD/DVD players, laser printers, certain life-saving cancer treatments, or precise navigation techniques for commercial aircraft could only be possible because of lasers. New and popular medical procedures using lasers have enabled to get rid of eyeglasses, removal of unsightly moles, wrinkles, and tattoos, and even streamline bikini lines. In industries, lasers are employed for a variety of material processing, including—cutting, drilling, welding, brazing, surface hardening, cladding, alloying, and rapid manufacturing. Laser-based manufacturing has several advantages over conventional methods. Some of them are listed below:

1. As non-contact process, it is well suited for processing advanced engineering materials such as brittle materials, electric and non-electric conductors, and soft and thin materials.
2. It is a thermal process and materials with favorable thermal properties can be successfully processed regardless of their mechanical properties.
3. It is a flexible process.

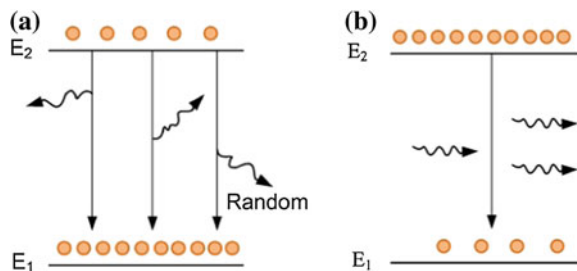
Before proceeding further, first, we will briefly discuss how a laser works, what its special properties are, and how these are being exploited for various applications.

1.2 Lasers Basics

LASER is the acronym of light amplification by stimulated emission of radiation and is essentially a source of intense coherent radiation. The laser differs from ordinary source of light in the emission process of radiation. In an ordinary source, atoms or molecules are excited by thermal excitation, for example, electrical discharge which emits photons spontaneously in a random manner. Photons emitted in all directions with no correlation in wavelength, phase, and polarization between them (Fig. 1.1a). In lasers, photons are emitted by stimulated emission—a characteristic process that generates the photons with all properties (namely—wavelength, phase, direction, and polarization) as those of stimulated photons. Thus, the photons get amplified in an orderly manner (Fig. 1.1b).

Now consider a medium with a large number of atoms (molecules), some of which are in the excited state and rest unexcited. Since the photons get absorbed by

Fig. 1.1 **a** Spontaneous emission. **b** Stimulated emission



the unexcited atoms, the number of excited atoms should be more than that of unexcited atoms for net amplification. This situation is called population inversion. The name is derived from normal trend of the population in the thermal equilibrium, where unexcited atoms are more abundant. Under normal or thermal equilibrium conditions, the lower energy levels are more highly populated than the higher levels ($N_1 > N_2$), and the distribution is given by Boltzmann's law that relates N_1 and N_2 as

$$\frac{N_2}{N_1} = e^{-\frac{E_2 - E_1}{k_B T}}$$

where k_B is Boltzmann's constant = 1.38×10^{-23} J/K and T is the absolute temperature of the system (K). Population inversion ($N_2 > N_1$) though is the primary condition, but in itself is not sufficient for producing a laser. As there are certain losses of the emitted photons within the material itself in addition to spontaneous emission, one has to think about the geometry that can overcome these losses and there is overall gain.

It derives to the following three prerequisites:

- An active medium with a suitable set of energy levels to support laser action.
- A source of pumping energy in order to establish a population inversion.
- An optical cavity or resonator to introduce optical feedback and so maintain the gain of the system overcoming all losses.

In order to create a laser beam from an active medium, that is, the medium in which population inversion is created, the medium is placed between two mirrors (Fig. 1.2). The photons are reflected back and forth by mirrors and get amplified more and more by the active medium. One of the mirrors is partially transmitting through which the laser beam comes out. Stimulated emission and optical resonator arm the laser with certain unique properties. These properties are briefly discussed in the following sections [3, 4].

1. *Monochromaticity*. The energy of a photon determines its wavelength through the relationship $E = hc/\lambda$, where c is the speed of light, h is Planck's constant,

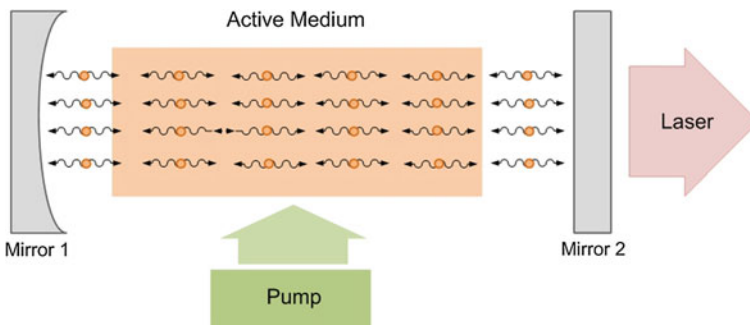


Fig. 1.2 Basic laser system

and λ is the wavelength. In an ideal case, the laser emits all photons with the same energy, thus the same wavelength, and it is said to be monochromatic. However, in all practical cases, the laser light is not truly monochromatic. A truly monochromatic wave requires a wave train of infinite duration. The spectral emission line from which it originates does have a finite width, because of the Doppler effect of the moving atoms or molecules from which it comes. However, compared to the ordinary sources of light, the range of frequency (line width) of the laser is extremely small.

2. *Coherence*. Coherent means that all the individual waves of light are moving precisely together through time and space, that is, they are in phase. Since a common stimulus triggers the emission events, which provide the amplified light, the emitted photons are “in step” and have a definite phase relation to each other. These emitted photons having a definite phase relation to each other generate coherent output, that is, the atoms emit photons in phase with the incoming stimulating photons and emitted waves add to the incoming waves, generating brighter output. Addition is due to the relative phase relationship. Photons of ordinary light also come from atoms, but independent of each other and without any phase relationship with each other and are not coherent. Therefore, laser is called a coherent light source where as an ordinary light is called an incoherent source of light. The concept of coherence can be well understood from the following Fig. 1.3.

There are two types of coherence—spatial and temporal. Correlation between the waves at one place at different times, or along the path of a beam at a single instant, is effectively the same thing and is called “temporal coherence.” Correlation between different places (but not along the path) is called “spatial coherence.”

3. *Directionality*. One of the important properties of laser is its high directionality. The mirrors placed at opposite ends of a laser cavity enable the beam to travel back and forth in order to gain intensity by the stimulated emission of more photons at the same wavelength, which results in increased amplification due to the longer path length through the medium. The multiple reflections also produce a well-collimated beam, because only photons traveling parallel to the cavity walls will be reflected from both mirrors. If the photon is the slightest bit off axis, it will be lost from the beam. The resonant cavity, thus, makes certain

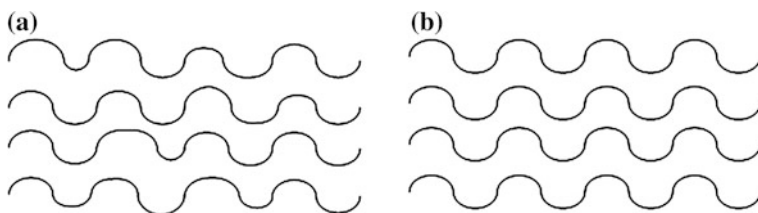


Fig. 1.3 a Incoherent. b Coherent beam

that only electromagnetic waves traveling along the optic axis can be sustained, consequent building of the gain. The high degree of collimation arises from the fact that the cavity of the laser has very nearly parallel front and back mirrors, which constrain the final laser beam to a path, which is perpendicular to those mirrors. For a laser, the beam emerging from the output mirror can be thought of as the opening or aperture, and the diffraction effects on the beam by the mirror will limit the minimum divergence and spot size of the beam (Fig. 1.4).

From diffraction theory, the divergence angle θ_d is:

$$\theta_d = \frac{\beta\lambda}{D}$$

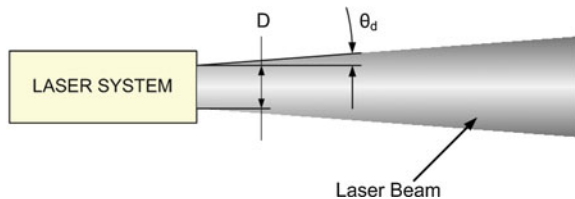
where λ and D are the wavelength and the diameter of the beam, respectively, and β is a coefficient whose value is around unity and depends on the type of light amplitude distribution and the definition of beam diameter. θ_d is called diffraction-limited divergence.

4. *Brightness*. The brightness of a light source is defined as the power emitted per unit surface area per unit solid angle. A laser beam of power P , with a circular beam cross section of diameter D and a divergence angle θ_d and the result emission solid angle is $\pi\theta_d^2$, then the brightness of laser beam is

$$B = \frac{4P}{(\pi D\theta_d)^2}$$

5. *Focussability*. Focusing of laser beams enables high intensity at the focusing spot. Laser power at the spot and its spot size are some of the crucial parameters during various techniques of laser material processing. Very low divergence of the laser beam allows it to be focused to very small spot $\approx \lambda$
6. *High power*. The accumulated photon density directly depends on the density of excited atoms in active medium and volume of active medium. Higher photon density results in higher laser power.
7. *Short-pulse generation*. Very high powers of lasers are also achieved by different methods of pulse generation/pulse compression techniques. Pulsed laser power in μs , ns , and fs time durations are widely available in MWs, GWs, and

Fig. 1.4 Divergence in laser beam



TWs power ranges while cw laser power is in the range of 10–100 kW. High harmonic generation allows the generation of attosecond pulses with even higher powers of lasers.

1.3 Lasers and Manufacturing Techniques

Though lasers did wonders for advanced applications of science, engineering, and medicine, but they failed in many simple applications. For example, when it was attempted to cut the chocolate candy and slice the bread, the outcomes were burnt charcoal and toast, respectively. These efforts just failed because of incorrect choice of laser and improper selection of processing parameters. Thus, right choice of laser and proper selection of processing parameters are mandatory to realize the applicability and capability of a laser in any application.

Figure 1.5 presents the schematic arrangement of a typical laser processing station. The system shows a laser integrated with a beam delivery system. The beam delivery system may be optical-fiber based or reflecting optics based. The optical-fiber-based beam delivery system is preferred over reflecting optics based due to ease of operations during the material processing. Various CNC laser workstations are used for the beam or job manipulations during laser material processing. Robots are not very common in laser processing due to inferior position accuracy. Among CNC workstations, 3-axis interpolation (X , Y , and Z) is sufficient to reach to any point in the space, but two more axes (A and C) are required to orient particular direction to reach. Therefore, 3-axis configuration is minimum system requirement and 5-axis is universal requirement without redundancy. Apart from axes-movements, laser workstation needs some more features, like laser on/off, gas on/off, powder feeder on/off, for laser rapid manufacturing (LRM). Depending upon the applications, various processing heads are used. The processing heads for cutting, welding, and cladding are different and specific to the applications. For the consolidated control of the laser material processing, the use of integrated controller is the recent trend.

Though a large variety of lasers employing different kinds of active medium covering a wide range of wavelengths and powers has been developed, only few are being used for material processing. CO_2 , Nd:YAG, and fiber lasers are the most popular systems, while excimer and diode lasers are also being employed for various other applications [2, 4]. Table 1.1 presents different type of lasers and their potential application.

In the field of industrial material processing, lasers have given a new direction to cutting of metallic and non-metallic sheets, welding of similar and dissimilar metals and composites, drilling, marking, metal forming, surface hardening, peening, surface alloying, cladding, and rapid manufacturing. Figure 1.6 presents the overview of laser-based manufacturing processes and their process domain in terms of laser power density and interaction time [2, 5]. Consequently, the scenario

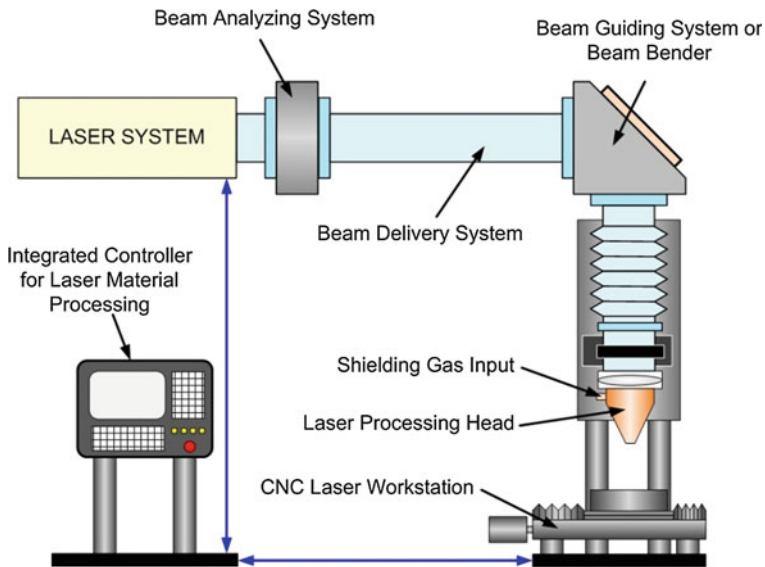


Fig. 1.5 Schematic arrangement of a typical laser processing station

Table 1.1 Different types of lasers and their applications

Laser (wavelength)	Applications
CO ₂ laser (10.6 μm)	Light- to heavy-duty industrial cutting, welding, and rapid manufacturing Laser surface modification including cladding, alloying, and rapid manufacturing for wear/corrosion resistance and dimensional restoration Laser ablation, and laser glazing
Nd:YAG laser (1.06 μm)	Light- to heavy-duty job shops in drilling, welding, cutting, marking, and rapid manufacturing
Fiber laser (1.08 μm)	Laser cleaning in conservation of artifact, paint stripping
Excimer laser KrF (0.248 μm)	Optical stereolithography
XeCl (0.309 μm)	Marking, scribing, and precision micromachining involving drilling, cutting, etching of profile
Copper vapor laser (0.51 μm)	High-speed photography Detection of finger prints for forensic applications Excitation source for tunable dye laser for isotope separation Precision microhole drilling and cutting
Semiconductor laser/diode laser (0.8–1.0 μm)	Optical computers, CD drivers, laser printers, scanners, and photocopiers Optical communication Industrial alignment Holography, spectroscopy, bio-detectors, ozone layer detector, pollution detection, bar code scanners, 3D image scanners

in manufacturing has changed, specifically for automobile, chemical, nuclear, and aerospace industries.

1.3.1 Laser Cutting

Laser cutting is one of the largest applications of lasers in metal-working industry and is a well-established universal cutting tool enables cutting of almost all known materials. One of the foremost reasons for wide acceptance of laser cutting was direct replacement of conventional cutting source with laser. When compared with other cutting processes (such as oxy-fuel cutting, plasma cutting, sawing and punching), its advantages are numerous, namely a narrow cut, minimal area subjected to heat, a proper cut profile, smooth and flat edges, minimal deformation of a workpiece, the possibility of applying high cutting speed, intricate profile manufacture and fast adaptation to changes in manufacturing programs [6]. The laser cutting uses different cutting mechanisms to cut different materials. Some of the mechanisms are vaporization, scribing, melt and blow, melt blow and burn, and thermal stress cracking [2].

Vaporization: In vaporization cutting, the focused beam heats the surface of the material to boiling point and generates a keyhole. The keyhole leads to a sudden increase in absorptivity and it results in quickly deepening the hole. As the hole deepens and the material boils, generated vapors erode the molten walls that ejects out the wall material, further enlarging the hole. Organic materials such as wood, Perspex, thermoset plastics, fiber-reinforced plastics are usually cut by this method.

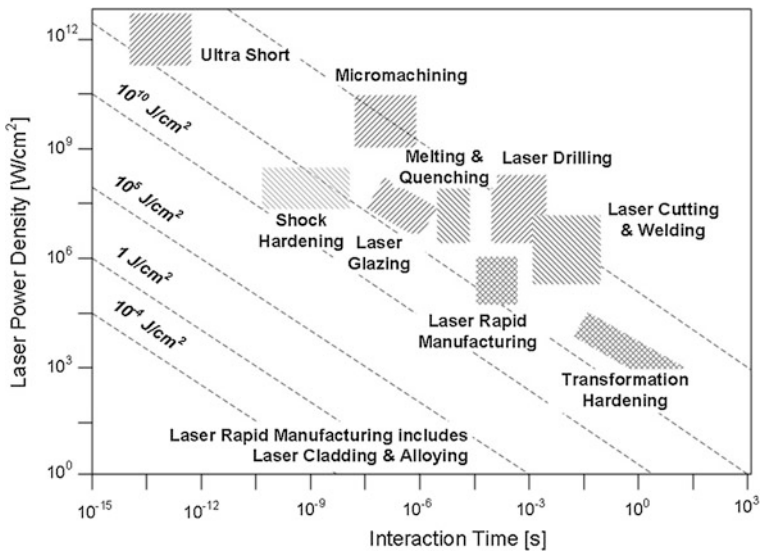


Fig. 1.6 Overview of various laser-based manufacturing processes and their process domain in terms of laser power density and interaction time [2, 5]

Melt and blow: Melt and blow or fusion cutting mode uses high-pressure gas to blow molten material from the cutting area, greatly decreasing the power requirement. First the material is heated to melting point then a gas jet blows the molten material out of the kerf avoiding the need to raise the temperature of the material any further. Materials cut with this process are usually metals. The distinct feature of this cutting mode is that the cut-edge material is same as the base metal and can be put to weld without cleaning the edge. The re-solidified layer has microcrack and ripple along the edge.

Scribing: This mode of cutting involves the drilling of small overlapping hole along the desired cut line by vaporization of the material. The sheet is then crack along the cut line. Generally, hard and brittle materials like ceramics and glass are cut by this mode of cutting.

Melt blow and burn: Melt blow and burn is a reactive cutting. This mechanism is successfully demonstrated in metals especially mild and stainless steel during oxygen-assisted cutting. This mechanism allows the cutting of very thick steel plates with relatively little laser power. The distinct feature of this cutting mode is that there is edge hardening due to existence of oxide and thermal cycle on the cut edge. This mode of cutting is also known as “burning stabilized laser gas cutting.”

Thermal stress cracking: Brittle materials are particularly sensitive to thermal fracture, a feature exploited in thermal stress cracking. A beam is focused on the surface causing localized heating and thermal expansion. This results in a crack that can then be guided by moving the beam. The crack can be moved as fast as in order of few m/s. It is generally used in cutting of glasses.

The use of various mechanisms during laser cutting of various materials leads to various advantages over the conventional cutting. The cutting capacity for particular set of processing parameters can be estimated by severance energy (SE). SE is defined as follows:

$$SE = \frac{P}{Vt}$$

where P is laser power (W), V is cutting speed (mm/sec), and t is thickness of the material. The quality of laser cut, that is, width of laser cut or kerf and the quality of cut edges depend upon laser, laser power (average for continuous wave (cw) and peak for pulsed), the motion of laser beam and workpiece. Table 1.2 presents laser cutting kerf width versus material thickness for some of the important engineering materials [7].

With increasing demands of personal customization and to provide variations, the laser cutting with three-dimensional processing is being widely used in interior of cars and high-end buses (most popular application is in roof linings, door, instrument panels, and arm rests), cutting of complex pipe profiles and hydro-formed parts [7, 8]. Most of the parts used in above applications area are primarily made up of polymer-based materials, and hence, the availability of robots resulted in increased popularity of this technology.

Table 1.2 Laser cutting kerf width and material thickness for important engineering materials [7]

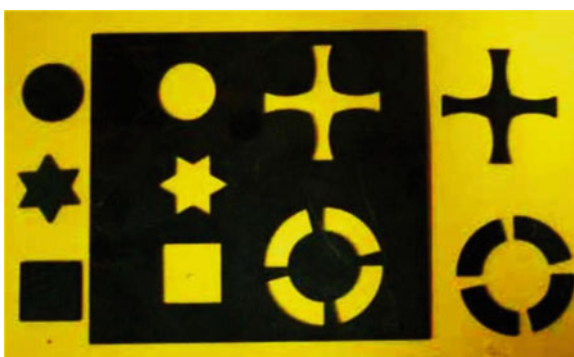
Material	Material thickness	Kerf width
Aluminum	2–3 mm	0.2–0.3 mm
Plastics	50–500 μm	$2 \times$ beam diameter
Steels	1.5 mm	50 μm
	2.5 mm	150 μm
	3.0 mm	200 μm
	6.0 mm	300 μm

Recent developments in laser systems in terms of power, beam quality, and different novel power modulation schemes have aided in addressing many complex problems of laser cutting in more productive way. Figure 1.7 presents the various profile cutting carried out at the authors' laboratory. The recent studies on the phenomenon of "striation free cutting," which is a feature of fiber laser assisted oxygen cutting of thin-section mild steel, concluded that the creation of very low roughness edges is related to an optimization of the cut front geometry when the cut front is inclined at angles close to the Brewster angle for the laser-material combination [9]. The studies to obtain fine and spatter-free pierced holes at the site of cut initiation along with dross free cut edges of minimum roughness and microstructural changes were also carried out. These studies indicated that suitable close-loop control of duty cycle in proportion to cutting speed in progressive change in pulse duty cycle in proportion to cutting speed will effectively suppress unwanted heating effects at sharp corners of laser cut profiles [10].

1.3.2 Laser Drilling

Since the invention of the laser, there has been a constant development to shorter pulse times. Not long ago 10-ns pulses were the shortest obtainable but now femtosecond lasers are widely applied and even shorter pulses can be obtained in

Fig. 1.7 Profile laser cutting carried out at RRCAT



the laboratory. When energy is released in very short time, it results in high peak powers as high as 10^{10} W or orders more. The intensity of the incoming beam is expressed as I_0 . The decrease in the laser intensity into the depth of material is given by $I_x = I_0 e^{-\alpha x}$, where α optical absorptivity of the material and x the depth into the material. The optical penetration depth δ ($\delta = 2/\alpha$) is the depth of material whereby almost all laser energy is absorbed. This optical penetration depth for metals is found to be in the order of 10 nm. It means that the laser energy heats a 10-nm-thick layer of metal in 1 ps. This heat will diffuse from that skin layer (δ) to the bulk. The diffusion depth is expressed by $d = \sqrt{4at}$ with a as the thermal diffusivity and t the diffusion time. In case of steel, for 10-fs pulse, we obtain a diffusion depth of 1 nm while during a 1-ps pulse, the heat diffuses over 10 nm. Taking the results together than we see that

- It takes 1 ps to convert laser energy into heat.
- This takes place in a 10-nm-thick skin layer.
- The diffusion depth for 1 ps is also 10 nm.

From these results, we consider a pulse as ultrashort when the (thermal) diffusion depth during the pulse is in the same order or less than the skin layer depth (optical penetration depth). The optical penetration depth depends on the material and the laser wavelength. The diffusion depth depends on the material properties. Table 1.3 presents the ultrashort pulses common for some of the important engineering materials.

When very short pulsed laser beam is focused on any metallic surface, it simply ablates the thin layer of material due to very high power density. The single or repetitive use with appropriate position of focal spot of such pulse results in drilling. In terms of process technology, this technology can be deployed in four ways: single-pulse drilling, percussion drilling, trepanning, and helical drilling. Figure 1.8 presents the schematic diagram of these processes.

In single-pulse drilling, the hole is created in single pulse. Since the drilling is depending on single pulse, the pulse duration and beam profile plays a vital role. The attainable depths in single-pulse drilling range from several micrometers for nanosecond pulse and several millimeters for microsecond pulse. For drilling, higher depth repetitive pulses with appropriate position of focal spot are used and this process is known as percussion drilling. For drilling holes greater than the focal spot and of non-circular shape, the laser beam spot is translated in the profile plan and this drilling process is called laser trepanning. Helical drilling is special

Table 1.3 Ultrashort pulse for some of the important engineering materials [7]

Material	Ultrashort pulse
Metal	1 ps
Ceramic	10 ps
Plastic	1 ns

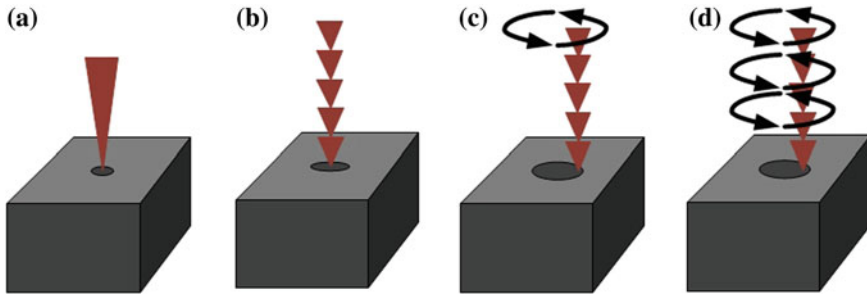


Fig. 1.8 Schematic diagram presenting different drilling processes **a** single drilling **b** percussion **c** trepanning, and **d** helical drilling

case of laser trepanning when the focal spot of laser beam is positioned appropriately along the drilling depth.

Drilling holes on aerospace and avionic components to improve the heat transfer, tool filers of automobiles, are some of the important industrial applications of laser drilling. As compared to electro-eroded and mechanically drilled holes, the laser-drilled holes still have limitations especially in terms of concentricity and burring. Laser drilling is also used in drilling holes in diamond, one of the hardest material on earth. There is difficulty in diamond drilling because it is transparent for a wide range of wavelength. At high power densities, however, the diamond is transformed into graphite, which absorbs the laser power and is removed by ablation subsequently. Diamond machining is currently done by microsecond pulses of Nd:YAG lasers and nanosecond pulses of excimer lasers [11]. Thin layers of graphite or amorphous carbon are found on the surface after laser machining which requires an extra polishing operation to remove the graphite. However, this extra step of polishing can be removed if ultrashort femtosecond lasers are used [12].

In the domain of microdrilling, Excimer lasers are preferred over other lasers, as they offer three significant advantages. First, the short ultraviolet light can be imaged to a smaller spot size than the longer wavelengths. This is because the minimum feature size is limited by diffraction, which depends linearly with the wavelength. The second advantage is that due to the mechanism of “photoablation” there is less thermal influence or melting of the surrounding material. Finally, most materials show a strong absorption in the ultraviolet region. This means that the penetration depth is small and each pulse removes only a thin layer of material, allowing precise control of the drilling depth [8, 13].

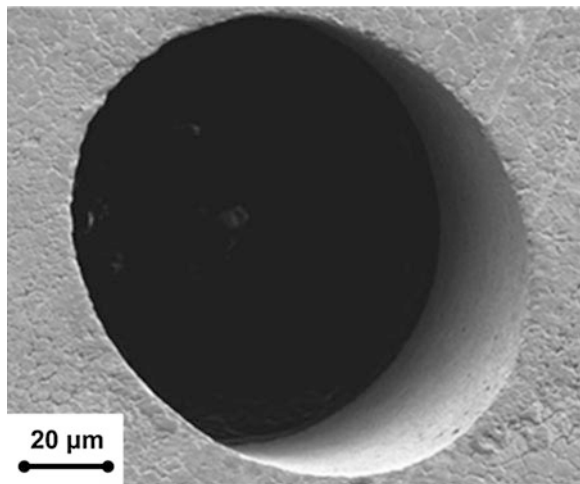
One of the exciting applications is fabrication of printed circuit board (PCB), where many bridging holes (vias) are produced to make electrical connections in multi-layer PCBs. The holes are drilled in dielectric polyimide layer until the underlying copper layer is uncovered. The drilling then stops automatically because of the higher threshold (one order of magnitude) of copper. The conducting connection is made by a following chemical deposition of copper on the walls. The process has been developed by Bachmann [14] and is used for drilling

small $\approx 10 \mu\text{m}$ holes. For bigger holes of $100 \mu\text{m}$ and above, the cheaper and faster CO_2 lasers are currently used. In the fabrication of nozzle for the ink jet printers, an array of small orifice with precisely defined diameter and taper are required. These holes are located on the top of a channel with resistor heater. Small bubbles are formed when the ink is heated, ejecting small (3–80 pl) drops out of the nozzle. Riccardi et al. [15] describes the fabrication of high-resolution bubble ink jet nozzles (similar application is referred in Fig. 1.9). Depending on the design, up to 300 holes have to be drilled simultaneously in a $0.5 \times 15 \text{ mm}$ area. The total drilling time is about 1 s, using a 300 Hz, KrF laser. Recent developments have facilitated the smaller holes below $25 \mu\text{m}$ diameter for this application.

1.3.3 Laser Welding

When high-power laser beam is focused, it produces very high intensities of the order of 10^4 – 10^7 W/cm^2 at the focal spot. When such a high-intensity spot is placed on the edges of the materials forming a joint in butt or lap joint configuration, the material melts and solidifies as soon as the beam is passed away. This melting and solidification of the edges under proper shielding result in welding of the material. Among various welding processes, high-energy beam welding employing laser has the key benefits in terms of localized heating, faster rate of cooling, smaller heat-affected zone (HAZ), easier access weld seam through fiber delivery, access to weld intricate geometrical shapes and sizes, reduced workpiece distortion and undulation and possibility of performing welding in ambient and controlled environment [16–21]. The following are main characteristics of the laser-welded joints:

Fig. 1.9 An injection nozzle hole with a high-power picosecond laser produces very sharp edges with no burr or melt and low surface roughness inside the hole, resulting in an optimum spray cloud of the fuel



- Deep and narrow weld.
- Very low thermal distortion and residual welding stresses.
- Narrow HAZ and minimum metallurgical damage.
- High speed and high production rate.
- High precision control in space and energy.
- Autogenous welding, that is, no-filler is required.
- Possibility of dissimilar material joints.
- Welding of relatively remote- and limited-access locations.
- Easy to automate.

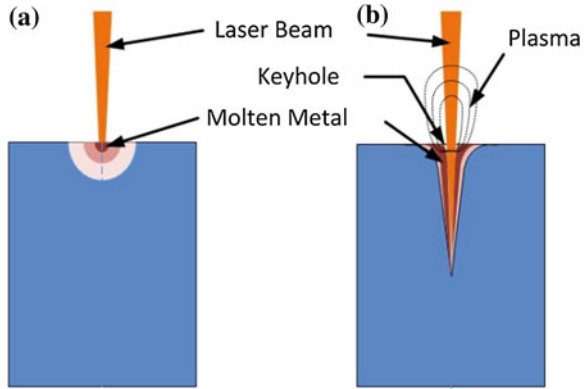
Because of these distinguished advantages, it is widely employed for welding coarse to fine precision of thick to thin metals, ceramics, and polymers. The applicability and preference of laser welding depends on laser properties and parameters, material properties and methodology, but the selection of welding joint is broadly governed by the functionality of components. There are few limitations of the laser welding:

- Close fitting of joints and accurate beam/joint alignment is required.
- Precision control of laser and process parameters are required.
- Fixed and running cost of the laser welding machines is high.

To form a laser weld, the laser beam is finely focused on the center line of the joint. Initially most of the incident laser power (even more than 90 %) is reflected, since at the room temperature, metals are good reflector of the infrared radiation. As the metal surface is heated, the surface reflectivity decreases until at the boiling, where it is negligible. The laser energy is absorbed in the skin depth and depending upon the power intensities, two different modes of the laser welding takes place. One is conduction welding and another is keyhole welding. When the material thickness is small and the intensity of the incident laser is relatively low, the material melts and temperature does not exceed the boiling temperature of the material. The aspect ratio (ratio of weld bead height to width) of the weld bead is between 1 and 1.5 for this mode of laser welding. When the power intensities are sufficiently high to cause the vaporization of the material, a hole is created at the center of the molten pool by rapidly escaping metal vapors. In this case, the laser beam further melts and vaporizes the material at the bottom of the created hole. Thus, a narrow hole is formed along the depth of the material. There is dynamic equilibrium among the molten metal, escaping vapor, heat input due to laser, and associated heat transfer phenomena. At the trails edge of the keyhole, the molten material collapses and solidifies forming a deep penetration welding. This mode of welding leads to high aspect ratio in the range of 6–10 (Fig. 1.10).

There has been an extensive experimental and modeling efforts giving insight into laser welding process and associated control for quality and repeatability. In laser welding, when metal melts, its volume increases due to thermal expansion and it forms a convex-shaped weld bead after solidification. The improper selection of

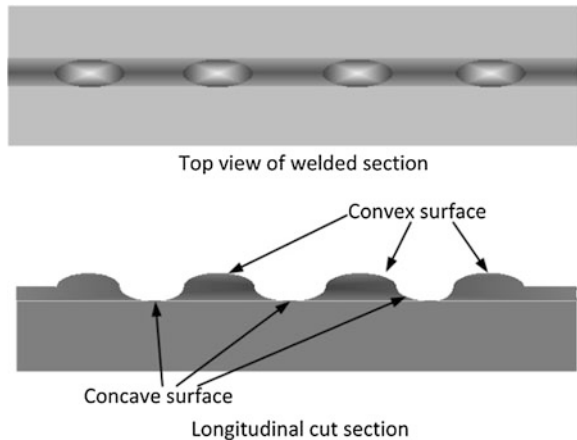
Fig. 1.10 Schematics of **a** heat conduction and **b** deep penetration welding



process parameters results in humping. In humping, there is periodic formation of convex and concave weld bead formation (Refer Fig. 1.11 for details) [22].

In many applications, this protruding convex-shaped weld bead is not acceptable. This can be reduced by appropriate edge preparation. In one of the recent efforts, the size and shape of the edge preparation were estimated experimentally in the authors' laboratory. 6-mm-thick sample of austenitic stainless steel-type 304 (size 15×100 mm) having chamfered edges with an included angle of 60° at various chamfered depth ($d = 0.5, 0.8$ and 1.0 mm) was used for the investigation. The detail of chamfered edges is presented in Fig. 1.12. During laser welding, the molten material has tendency to escape away from the molten pool due to its dynamics. Figure 1.13 presents the typical flow molten metal in the molten pool during laser welding. The selected chamfered edges provided a wider wetting surface and easy expansion of the molten material. The depth of the chamfered is selected to provide the compensation to convexity. Table 1.4 presents the results of the laser welding experiments. Fig. 1.14a and b presents the top view of weld sample without chamfered edges and with 0.8-mm-deep chamfered edges, respectively.

Fig. 1.11 Schematic diagram of humping



During the laser welding, there is angular distortion of the plates due to heating and cooling of the material near the weld zone. There have been several theoretical and experimental studies to predict the distortion [23, 24]. These studies are the extension of the similar studies carried out for the conventional welding processes. For butt-joint configuration, the distortion can be minimized by suitably selecting the proper joint geometry. The angular distortions of 6-mm austenitic stainless steel 304 plates were also studied, and an alternative methodology for minimizing distortion in butt-joint configuration was developed recently in authors' laboratory. Laser welding in butt-joint configuration for the sample with and without chamfered edges was carried out. It was found that the angular distortion for the samples with edges was significantly lesser than that of without chamfered edge. The angular deformation of laser-welded joints having different depth of chamfered edges as a function of laser energy per unit length is shown in Fig. 1.15. Minimum distortion was obtained with 0.8 mm groove depth with laser power per scan speed of 145 kJ/m. For further reduction in the angular distortion, the laser welding was tried from both top and bottom sides. Negligible angular distortion was obtained for both sides welding. The effect of groove on deformation is presented in Fig. 1.16a and b. It is just because the thermal stresses generated during the laser welding cancels each other when welded from the both sides.

Recently, a new approach of laser welding was reported by Fraunhofer IWS Dresden to weld dissimilar materials such as aluminum/copper, aluminum/magnesium, or stainless steel/copper clearly showing better quality [25]. They deployed a highly dynamic 2D scanner with high scanning frequency (up to 2.5 kHz) to generate extremely small weld seam with high aspect ratio. This leads to very short melt pool lifetime, thereby suppressing the formation of brittle intermetallic phases. In these experiments, the melting behavior of metallic mixed joint, seam geometry, chemical composition, melt pool turbulence, and solidification was controlled by high frequency, time, position, and power-controlled laser beam oscillation. Using this strategy, phase seam values less than 10 μm was obtained for the aluminum/copper dissimilar joint. The tensile strength of this dissimilar joint was found to be same value as that of aluminum/aluminum joint [25].

1.3.4 Laser Brazing

Dissimilar metals are preferred due to better material utilization with improved functionality in many engineering applications. It has encouraged the research thrust on various brazing processes including laser brazing. Among the various

Fig. 1.12 Details of chamfered edges preparation (d = depth of groove)

