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Jyotsna Dutta Majumdar
Indranil Manna *Editors*

Laser-Assisted Fabrication of Materials

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Jyotsna Dutta Majumdar · Indranil Manna
Editors

Laser-Assisted Fabrication of Materials

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Editors
Jyotsna Dutta Majumdar
Department of Metallurgical and
Materials Engineering
Indian Institute of Technology
Kharagpur, West Bengal
India

Indranil Manna
Department of Metallurgical and
Materials Engineering
Indian Institute of Technology
Kharagpur, West Bengal
India

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Dedicated to:
Professor B. L. Mordike—
A pioneer in Laser Materials Processing
and an academic par excellence

Foreword

This book opens the window on a new mode of manufacturing. Lasers are penetrating manufacturing technologies to an extent so pervasive that it could be compared to the effect of electrical-driven motor technology on manufacturing at the end of the nineteenth century, or of battery-charged handtools a decade or two ago. We are entering the age of photon-driven materials manufacturing, of light-beam manufacturing technologies. The higher the laser powers available, the more diverse the laser characteristics (wavelength, pulse duration, beam format), the more these new technologies will multiply. Ultimately, they will impact or intercede with another social change fast sweeping our earth, the trends toward eco-friendly manufacturing, energy efficiency, and the avoidance of toxic chemical processing. The future of laser-based technologies toward all these goals is very promising. High power diode-pumped lasers have wall-plug efficiency of 30% or more—70% is ultimately not unrealistic. Commercial lasers are starting to fill new temporal and spectral domains. High picosecond and nanosecond systems are now powerful enough for insertion into industrial processing manufacturing production lines. The ubiquitous femtosecond laser is now a fiber laser, simple, rugged, and compact in design, suitable for industrial deployment. New laser sources, with new laser media or non-linear optical conversion schemes provide laser beams with a range of photon energies, with wavelengths ranging from the UV to the mid-IR. These developments have spurred the scientific understanding of the light–materials interaction regimes that underpin these technologies. Many university centers, funded in part by forward-looking corporate sponsors explore the many new processing modalities offered by current high power laser technologies. The study of the interaction science has now opened a bridge to another important partner in this industrial revolution, namely materials science and engineering, even the new materials science called nanoscience. Nanoparticles and nanomaterial components like carbon nanotubes, metallic nanowires, and complex nanoparticles, are now beginning to enter the manufacturing business. They are becoming cheap, can be manufactured en masse, and specified to specific needs—commercial businesses are beginning to drive their development. The introduction of laser sources of pin-point variable, motional transportable high energy sources to these materials opens the whole new field of laser-synthesized materials, new alloys, metallo-ceramics, and nanoparticle doped dielectrics, to name a few. These I predict will open vast new levels to manufactured components.

This book sets the stage for some of these exciting developments. Drs. Dutta Majumdar, Manna, and Nath from IIT Kharagpur in West Bengal, India, open the book with introductions to laser-assisted fabrication and laser materials processing. These are then followed by chapters addressing laser machining by Drs. Brandt and Sun from IRI in Swinborne, UK, laser-assisted welding by Dr. Padmanabhan from ARCI, Hyderabad and direct laser cladding by Drs. Weishiet and Gasser from RWTH in Aachen, Germany. Andreas Oestendorf from the University of Bochum summarizes laser-assisted microfabrication and Jonathan Wolfson from Loughborough University reviews laser processing of polymers for biomedical applications. Drs. Pfleging and Rohde from Karlsruhe Institute of Technology in Germany describe laser micro and nanoprocessing of ceramics, polymers, and thin films, and Dr. Smurov Igor from the Ecole Nationale d'Ingenieurs, St. Etienne, France discusses all the important issue of temperature monitoring by optical methods in laser processing. Finally, Dr. Kukreja from RRCAT, Indore, India gives an overview of the future scope of Industrial Acceptability of Laser Assisted Fabrication. Overall this book, with contributions from well-known experts and practitioners in this new technology from European and Indian institutions provides perspectives of some of the many new manufacturing technologies that will evolve from this new field of laser-assisted manufacturing.

Orlando, FL, USA Prof. Martin Richardson

Prof. Martin Richardson
Trustee Chair Director
Townes Laser Institute
Northrop Grumman Professor of X-Ray Photonics
Professor of Optics, Physics & Electrical Engineering
University of Central Florida
College of Optics & Photonics
4000 Central Florida Blvd
Orlando, FL 32816-2700
USA
Tel.: +1-407-8236819
e-mail: mcr@creol.ucf.edu
http://lpl.creol.ucf.edu
http://www.townes.ucf.edu

Foreword

Materials processing and manufacturing is central to the economic and technology development of any nation. During the past decade new technological needs in the area of microelectronics, nanoscience, aerospace, and biology had motivated for the development of more precision, higher resolution, and better surface and volume localization processing techniques. This development would not have been possible without the rapid development of new laser sources. The highly coherent, convergent, and monochromatic electromagnetic radiation of the laser beam can result in power densities of the order of 10^{15} W/cm^2 and hence can be useful for applications such as but not limited to surface melting, surface cladding, cutting, ablation, and texturing. The capabilities and limitations of any laser system for a particular application depend on the fundamental interaction mechanism of the electromagnetic radiation with materials. The various phenomena that take place during the interaction of an electromagnetic radiation with the surface of a material is absorption, reflection, refraction, scattering and transmission. The extent of the above effects further depends both on the characteristics of electromagnetic radiation and thermo-physical properties of the material. Hence, laser materials processing is a complex interdisciplinary subject demanding understanding of various branches of sciences and engineering to gather a thorough knowledge and understanding.

A 5-kW CO_2 laser was first developed in 1977 for materials processing. Although it was developed in the United States, it gained popularity in Europe and more specifically in Germany due to the high demand in automotive manufacturing. Later, in 1990 a 10-kW and in 1995 a 30-kW CO_2 laser was also introduced in the world market. Most of these developments were not just focused on high power but also on beam quality, thus enabling high processing speeds and higher accuracy. As a result of these activities, the market for laser systems for materials processing kept continuously growing. Apart from the automotive technology, a wider distribution of laser technology was also stimulated with new fields of applications such as shipyard, aircraft, and steel making industries during those days. In the advent of the development of the state of art solid state and high power diode lasers, expensive, bulky, and least efficient CO_2 lasers are slowly fading away from the manufacturing arena and are being replaced by high power solid-state lasers.

The first lamp pumped Nd:YAG lasers in kilowatt range came to the market in the early 1990s. Due to the high monochromaticity and capabilities of beam guidance by fibers, Nd:YAG lasers gained popularity for three-dimensional processing in car body fabrication and other applications. A couple of years back another advancement in solid-state lasers came in the form of diode pumped Nd:YAG laser systems for materials processing. Due to the efficient pumping and cooling of the active medium the diode pumped Nd:YAG lasers are associated with better beam quality, higher power stabilities, longer maintenance intervals, and higher beam efficiency.

The above advancements not only led to rapid and economical shop floor production, but also improved the quality in terms of applications such as surface alloying, surface cladding, glazing, annealing, cutting, etc. Other developments that were associated with the laser system were its operation mode. Here, the output power of the laser beam was modulated to be either continuous with constant amplitude known as continuous wave (CW) mode, or periodic known as pulsed beam mode. Due to the constant output power of the laser, CW mode was mostly used for applications such as surface cladding, glazing, and annealing. For pulsed mode operation, pulsing was carried out by various ways such as normal pulsing, Q-switching, and mode-locking to achieve pulses in the range of milliseconds to femtoseconds. These short range pulses resulted in instantaneous high peak power for sudden temperature rise and cooling and thereby found new inroads into processes such as microdrilling, nanoscale laser processing, and micromachining of biomaterials and biological components, direct transfer, and microprinting of functional materials by laser-induced forward transfer (LIFT), self-organized surface nano structuring, thin film deposition, etc.

Some of the major advantages associated with laser-based microdrilling is its ability to cut holes without any direct contact, fast processing, flexibility for hole size and shape, compactness, and cost effectiveness. The high intensity of the laser beam associated with pulsed lasers also enables micromachining of any material. Further, the short range pulses enables controlled material removal and small heat affected zone (HAZ) owing to its short interaction time with material. Owing to the above interesting features, ultra-short range laser pulses (milliseconds to femtosecond) have already found engineering applications for microdrilling in inkjet printer nozzles, gas flow chemical sensors, biomedical sensors, fuel injection nozzles, aerosol atomisers, food packaging, solar cell technology, and turbine blade cooling. Hence, these lasers are nowadays a common microdrilling tool in industry sectors such as semiconductor, aerospace, automotive, electro-optics, photonics, optical, food, etc.

Apart from drilling, lasers in both pulsed and CW mode are also effectively established for two-dimensional machining process such as cutting and shaping. Here, a highly intense laser beam is focused on the workpiece to melt or vaporize the workpiece throughout its thickness or depth and simultaneously expelling the molten metal using an assist gas to create a cutting front. One of the first industrial applications of laser cutting is cutting of slots in die boards using a 200-W laser. Currently, lasers are capable of cutting a wide range of metallic materials such as steels, superalloys, copper, aluminum, and brass, and nonmetallic materials such as ceramic, quartz, plastic, rubber, wood, and cloth. Because of their numerous interesting features as discussed earlier they are also used for precision cutting of biodegradable and metallic stents and hence play a big role in medical device industries. Apart from manufacturing, lasers are also used in medicine and surgery for applications such as noncontact osteotomy of hard tissue, corneal surgery, skin resurfacing, etc.

For almost a decade now lasers had proved their usefulness in terms of bulk processing of materials and can be conveniently used for many other diverse applications such as hardening of automotive engine cylinder bore by laser cladding and laser surface treatment, joining of metals by laser welding. But with advancement in science and technology and the growing demand for miniaturization, lasers are not far away in terms of nanoscale processing of materials. A highly intense laser beam from a pulsed laser can be effectively used to transfer a nanoscale pattern from one surface to the other by LIFT, create self-organized nanostructures, and nano thin films on substrate materials by laser ablation.

The above advancement in terms of new avenues of processing and product development using lasers has quite surprisingly not yet been touched upon in a single volume book. This book edited by Dr. Jyotsna Dutta Majumdar and Professor Indranil Manna is definitely going to fulfill those shortcomings and provide the readers a compact and yet broad knowledge gathering in advance processing and developments in the area of laser materials processing. The book includes the chapters on various aspects of laser-based processing ranging from surface modification, nano/micro machining, joining to laser-based diagnostics in materials ranging from metallic, ceramic, polymers to biomaterials. These chapters provide an overview of processing technology as well as research summary and all the chapters are prepared by experts in the field from industry, academia, and research laboratories in various parts of the globe thereby providing the perspectives of laser materials processing in these parts of the world. We are pleased to receive this book prepared under the guidance and leadership of Dr. Dutta Mazumdar and Professor Manna and I undoubtedly say that the book chapters collected in this volume are going to foster the needs of researchers and engineers with a valuable and deeper understanding of this exciting field.

Denton, TX, USA Prof. Narendra B. Dahotre

Prof. Narendra B. Dahotre
Department of Materials Science and Engineering
Laboratory of Laser Materials
Synthesis and Fabrication
University of North Texas
Denton TX
USA

Preface

Due to its ability to deliver coherent beam with negligible divergence, laser as a source of heat enjoys immense importance in the field of maco and micro-processing of materials. Fabrication may be achieved by removal of materials (laser assisted cutting, drilling, etc.), deformation (bending, extrusion), joining (welding, soldering), and addition of materials (surface cladding or direct laser cladding). A faster processing speed, conservation of strategic alloying elements, a large heating/cooling rate associated with the processing and retention of metastability in the microstructure are the notable advantages associated with laser assisted fabrication of materials. However, in spite of the unique advantages associated with the technique, large-scale application of the technology needs to be ensured. Acceptance of the technology in industry scale is yet to be popular, predominantly due to lack of widespread knowledge on the different materials phenomena and the influence of laser parameters on it. However, extensive research efforts are undertaken and the significant contribution in this direction encompasses various fields like interaction of laser with materials, role of process parameters on the different materials processing and process optimization, solidification behavior of materials under non-equilibrium processing conditions, development of metastable microstructures/novel materials, and modeling/process control. A complete knowledge in this direction demands blending of the existing theory with the advanced research in this direction. The compilation on 'Laser assisted fabrication' is aimed at (a) Developing in-depth engineering concepts on various laser assisted macro and micro-fabrication techniques; (b) Engineering background-a review of engineering background of different micro/macro-fabrication techniques; thermal history of the treated zone; microstructural development and evolution of properties of the treated zone; (c) Application of laser assisted fabrication including laser cutting and drilling, welding, surface modification, laser forming, and rapid prototyping; (d) An in-depth understanding of laser assisted microfabrication of metallic, polymeric materials, and thin film and (e) finally introducing an industrially acceptable optical monitoring tool for control of laser processing. It consists of 11 chapters. The contributions from the authors who have expertise in different areas of laser materials processing are gratefully acknowledged. Needless to mention, without the time and efforts spent by the reviewers this special issue would not have been presented in this form. The invitation, cooperation, and encouragement from Dr. Claus Ascheron and necessary help from Dr. Elke Sauer from Springer Verlag were of immense help to nucleate and expand the contribution in the present form.

Laser parameters play an important role in determining the properties of the processed zone. Chapter 1 presents a brief introduction to different types of lasers and their general application, fundamentals of laser–matter interaction, and classification of laser material processing. The materials processing techniques covered have been broadly divided into four major categories; namely, laser assisted forming, joining, machining, and surface engineering. Besides discussing the scope and principle of these processes, each section enumerates a detailed update of the literature, scientific issues, and technological innovations. The entire discussion primarily focuses on correlating the properties with processing parameters and microstructure and composition.

Recently, a large numbers of lasers have been developed aimed at application for different purposes, especially, fabrication of miniature components. Chapter 2 presents a brief overview of recent developments of lasers and its application in materials processing. The applications of excimer lasers (operating in short wavelengths in ultraviolet spectrum) and Ti-sapphire on micro-machining like MEMS, microelectronics, telecommunication, optoelectronics, and biomedical devices have been discussed in detail.

Laser cutting is a popular manufacturing technique which has a potential scope of applications in cutting of different materials, especially, difficult to cut materials. Chapter 3 summarizes the up-to-date progress of laser assisted machining of metals, ceramics, and metal matrix composites. It also discusses the analysis of temperature distribution around the cutting region, material removal mechanisms, tool wear mechanisms, and the improvement in machined surface integrity of various engineering materials by the assistance of laser beam.

Laser as a source of heat can be effectively used for joining of materials by fusion welding and brazing in autogenous (without filler material) or with a filler or in hybrid modes. However, to overcome certain limitations associated with laser welding, modifications in process designing have been undertaken like laser-arc hybrid welding, remote welding, induction assisted welding, laser weld brazing, and SHADOW welding. The process may be extended to join plastics and ceramics. Chapter 4 describes the basic principles of various laser-based joining processes, laser system technology, process parameters, metallurgical effects on different base materials, joint performance, and applications.

Direct laser cladding (DLD) is the emerging manufacturing technique for development of near net shape components. A rapid processing speed, one-step processing, possibility in retention of metastability in the microstructure and development of components with improved properties are the advantages associated with the technique. Chapter 5 describes the additive manufacturing techniques by direct laser cladding along with its practical applications examples.

Processing of materials on the micro scale requires pulsed and/or short wavelength laser systems with moderate average powers in the range of a few watts or below along with good beam qualities. Chapter 6 provides an overview of pulsed laser assisted micromachining with a focus on structuring by laser ablation, laser generative processes, and finally nanomachining.

Polymers have numerous engineering applications where they need to be shaped. One of the important applications of polymeric materials is bio-implant materials, however, it is known that they offer excellent bulk properties for biological applications; however, their surface properties need to be tailored to improve their performance. Chapter 7 presents the detailed investigations on CO_2 laser surface processing of nylon 6,6 and its effect on surface characteristics and properties of modified surface.

Laser assisted fabrication of materials on micro and nanoscale offers a cost-effective solution for advanced material research and application. Laser ablation and surface modification are suitable for direct patterning of materials and their surface properties. Chapter 8 presents the application of lasers in patterning, rapid prototyping, and small-batch manufacturing. Especially, the applications of ultraviolet, NIR and IR laser radiation for precise and debris-free pattern generation, machining, and rapid manufacturing are discussed.

The thermal history of the processed zone plays an important role to determine the microstructure, thermal stress distribution, and properties of the fabricated components. However, due to very short laser–material interaction time during processing, measurement of temperatures by conventional techniques is difficult leading to the development of heat and mass-transfer model for prediction of performance of fabricated components. Recent developments in optical sensors led to invention of tools for precise measurement of temperature during laser processing. Chapter 9 discusses different optical-based techniques for monitoring of temperatures during laser materials processing.

The stumbling block for industrialization of laser is due to the following facts: high installation cost, lack of understanding on the microstructures and properties in the fabricated component due to non-equilibrium processing by laser, optimum fabrication quality under narrow process parameters, and unavailability of data points on optimum process parameters. However, laser assisted cutting, surface hardening and similar material welding are the three important fabrications where laser as a source of heat are gradually getting popular. Chapter 10 critically reviews the scope for the industrial acceptability and adaptability of high power lasers to assess the real potential of these research areas.

In conclusion, it may be stated that all the articles in the present issue present the details of laser assisted macro and micro-processing of materials, principle of individual technique and original research efforts on advanced field of laser materials processing. We sincerely acknowledge the secretarial help by Mr. Prashant Sharma and Subhasisa Nath, research scholars working with us for helping us during the preparation of the volume. The cooperation and help from our family members are gratefully acknowledged. Finally, we wish the issue to be a successful, popular, and useful one to engineers, scientists, and researchers in the field of materials science and manufacturing technology.

Kharagpur, India

Jyotsna Dutta Majumdar
Indranil Manna

Contents

Contributors

Gerhard Backes RWTH Aachen University, Aachen, Germany, e-mail: gerhard.backes@ilt.fraunhofer.de

Prof. M. Brandt Industrial Research Institute Swinburne, 264 Plenty Road Bundoora, Bundoora, VIC 3083, Australia, e-mail: milan.brandt@rmit.edu.au

P. Ganesh Laser Welding and Surface Engineering P.O.CAT, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India, e-mail: ganesh@rrcat.gov.in

Dr. Andres Gasser Fraunhofer-Institut fuer Lasertechnik, ILT, Steinbachstr. 15, 52074 RWTH, Aachen, Germany, e-mail: andres.gasser@ilt.fraunhofer.de

Prof. Smurov Igor Ecole Nationale d'Ingénieurs de Saint-Etienne (ENISE), DIPI Laboratory, 58 rue Jean Parot, 42023 Saint-Etienne Cedex 2, France, e-mail: smurov@enise.fr

Torsten Jambor RWTH Aachen University, Aachen, Germany, e-mail: torsten.jambor@ilt.fraunhofer.de

Rakesh Kaul Laser Welding and Surface Engineering P.O.CAT, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India, e-mail: rkaul@rrcat.gov.in

Robert Kohler Institute for Materials Research, Karlsruhe Institute of Technology, Karlsruhe, Germany

Prof. L. M. Kukreja Laser Welding and Surface Engineering P.O.CAT, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India, e-mail: kukreja@rrcat.gov.in

Prof. J. Lawrence Loughborough University, Leicestershire LE11 3TU, Great Britain, UK, e-mail: J.Lawrence@lboro.ac.uk

Dr. J. Dutta Majumdar Indian Institute of Technology, Kharagpur, West Bengal 721302, India, e-mail: jyotsna@metal.iitkgp.ernet.in

Prof. I. Manna Central Glass and Ceramic Research Institute, Kolkata 700032, India, e-mail: imanna@metal.iitkgp.ernet.in

Dr. Doubenskaia Maria DIPI Laboratory, Ecole Nationale d'Ingénieurs de Saint-Etienne (ENISE), 58 rue Jean Parot, 42023 Saint-Etienne Cedex 2, France

Prof. A. K. Nath Department of Metallurgical and Materials Engineering, Indian Institute of Technology, Kharagpur 721302, West Bengal, India, e-mail: aknath@mech.iitkgp.ernet.in

Prof. Andreas Ostendorf Ruhr-University Bochum, 44780 Bochum, Germany, e-mail: andreas.ostendorf@ruhr-uni-bochum.de

Dr. G. Padmanabhan Centre for Laser Processing of Materials (CLPM), ARCI, Hyderabad 500005, India, e-mail: gp@arci.res.in

Dr. C. P. Paul Laser Materials Processing Division, Raja Ramanna Centre for Advanced Technology P.O. CAT, Indore 452 013, India, e-mail: paulcp@rrcat.gov.in

Dr. Wilhelm Pfleging Institute for Materials Research, Karlsruhe Institute of Technology, Karlsruhe, Germany, e-mail: Wilhelm.Pfleging@kit.edu

Dr. Norbert Pirch Fraunhofer-Institut fuer Lasertechnik, ILT, Steinbachstr. 15, 52074 RWTH, Aachen, Germany

B. Tirumala Rao Raja Ramanna Centre for Advanced Technology P.O. CAT, Indore 452 013, India, e-mail: trao@rrcat.gov.in

Dr. Magnus Rohde Institute for Materials Research, Karlsruhe Institute of Technology, Karlsruhe, Germany, e-mail: Magnus.Rohde@kit.edu

Dr. B. Shanmugarajan Centre for Laser Processing of Materials (CLPM), ARCI, Hyderabad 500005, India, e-mail: bshanmu@arci.res.in

Isabelle Südmeyer Institute for Materials Research, Karlsruhe Institute of Technology, Karlsruhe, Germany

Dr. S. Sun Industrial Research Institute Swinburne, 264 Plenty Road Bundoora, Bundoora, VIC 3083, Australia, e-mail: shoujin.sun@rmit.edu.au

Dr. David Waugh University of Lincoln, Brayford Pool, Lincoln LN6 7TS, UK, e-mail: DWaugh@lincoln.ac.uk

Dr. Andreas Weisheit Fraunhofer-Institut fuer Lasertechnik, ILT, Steinbachstr. 15, 52074 RWTH, Aachen, Germany, e-mail: andreas.weisheit@ilt.fraunhofer.de

Dr. Konrad Wissenbach Fraunhofer-Institut fuer Lasertechnik, ILT, Steinbachstr. 15, 52074 RWTH, Aachen, Germany, e-mail: konrad.wissenbach@ilt.fraunhofer.de

Symbols

E_2	Excited or higher energy state
E_1	Ground state
v	Photon of frequency
h	Planck's constant
I	Laser beam intensity
Io	Incident beam of initial intensity
t	Time
R	Reflectivity coefficient
α	Absorption coefficient
R_E	Reflectivity for electron beam
x_P	Distance
$f_E\ (x/x_P)$	Spatial energy deposition profile
$C(z)$	Concentration of a given species at a vertical distance z
R_p	Projected range/distance
Q_T	Ion dose
ρ	Density
t_p	Pulse duration
α^{-1}	Laser absorption depth
κ	Thermal diffusivity
K	Thermal conductivity
c_p	Specific heat
T	Temperature
Q	Power density
T_m	Melting temperature
T_i	Interface temperature
η	Power (or energy) transfer coefficient
ε	Rate of melting
P	Incident laser power
v	Welding speed
d	Sheet thickness
W	Beam width
ΔH_m	Enthalpy

P_l	Laser power (Watt)
M^*	Mass flow rate of laser gas (g/s)
n	Real part of refractive index
k	Extinction coefficient
n^*	Complex form of refractive index
R	Reflectivity of a material
A	Absorptivity of a material
T	Transmitivity of a material
λ	Laser wavelength
σ_0	Electrical DC conductivity of the material
$I(z)$	Intensity at a depth z
I_0	Incident laser intensity
α	Absorption coefficient
$P(z)$	Laser power absorbed
l_a	Attenuation length (nm)
E_g	Energy band gap
H	Planck’s constant
v	Laser frequency
γ	Adiabaticity parameter
ε	Strength of the electric field
ω	Frequency of the electric field
m	Reduced mass of electron
e	Electric charge of electron
ρ	Density of the material
L_v	Latent heat of vaporization of the material
M^2	Beam product (beam diameter × half-divergence angle)
$\theta_{1/2}$	Half-divergence angle of a real beam
d_b	Laser beam diameter
f	Focal length
d_f	Focal spot diameter
l_d	Thermal diffusion length
κ	Thermal diffusivity of the material
τ_l	Laser pulse duration
Z_a	Ablation depth
T	Temperature
Z	Axial coordinate
κ	Thermal conductivity
ρ	Density
C_P	Specific heat
ω	Workpiece rotation speed
V_Z	Feed speed
$\mathrm{R_w}$	Workpiece radius
t	Time
tp	Preheat time
z	Axial coordinate

z_{c}	Axial location of the laser center
ϕ	Circumferential coordinate
ϕ_{c}	Circumferential location of the laser center
q''	Heat flux
q'''	Volumetric heat generation
F_{c}	Cutting force
$\overline{V_{\mathrm{w}}}$	Average workpiece velocity
F_{ct}	Friction force
V_{chip}	Average chip velocity
d	Depth of cut
L_{f}	Tool feed
T_{mr}	Material removal temperature
$P_{\mathrm{CO_2}}$	Laser power for the CO_2 laser
P_{YAG}	Laser power for the Nd:YAG laser
D_{w}	Diameter of the workpiece
f	Feed
V_{c}	Cutting speed
u_{c}	Specific cutting energy
w	Width of the cut
L_{l}	Laser-tool lead distance
F_{f}	Feed forceFeed force
D	Laser spot size
L_2	Tool-beam distance
$T_{\mathrm{s,ch}}$	Near-chamfer surface temperature
$T_{\mathrm{mr,se}}$	Average material removal temperaturematerial removal temperature
σ_y	Yield strength of workpiece at a given strain rate
β	Angle of kinetic friction for sliding motion
μ	Coefficient of friction
θ	Shear plane angle
α	Rake angle
K_{IC}	Fracture toughness of workpiece
VB_{max}	Maximum flank wearwear
VB_{ave}	Average flank wearwear
T_{int}	Tool–chip interface temperature
η	Preheating efficiency
u_{total}	Total specific energy
r_{foc}	Beam spot radius at the focal plane
f	Focal length
λ	Wavelength of the laser
r	Radius of the raw beam
K	Beam quality
ρ	Density
C_{p}	Heat capacity
κ	Thermal diffusivity

P_M	Mean laser Power
E_P	Pulse energy
τ_P	Pulse duration
T_F	Pulse-to-pulse time (ms)
PRR	Pulse repetition rate (s^{-1})
D	Spot area (mm^2)
V	Welding speed (mm/s)
P_P	Peak power (kW)
P_D	Power density (kW/mm^2)
C_D	Duty cycle
I_m	Threshold irradiance
T_{melt}	Melting point
T_0	Ambient temperature
d	Beam diameter
J_{max}	Function of ratio of thermal diffusivity to the product of the traverse speed and diameter of the incident beam
Φ	Phase difference
ν_0	Central mode frequency
τ_P	Pulse width
n_e	Electron number density
k_B	Boltzmann constant
k_e	Electron thermal conductivityconductivity
v_F	Fermi-velocity
τ	Electron relaxation constant
D	Diffusion coefficient
T_e	Electron temperature
T_l	Lattice temperature
C_l	Lattice thermal capacity
τ_a	Ablation interval
δ	Optical penetration length
ρ	Density
Ω	Specific enthalpy of evaporation
P_L	Average output power
λ	WavelengthWavelength
q	Number of photons
NA	Numerical aperture
θ	Contact angle
γ_{sv}	Solid surface energysurface energy
γ_{lv}	Liquid surface energysurface energy
γ_{sl}	Solid–liquid interfacial energy
γ_s^d	Dispersive component surface free energy
γ_s^p	Polar component surface free energy
γ_s^h	Hydrogen component surface free energy
γ_s^i	Induction component surface free energy
γ_s^{ab}	Acid–base component surface free energy

γ^{T}	Total surface energysurface energy
ε	Laser fluence
E	Pulse energy
I	Maximum peak Intensity
P	Maximum peak power
A	Focal spot area
T	Pulse duration
v_{rep}	Laser repetition rate
δ_{w}	Thermal diffusion length
R	Reflectance
T	Laser processing time
ρ	Density
C_{p}	Specific heat capacity
λ,K	Thermal conductivitythermal conductivity
η	Absorption efficiency
P_{Las}	Power density of laser beam
v_{Scan}	Scanning velocity
d	Ablationablation depth
P_{L}	Laser power
V	Feed rate
R	Ablation rate
ε_{t}	Ablation threshold
α_{eff}	Effective absorption coefficient
ε_{o}	Characteristic laser fluence
σ_1	Single-photon absorption cross-section
ρ_0	Density of absorbing constituents
α	Absorption coefficient
α_{eff}	Effective absorption coefficient
T_{B}	Temperature of non blackbody
T_0	Temperature of blackbody
$L(\lambda, T_0)$	Spectral radiant intensity
ε	Spectral emissivity
λ	Wavelength
N	Number of pyrometer wavelengths
E	Energy per pulse
T_{max}	Maximum peak temperature
τ_{lt}	Melt life-time
τ_{s}	Duration of solidification
$\Delta\tau$	Pulse duration
F	Powder feeding rate
P	Laser power
v	Laser cladding speed
G_{c}	Carrier gas flow rate

Chapter 1
Introduction to Laser-Assisted Fabrication of Materials

Jyotsna Dutta Majumdar and Indranil Manna

Abstract Light amplification by stimulated emission of radiation (laser) is a coherent and monochromatic source of electromagnetic radiation that can propagate in a straight line and hence, finds diverse applications. High power lasers can perform various manufacturing operations or material processing. This contribution provides the principle of laser materials processing and an overview of the engineering application of laser material processing. The manufacturing processes covered have been broadly divided into four major categories; namely, laser assisted forming, joining, machining, and surface engineering. Followed by a brief introduction to different types of lasers and their general application, fundamentals of laser–matter interaction and classification of laser material processing have been provided. The scope and principle of an individual process is described followed by a detailed update of the literature, scientific issues, and technological innovations. The entire discussion primarily focuses on correlating the properties with processing parameters and microstructure and composition.

1.1 Introduction

Laser, the acronym of light amplification by stimulated emission of radiation is a coherent and monochromatic source of electromagnetic radiation with wavelength ranging from the ultraviolet to the infrared range [1–4]. Lasers can deliver very

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J. D. Majumdar (✉) · I. Manna
Metallurgical and Materials Engineering Department,
Indian Institute of Technology, Kharagpur 721 302, West Bengal, India
e-mail: jyotsna@metal.iitkgp.ernet.in

I. Manna
Central Glass and Ceramic Research Institute,
Kolkata 700 032, West Bengal, India
e-mail: imanna@metal.iitkgp.ernet.in

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low (∼ mW) to extremely high (1–100 kW) focused power with a precise spot size/dimension and spatial/temporal distribution on a given substrate through any intervening medium [1–4]. As a result, lasers have wide-ranging applications in different materials processing [5, 6].

The initial foundation of the laser theory was laid by Einstein [7]. Subsequently, Kopfermann and Ladenburg [8] presented the first experimental confirmation of Einstein's prediction. In 1960, Maiman [9] invented the first working ruby laser for which he was awarded the Nobel Prize. Subsequently, several new lasers including semiconductor lasers, Nd:YAG lasers, CO_2 gas lasers, dye lasers, and other types of gas lasers were designed and fabricated with better reliability and durability. By the mid 1970s, more reliable and powerful lasers were developed for industrial applications such as cutting, welding, drilling, and melting. During the 1980s and early 1990s, lasers were successfully applied for heating, cladding, alloying, glazing, and thin film deposition.

Depending on the type of laser and wavelength desired, the laser medium could be solid, liquid, or gaseous. Different laser types are commonly named according to the state or the physical properties of the active medium. Consequently, there are glass or semiconductor, solid state, liquid, and gas lasers. Gas-based lasers can be further subdivided into neutral atom lasers, ion lasers, molecular lasers, and excimer lasers. The typical commercially available lasers are (a) solid state or glass laser (Nd:YAG, Ruby), (b) semiconductor or diode laser (AlGaAs, GaAsSb and GaAlSb), (c) dye or liquid lasers (solutions of dyes in water/alcohol and other solvents), (d) neutral or atomic gas lasers (He–Ne, Cu or Au vapour), (e) ion lasers [argon (Ar^+) and krypton (Kr^+) ion], (f) molecular gas lasers (CO_2 or CO), and (g) excimer laser (XeCl, KrF). The wavelengths of the presently available lasers cover a wide spectral range from the far infrared to the soft X-ray.

1.2 Principle, Type, and Application of Laser

Laser comprises three principal components, namely, a gain medium, a device for exciting the gain medium, and an optical delivery/feedback system. Additional provisions of cooling the mirrors, guiding the beam, and manipulating the target are necessary to facilitate material processing. Figure 1.1 schematically shows the operating principle of a CO_2 laser. As illustrated in Fig. 1.1a, the laser device consists of three main parts: a gain or laser medium CO_2, an optical resonator or cavity with two mirrors (mirror 1 and 2, placed at opposite ends), and an energizing or pumping source that supplies energy to the gain medium to activate CO_2 into amplifying state [10]. The chemical species in the gain medium (composition, bond energy, band gap, etc.) determines the wavelength of the optical output. Between the two mirrors, one is a fully reflecting and the other a partially reflecting one. From the quantum mechanical principle, when an external energy is supplied to an atom/molecule, the irradiated species attains an excited or higher energy state (E_2) only to spontaneously and instantaneously return to the ground state (E_1) by emitting the energy difference as a photon of frequency (ν):

$$\nu = (E_2 - E_1)/h, \tag{1.1}$$

Where, h is the Planck's constant. This phenomenon is known as spontaneous emission, which subsequently may excite another atom and stimulate it to emit a photon by de-exciting it to a lower energy level through a process called stimulated emission of radiation. This process in the initial stage occurs randomly and can multiply itself (Fig. 1.1b). However, the emitted radiation is coherent with the stimulating source so that the wavelength, phase, and polarization between the two are identical. A photon interacting with a ground state atom may get absorbed in order to excite it to a higher energy state. This situation, called 'population inversion' is created by the pumping source. The photons moving along the optical axis interact with a large number of excited atoms, stimulate them and in the process get amplified. They are reflected back and forth by the resonator mirrors and pass through the excited medium creating more photons. In each of these cycles, a percentage of these photons exit through the partially transmitting mirror as intense laser beam (Fig. 1.1c). Finally, the laser beam is guided on to the workpiece by using reflecting mirrors and prisms. Instead of CO_2, the active medium could be a solid (e.g. Nd:YAG or neodymium doped yttrium–aluminium–garnet), liquid (dye) or another gas (e.g. He, Ne, etc.). In addition, there is the free-electron laser, which exploits a beam of accelerated electron moving through a magnetic assembly (modulator) as an active medium to generate a periodic magnetic field. For a ready reference, the characteristic features of some commonly used lasers, other than CO_2 laser, will now be outlined in brief.

1.2.1 Solid-State Laser

One of the most commonly used solid-state lasers is based on neodymium doped yttrium aluminium garnet (Nd:YAG) [11]. Here, neodymium atom is utilized in its trivalent state in the yttrium aluminium garnet crystal ($Y_3Al_5O_{12}$orYAG). The excitation is accomplished by irradiating the material by a flash and arc lamp. The output power of this laser for continuous wave operation is in the range of a few watts up to a few kW. The output energies for pulsed lasers range from a few mJ to a few tens of Joules. The total efficiency is around 2%. Nd:YAG laser is commonly used for materials processing (cutting, drilling, welding, marking, surface engineering), medical (endoscopic surgery), and military (long range finders) applications. The major advantages of Nd:YAG laser over CO_2 laser lie in its smaller wavelength (1.06 μm) and ability to deliver laser radiation through optical fibers. To increase the overall efficiency, attempts are being made to introduce new active materials containing sensitizer atoms to increase the overall efficiency of laser by absorbing the larger fraction of pump radiation and transferring it to active atom.

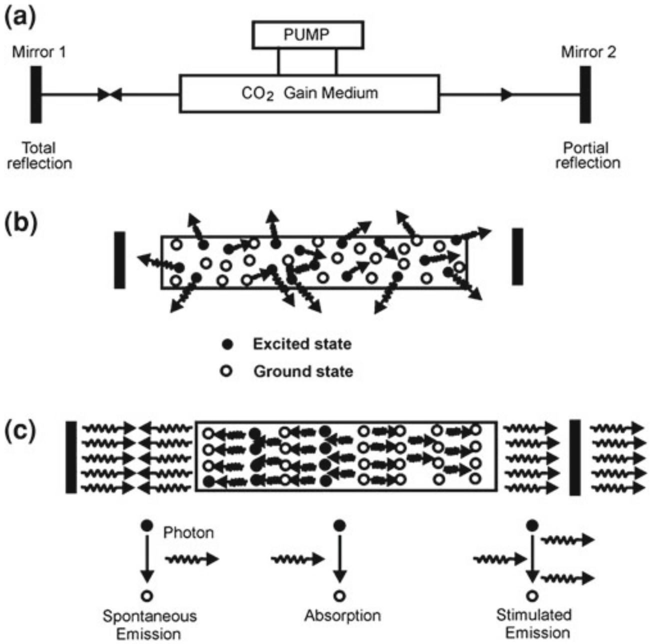

Fig. 1.1 Schematic setup showing generation of laser (**a**) the major constituents of the machine, (**b**) excitation and de-excitation of the atoms in the medium, and (**c**) stimulated emission and formation of laser beam [10]

1.2.2 Semiconductor or Diode Lasers

Laser action in GaAs and GaAsP laser diodes at cryogenic temperature was demonstrated as early as 1962 [11, 12]. The application of diode laser in that period was limited by the poor output power. However, these semiconductor lasers are now becoming increasingly popular both as a pump source for solid-state laser and in materials processing because of their unique features like small size, low weight, high efficiency, and reliability. More frequently used diodes are based on double hetero-junction using ternary compounds such as AlGaAs (p) and GaAs/GaAlAs (n). In this type of laser, the emitted radiation comes from the stimulated emission resulting from the recombination of electrons in the conduction band with holes in the valence band. However, several diode bars mounted into the multi-channel heat sinks are stacked on top of each other to further increase the power. Diode lasers have a potential scope of application in materials processing and gaining increasing popularity because of its lower installation/ maintenance cost and greater efficiency over CO_2 and Nd:YAG lasers [13].

1.2.3 Gas-Based Lasers

As already stated, CO_2 lasers seem to be one of the earliest developed and most popular lasers among the commercially available lasers for material processing because they are electrically more efficient (15–20%) and produce higher powers (0.1–50 kW) than other lasers in the continuous mode [14]. Despite being less efficient in energy coupling with metals due to longer wavelength (10.6 μm), the higher wall plug (∼ 12%) and quantum (∼ 45%) efficiency along with higher level of output power of CO_2 lasers more than compensate for the poor laser–matter energy coupling capability. On the other hand, Nd:YAG and Ruby lasers possess shorter wavelength and are more suited to pulsed mode of applications requiring deeper penetration, smaller area coverage, and precision treatment of materials for specific purposes. However, sheer size/volume of the CO_2 laser unit and operational/maintenance complexities are major disadvantages that have contributed in shifting attention toward solid-state lasers.

1.2.4 Free-Electron Lasers

Free-electron lasers are capable of operation over the entire electromagnetic spectrum from the microwave to the vacuum ultraviolet regions at average powers up to several kilowatts and peak powers up to a gigawatt [15]. At present, there are two principal areas for future free-electron laser development: higher average power and shorter wavelengths. Free-electron lasers consist of an electron beam propagating through a periodic magnetic field, called a wiggler or undulator [15]. Undulators are also used in incoherent synchrotron light sources. Lasing occurs because the wiggler and radiation combine to produce a heat wave that travels slower than the speed of light and can be synchronous with the electrons. The free-electron laser is continuously tunable, capable of high peak and average powers, and can produce a wide variety of pulse formats. The average power of this laser can be further raised. In continuous mode, a record average power of 1.7 kW has been produced at a wavelength of 3 μm. Similar power levels of about 2 kW in 1 ms pulse have also been produced in the infrared region. The high average power goal is several tens of kilowatts at infrared to ultraviolet wavelengths. The most likely configuration for generating a free-electron laser is an oscillator driven by a radiofrequency linear accelerator.

1.2.5 Ultra High Field Lasers

The development of lasers that are capable of producing short pulses of very high power has progressed enormously over the past 10 years [13]. There are two main types of ultra high field lasers in common use. On account of its broad gain bandwidth, Ti:sapphire (TiS) lasers enable pulses of very short durations (few tens of femtoseconds) to be produced and energies of up to 1 J can be achieved at relatively high repetition rates (typically 10 Hz). Higher energy pulses (with a focused intensity of 10^{25} W/m^2) can be obtained from Nd:glass lasers with a longer (several hundred femtoseconds) pulse durations and lower repetition rates [16, 17].

1.2.6 Excimer Lasers

Gas lasers make use of unstable molecules as the active material that is formed within the same electrical discharge used for the excitation. These molecules originate from the association of noble gas atoms such as Ar, Kr, Xe with halogen atoms such as F, Cl, Br. The available average power can reach the few hundred watts level in commercial units with an energy per pulse of the order of one joule and pulse repetition frequencies in the 100 Hz range. The achievable efficiencies can reach 4%, and the use of corrosion resistant materials has improved the discharge tube lifetime. These lasers are used for spectroscopy and photochemistry experiments in the ultraviolet range and for many applications related to surface treatment.

1.3 Laser–Matter Interaction for Material Processing

Laser–matter interaction within the near-surface region achieves extreme heating and cooling rates (10^3–10^{10} K/s), while the total deposited energy (typically, 0.1–10 J/cm^2) is insufficient to affect, in a significant way, the temperature of the bulk material. This allows the near-surface region to be processed under extreme conditions with little effect on the bulk properties.

1.3.1 Lattice Heating

The initial stage in all laser assisted material processing applications involves the coupling of laser radiation to electrons within the metal. Initially, this occurs by the absorption of photons from the incident laser beam promoting the electrons from the valence/conduction bands to states of higher energy. Electrons that have been excited in this manner can divest themselves of their excess energy in a variety of ways. For example, if the photon energy is large enough ($>$ several eV), the excited electrons can be removed entirely from the metal, causing the photoelectric effect. Most laser processing applications, however, utilize lasers emitting photons with relatively low energy. The energy of CO_2 laser photons is only 0.12 eV while the photons obtained from the Nd:YAG laser have about 1.2 eV of energy. Electrons excited by absorption of CO_2 or Nd:YAG laser radiation does not therefore have enough energy to be ejected from the metal surface. Such electrons must,

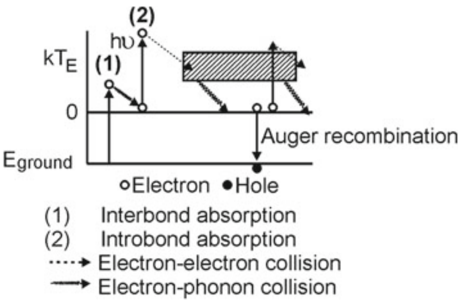

Fig. 1.2 Schematic diagram depicting electron excitation and carrier relaxation process in solids subjected to intense laser irradiation [18]

nevertheless, lose energy to return to an equilibrium state after photon excitation. This occurs when excited electrons are scattered by lattice defects like non-crystalline regions in a crystal such as dislocations and grain boundaries. In either case, the overall effect is to convert electronic energy derived from the beam of incident photons into heat. It is this heat that is useful (indeed necessary) in all material processing applications.

Figure 1.2 summarizes the process of electron excitation and excited carrier relaxation involved during laser–matter interaction schematically [18]. Photon interaction with matter occurs usually through the excitation of valence and conduction band electrons throughout the wavelength band from infrared (10 μm) to ultraviolet (0.2 μm) region. Absorption of wavelength between 0.2–10 μm leads to intraband transition (free electrons only) in metals and interband transition (valence to conduction) in semiconductors. Conversion of the absorbed energy to heat involves (a) excitation of valence and/or conduction band electrons, (b) excited electron–phonon interaction within a span of 10^{-11}–10^{-12} s, (c) electron–electron or electron–plasma interaction, and (d) electron–hole recombination within 10^{-9}–10^{-10} s (Auger-process). Since free carrier absorption (by conduction band electrons) is the primary route of energy absorption in metals, beam energy is almost instantaneously transferred to the lattice by electron–phonon interaction. Similarly, transition in semiconductor or polymers having ionic/covalent bonding with energy gap between conduction and valence bands is marginally slower.

1.3.2 Spatial Distribution of Deposited Energy

The spatial profile of deposited energy from laser beam is illustrated in Fig. 1.3. The laser beam intensity I at a depth z for the normally incident beam of initial intensity I_o is given by [18]

$$I(z,t) = I_o(t)(1 - R)exp(-\alpha z). \tag{1.2}$$

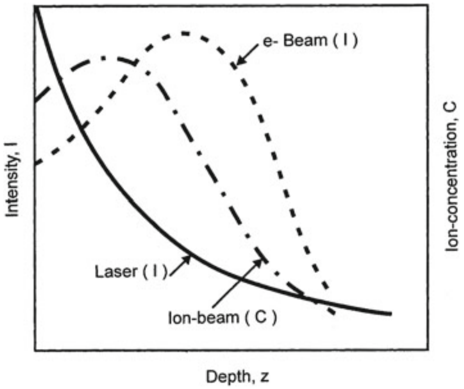

Fig. 1.3 Spatial profile of deposited energy intensity (*I*) or concentration (*C*) with depth (*z*) following irradiation/implantation of solid matter by laser, electron, and ion beams, respectively [18]

Here, I_o is the incident intensity, *t* is time, *R* and α are the reflectivity and absorption coefficient, respectively. Since α is very high ($\sim 10^8\ \text{m}^{-1}$) for metals, light is totally absorbed within a depth of 10–20 nm. The efficiency of optical coupling is determined by the reflectivity (*R*). *R* for metals is relatively low at short wavelengths, rises abruptly at a critical wavelength, then remains very high at long wavelength [18].

For comparison, the deposited energy profile from the other two important directed-energy-sources, namely electron and ion beams, are also shown in Fig. 1.3. The energy deposition profile for electron beam irradiation of matter is given by a Gaussian function,

$$I(z,t) = I_o(t)(1 - R_E) f_E(x/x_P) \tag{1.3}$$

Here, R_E is the reflectivity for electron beam, x_P is the distance (*x*) that coincides with the peak intensity, and $f_E(x/x_P)$ is the spatial energy deposition profile. The deposition profile depends on the energy loss, hence on incident energy and atomic number. Thus, electron beam is more suited to deep penetration welding than to surface engineering applications. The concentration (*C*) of the implanted species in ion beam irradiation does not coincide with the top surface but lies underneath the surface as follows:

$$C(z) = \frac{Q_T}{\sqrt{2\pi}\Delta R_P} exp\left[-\left(\frac{z - R_P}{\sqrt{2}\Delta R_P}\right)^2\right] \tag{1.4}$$

Here, $C(z)$ is the concentration of a given species at a vertical distance *z*, R_p is the projected range/distance and Q_T is the ion dose.

1.3.3 Heat Transfer by Laser Irradiation

Usually, the deposited energy of laser irradiation is converted into heat on a timescale shorter than the pulse duration or laser interaction time [18]. The resulting temperature profile depends on the deposited energy profile and thermal diffusion rate during laser irradiation. Thermal diffusivity (D) is related to thermal conductivity (k) and specific heat (c_p) as follows:

$$D = k/(\rho c_p) \tag{1.5}$$

where, ρ is the density. The vertical distance (z) over which heat diffuses during the pulse duration (t_p) is given by, $z = (2Dt_p)^{1/2}$. Here, z in comparison to laser absorption depth (α^{-1}) determines the temperature profile. For laser irradiation of metals, the typical value of α^{-1} is much less than z.

Under the one-dimensional heat flow condition, the heat balance can be expressed as [6]:

$$\rho c_p \frac{\partial T(z,t)}{\partial T} = Q(z,t) + \frac{\partial}{\partial z} k \frac{\partial T(z,t)}{\partial z} \tag{1.6}$$

where, T and Q are the temperature and power density at a given vertical distance of depth (z) and time (t), respectively. Q follows the functional relation with z as in Eq. (1.2). The heat balance Eq. (1.6) may be solved analytically if the coupling parameters (α and R) and materials parameters (ρ, k and c_P) are not temperature and phase dependent. However, phase changes are unavoidable except in solid-state processing. Thus, the heat balance equation is solved by numerical techniques like finite difference/element or controlled volume methods.

Depending on the temperature profile, the irradiated material may undergo only heating, melting, or vaporization. For surface melting and subsequent re-solidification, the solid–liquid interface initially moves away from and then travels back to the surface with a velocity as high as 1–30 m/s. The interface velocity is given by $v \propto (T_m - T_i)$, where T_m and T_i are the melting and interface temperatures, respectively [18]. Further details on mathematical modeling of heat transfer and phase evolution in laser material processing may be obtained in several textbooks dealing with laser material processing [4–6, 18].

1.3.4 Plasma Formation During Laser Irradiation

Laser-driven processes in which vaporization takes place are important for many applications like laser drilling and cutting, laser-induced surface chemical reactions in the reactive atmospheres, etc. [16, 19]. What is common to all these diverse applications of laser is the formation of a charged vapor stream. The ionized vapor contains not only the electrons and simple ions (as usually understood in a simple picture) but also the clusters of metals, reacted particles of oxides, nitrides, etc., which are charged and behave as Coulomb particles. They may form very complex structures of Coulomb liquids and solids, and show some new effects. Such plasma, called 'dusty' or 'colloidal' plasma has been considered in many studies [20]. Chu and Lin

[21], Melzer et al. [22], and Piel and Melzer [23] presented direct evidence of generation of plasma during laser-induced vaporization. Gnedovets et al. [24] synthesized ultrafine particles by laser vaporization of materials (metals, metal oxides, carbon) in a high-pressure atmosphere of chemically active (hydrogen, oxygen, air) and inert (helium, argon, xenon) gases as a result of vapor condensation. The dimensions of particles increased with increasing the ambient gas pressure. A particle nucleation and growth theory is used to describe the formation of the dispersed condensate in the erosive plasma. Cauble et al. [25] showed that the particle size, the particle–particle distance, and the particle density developed by laser assisted vaporization technique would depend on the laser power, gas pressure, and evaporation rate (i.e. on the boiling point of the material). Moreover, the vapor particle size should decrease with decreasing pressure and evaporation rate [26].

1.3.5 Effect of Ultra High Power Laser Irradiation

At very high intensities, the interaction between the radiation and matter gives rise to quite different phenomena from that observed at lower intensities [16]. For example, the energy acquired by an electron driven by the very high oscillating electric field of the intense radiation is approximately 10 MeV for laser intensity of 10^{24} W/m^2. Electrons with this energy can produce Bremsstrahlung or continuous radiation in the γ-ray range that is sufficiently energetic to induce (γ, n) nuclear reactions. Electrons can be accelerated to 100 MeV by plasma waves created by intense laser pulses and these interactions can also give rise to beams of energetic protons with applications in time-resolved imaging and tomography. Ultra high field lasers have been used to compress materials to ultra-high pressures and characterize their thermodynamic and transport properties [26]. When an ultra-high power laser pulse is focused into dense plasma, magnetic fields up to 10^9 G are generated and this has been predicted by both computer simulations and analytical calculations [16]. These fields are predicted to be localized near the critical density surface, i.e., the region where the laser frequency equals the plasma frequency and where most of the laser absorption takes place.

1.4 Application of Laser

Figure 1.4 presents a brief overview of the application of lasers in different fields with diverse objectives [2]. The list is neither complete nor exhaustive but is meant for providing an overview with representative examples. It serves only to show the diversity of the application of laser. In some applications, the power output is of main concern, e.g. atomic fusion and isotope separation. Sometimes, the main reason for using laser lies in spectral purity and coherence (pollution detection, length/velocity measurement, interferometry, etc.), low divergence (laser show, pointer/guide, audio-player), or a combination of all of them (communication, holography, metrology).

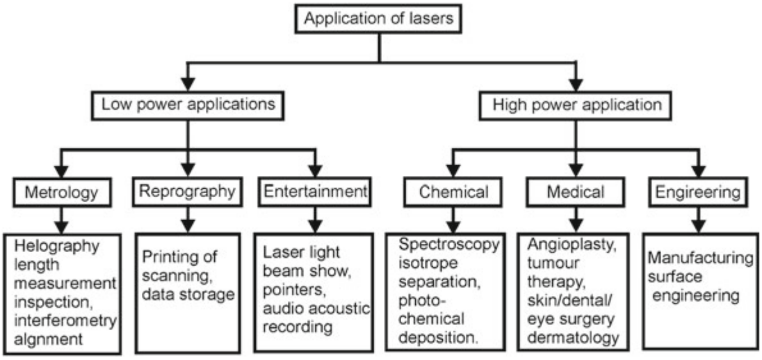

Fig. 1.4 Application spectrum of laser for the benefit of mankind [2]

Accordingly, a host of lasers capable of delivering a wide variety of wavelength, energy, temporal/spectral distribution, and efficiency have been developed over the past several decades [1–3].

1.5 Laser Assisted Fabrication of Engineering Materials

The increasing demand for laser in materials fabrication can be attributed to several unique advantages like fast processing speed, complete automation worthiness, non-contact processing, elimination of subsequent finishing operation, reduced processing or operational cost, improved product quality, greater material utilization, and minimum heat affected zone [1–3]. Figure 1.5 shows a general classification of the laser assisted fabrication techniques. In general, application of laser to materials fabrication can be grouped into two major classes (a) applications requiring limited energy/power and causing limited microstructural changes only within a small volume/area without change of state and (b) applications requiring substantial amount of energy to induce the change in state and phase transformation in large volume/area. The first category includes polymer curing, scribing/marking of integrated circuit substrates, etc. The second type of application encompasses cutting, welding, surface hardening, alloying, and cladding. The average power or energy input is relatively low in the first category, while that for the second category is higher as the processes involve single or multiple phase changes within a very short time. Almost all varieties of lasers can perform both types of operations in continuous wave and pulsed mode provided appropriate power/energy density and interaction time for the given wavelength are applied.

The classification based on state or phase change is too academic to be of practical use to end users. From the application point of view, laser material processing, as earlier stated, can be broadly divided into four major categories, namely, forming (changing shape or producing a component to manufacture a near net shape

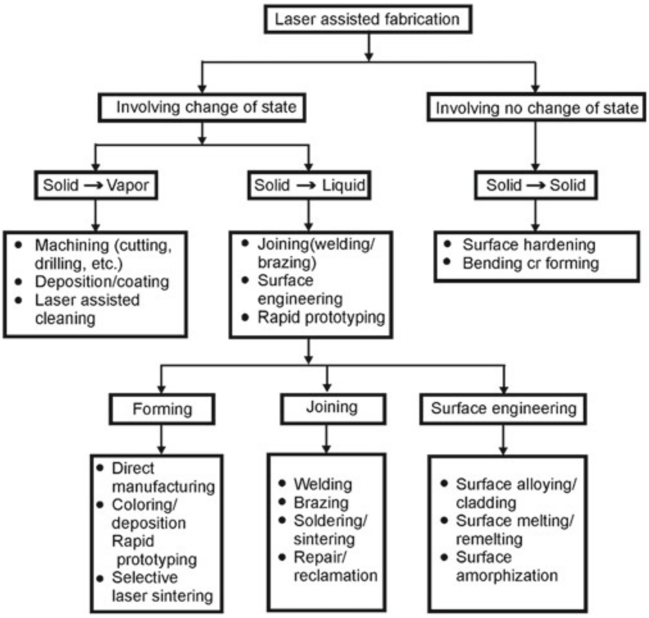

Fig. 1.5 General classification of laser assisted fabrication of materials for engineering applications

or finished product), joining (combining components by fusion welding, brazing, etc.), machining (removing material by cutting, drilling, etc.) and surface engineering (processing confined only to the near-surface region) [2–4]. Figure 1.5 presents this classification with a few representative examples from each category of application. However, this classification is based on the general definition and scope of the processes as understood in conventional practices.

The domain for different laser assisted fabrication techniques as a function of laser power and interaction time is illustrated in Fig. 1.6 [2]. The processes are divided into three major classes, namely involving only heating (without melting/vaporizing), melting (no vaporizing), and vaporizing. It is evident that transformation hardening, bending, and magnetic domain control which rely on surface heating without surface melting require low power density. On the other hand, surface melting, glazing, cladding, welding, and cutting that involve melting require high power density. Similarly, cutting, drilling, and similar machining operations remove material as vapor hence, need delivery of a substantially high power density within a very short interaction/pulse time. Since all laser material processing operations can be defined by an appropriate combination of power density and interaction time, one is tempted to combine these two into a single scalar parameter like energy density (power density multiplied by time, J/mm^2) for the sake of simplification and convenience. However, the exercise is bound to prove futile and not advisable as both the quantum of energy and its temporal and spatial interaction with matter (rather than their product) is crucial to achieve the desired microstructural/phase/state changes and properties for

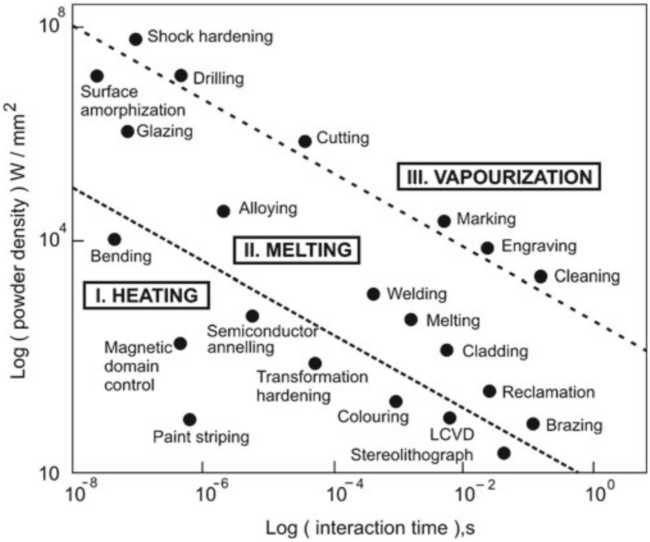

Fig. 1.6 Schematic process map in terms of combination of laser power density and interaction time for different types of laser material processing involving either no (only heating) or change of state (melting or vaporization) [2]

a given material. For instance, application of 10^{-2} J/mm^2 energy density may induce either surface hardening (say, for a given material combination of 10^2 W/mm^2 power density and 10^{-4} s interaction time) or surface melting (say, for a combination of 10^4 W/mm^2 power density and 10^{-6} s interaction time).

In laser assisted fabrication, a high-power laser beam interacts with the workpiece while a high relative speed is maintained between the two. The workpiece is usually mounted on a table capable of translation along two mutually perpendicular directions with a speed precisely controlled by a computer numerical controller. For convenience, the laser beam is kept stationary and the specimen is moved at a high speed. Several laser and material variables, either independent or dependent, play important roles in determining the final properties and characteristics of the processed zone. The independent variables are laser power, beam size, beam configuration, traverse speed of the workpiece, surface roughness, temperature, and surface condition of the substrate. The dependent variables are absorption coefficient, coverage rate, composition, and microstructure of the surface/near-surface region, hardness, residual stresses, heat-affected zone (HAZ) size, physical, mechanical, and electrochemical properties of the workpiece.

Laser power necessary for surface melting of metallic materials is generally high due to high reflectivity and thermal conductivity of metals. Reflectivity of the metal surface is actually related to electrical conductivity. The beam size determines the power density on the specimen surface (power density is defined as the power divided by the cross-sectional area of the laser beam). As already explained, the combination of laser power density and interaction time should be carefully chosen during processing of materials by laser as this very combination primarily determines the scope and success of the process and properties for a given materials (Fig. 1.6).

Beam configuration or beam profile plays an important role in determining the energy distribution at the interaction zone during laser processing. Four types of beam profiles, namely Gaussian, multimode, square (or rectangular), and top hat are commonly used for material processing [2]. A Gaussian beam is most suitable for cutting and welding applications rather than for surface treatment because, being a ‘sharp tool,’ it tends to vaporize and melt the substrate deeply. In contrast, multimode, top hat, and square profiles (‘blunt tools’) are preferred for surface engineering. These beam profiles offer suitable surface casing with wider coverage rates and uniform case depths. Square and rectangular beam profiles are generated by using an optical integrator or scanner.

In the following sections, we will now review the individual classes of laser material processing and the current status of understanding.

1.6 Laser Assisted Shaping

The high power laser beam may be used as a source of heat to shape components in the desired dimension, shape, geometry, design, and properties. Laser material processing offers a unique possibility of manufacturing finished components directly from the raw materials without any elaborate intermediate operation [1–4, 27]. A one-step fabrication is most attractive, obviously for the tremendous economy in time, cost, material, and manpower associated with it than that necessary in the usual route of fabrication involving several intermediate stages/steps. Shaping of components by laser may be achieved by thermal stress assisted deformation (bending), direct forming of component from powder or wire by rapid prototyping/manufacturing, and reclamation/repairing [1–4]. These processes distinguish themselves from other laser material processing methods in their proclaimed objective of single-step manufacturing of a finished or semi-finished product than contributing toward any other intermediate processing steps like machining, joining, or surface engineering. For brevity, we will address all these laser assisted versions of otherwise conventional manufacturing processes as laser forming. In this section, laser assisted manufacturing techniques like laser bending and direct laser manufacturing techniques will be discussed in detail.

1.6.1 Laser Assisted Bending

Laser assisted bending involves modifying the curvature of sheet metal by thermal residual stresses induced by laser assisted heating without any externally applied mechanical forces [28–34]. Laser assisted bending also serves the purpose of straightening thin sheets by a similar laser-based non-contact process. The process assumes significance due to the ease and flexibility of non-contact processing, amenability to various types of materials and direct manufacturing of components with diverse shape/geometry, properties and composition with high precision/ productivity. Laser assisted bending involves a complex interplay between the thermal profile and stresses generated by laser irradiation, which in turn depend on many parameters such as laser power density, interaction/pulse time, material properties (thermal, physical or chemical), and dimension/geometry of the work piece (thickness, curvature, etc.). Bending of strong and difficult-to-bend metals (body centred cubic, BCC or hexagonal close packed, HCP), intermetallics, composites, and ceramics have been an important motivation for the increasing interest in laser assisted bending. The success of laser bending of semiconductor and polymeric sheets are of great interest to the semiconductor and packaging industry.

There are three mechanisms of laser assisted bending, i.e., temperature gradient mechanism, buckling mechanism, and upsetting mechanism [30–35]. Many applications involve a complex combination of these mechanisms rather than only one of them.

1. Temperature Gradient Mechanism

Temperature gradient mechanism is operative when a steep temperature gradient across the thickness of sheet metal is encountered, particularly when the beam diameter is typically of the order of sheet metal thickness or width and the traverse rate is fast enough to maintain a steep temperature gradient. Figure 1.7a explains the thermal history and mechanism associated with temperature gradient assisted bending of sheet. At the initial stage of laser heating, the surface of the metal facing laser is heated up leading to counter-bending of the sheet away from the laser beam as a result of rapid thermal expansion of the top-surface than the bottom layer. Further heating leads to decreasing the flow stress in the heated area and increasing thermal expansion of the surface layer. At a certain temperature, the geometry and degree of counter-bending reach the maximum elastic strain that the metal can endure beyond which plastic compressive strain sets in with further increase in temperature and thermal expansion. These plastic compressive strains accumulate until laser irradiation shifts to allow cooling to begin mainly due to self-quenching with the heat flowing into the surrounding bulk to cool the irradiated zone within 10–20 s. During cooling, shrinkage of the heated material occurs both due to natural contraction on cooling and plastic compression induced by prior laser heating. Due to the differential lengths between the top and bottom surface layers of the sheet, a bending angle develops toward the laser beam.

2. Buckling mechanism

The buckling mechanism will occur if the beam diameter of laser is large compared to the sheet metal thickness, laser beam intensity profile is Gaussian or multiple Gaussian, and the processing time is low, resulting in a small temperature gradient across the sheet metal thickness. Figure 1.7b describes the principle of laser bending by buckling mechanism. Primarily, the material is heated, which in turn leads to the thermal expansion and generation of compressive stresses in the neighboring heated

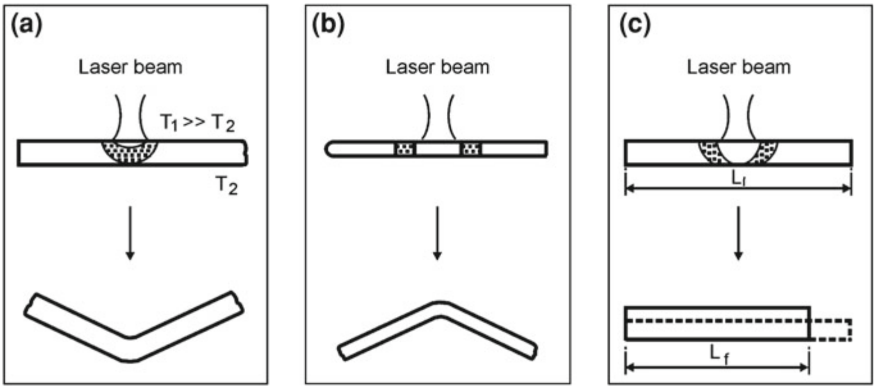

Fig. 1.7 Deformation modes of laser bending based on (**a**) temperature gradient mechanism, (**b**) buckling mechanism, and **c** upsetting mechanism, respectively. T_1 and T_2 are temperatures on opposite surfaces. L_i and L_f are the initial and final lengths of the sheet [30]

region. If the heated area is large enough with a small natural deviation from the perfect plane, an instability, or buckle, develops. At the center of the buckle, the temperature is extremely high, therefore the flow stress in this region is relatively low and the bending of the sheet in this region is totally plastic. In contrast, the root (or end) of the buckle, which is far away from the center of the laser beam, is heated to a much lesser extent with smaller temperature rise. If the flow stress is relatively high, this small temperature rise can only result in complete elastic bending. By controlling appropriate parameters, positive (concave bending toward the laser beam) or negative (convex bending away from the laser beam) bending can be achieved with the buckling mechanism [35]. As the beam moves along the surface, the buckle shifts along the bending edge. The relative motion between the beam and work piece along the surface can also alter the stiffness of the work piece. At the start of the buckling process, the bending legs are held in the original plane due to the stiff surrounding material. However, the force that holds the bending legs straight decreases with increase in amount of forming. Therefore, the elastic part of the buckle relaxes and only the plastic part remains in the sheet, resulting in an angular bend. Because the buckling mechanism results in more energy being coupled to the work piece, bending angle often up to 15° is achieved after a single pass.

3. Upsetting Mechanism

The upsetting mechanism occurs if the laser beam diameter is in the order of or less than the sheet metal thickness with a very low traverse speed. The low processing speed will result in almost homogeneous heating across the thickness of the sheet metal. Owing to the temperature increase, the flow stress decreases in the heated area and the thermal stress approaches the elastic limit. Additional heating leads to a plastic compression of the heated material as it is hindered in free expansion by the surrounding bulk material. Therefore, a large amount of thermal expansion is converted into plastic compression. During cooling the material contracts and the plastic compressive strain remains in the sheet for exactly the same reason as in the temperature gradient mechanism. Owing to the constancy of volume, there is an increase in the sheet thickness in the compressed area. Figure 1.7c shows the process of laser assisted upsetting that leads to shrinkage of initial length, L_i to smaller final length, L_f with a concomitant increase in thickness from the initial dimension (shown by broken lines).

The concept of laser bending may be extended to straightening of a welded component in a car body to reduce distortion arising out of welding [35], and deep drawing [36]. Laser bending may be combined with conventional forming to blend the high speed of conventional forming with the accuracy of laser forming without any special setup [37]. In laser assisted deep drawing, a laser beam is used to heat the wire to a critical temperature in order to make the wire plastic and easily deformable. Wire feeding and pulling rates are maintained through a feeder and puller roller at a predetermined speed to achieve the desired drawing ratio. The process was applied to nickel wire and was reported to exhibit an increased drawability as compared to the conventional technique, though laser parameters were reported to play a role in determining the drawing limit [36]. Brittle materials can also be successfully drawn without any rupture or micro-crack using laser.

The prediction/optimization of laser parameters may be attained by a detailed theoretical model. Deformation behaviors of Ti-based alloys were extensively studied Chen et al. [38] using finite element method. Marya and Edwards [39] analyzed the laser bending of two titanium alloy sheets, Ti–6Al–2Sn–4Zr–2Mo (near-alpha alloy) and Ti–15V–3Al–3Cr–3Sn (beta alloy) using a conduction model with a traveling Gaussian heat source. Temperature and bending angle were predicted and correlated with process parameters. Bending was found to initiate at 0.48 of the melting temperature and attained a maximum value at approximately 0.65 of the melting temperature. The effect of process parameter on bending angle was explained by analytical model developed by Cheng and Lin [40] and also 3-D finite element simulation by Kovacevic et al. [41]. The experimental results were suitably compared with the theoretical prediction. Laser bending of cold rolled steel was studied by Peng and Lawrence [42] where, the effects of the plastic anisotropy on bending deformation during the laser forming process have been investigated both experimentally and numerically. Most of the research artiucles concern a detailed experimental observation of studying the effect of laser parameters on the bending characteristics of different materials. Studies on AISI 1008 steel and mild steel show that bending angle increases with increase in laser power and number of repetitions, on the other hand, it decreases with increase in can-speed and beam size/diameter for [43, 44]. The bending angle usually increases with increase in thermal-effect index (coefficient of thermal expansion divided by the product of density and specific heat). However, strength or modulus has no significant influence on it [43]. Among the geometric parameters, sheet thickness influences the bending angle the most, and the latter decreases sharply with increase in sheet thickness [43]. The bending behavior of AISI 304 austenitic stainless steel wire (0.1 mm diameter) to develop complex frame structures such as zigzag or crank wire frames was studied by Yoshika et al. [45] with a Nd:YAG laser offering $0.02 - 0.2$ J energy. Besides fabricating to the desired complex shape, it also improved the strength of the frame structure. The investigation on laser bending of AISI 304 stainless steel of different thicknesses using continuous wave CO_2 laser showed that the rate of bending increased with increase in applied power density and the effect was more significant at a higher number of passes. However, an optimum range of laser power should be selected so that the applied power density is capable of bending without excess melting, evaporation, or crater formation. The rate of bending increased with increase in the number of passes due to increase in cumulative thermal stress. The thermal stress generated in each pass was proportional to the thermal gradient. Furthermore, cross-sectional thickness at the bent region is progressively reduced during successive passes due to material flow away from the bent region after each pass. Microstructural analysis of different regions of the bent surface and its variation with laser parameters were undertaken to understand the mechanism of bending. Figure 1.8a–c show the microstructure of the (a) irradiated region, i.e. inner side of bending, (b) solid-liquid interface and (c) heat affected zone of the irradiated zone, of laser bent AISI 304 stainless steel lased with a power density of 19.6×10^7 W/m^2, scan speed of 4 m/min and 10 passes. Figure 1.8a suggests that laser irradiation causes melting and high rate of quenching of the near-surface region to develop a very fine-grained and equiaxed microstructure at the near-surface region. Refinement of microstructure achieved in laser bending operation is beneficial in increasing the strength without sacrificing the ductility of the inner side of the laser bent zone. Although melting occurs at the irradiated region, subsequent rapid solidification leads to formation of a defect-free and continuous remelted region or interface (Fig. 1.8b). It is apparent that fine dendrites form and grow from the former solid–liquid interface. Microstructure in the narrow heat effected zone shows evidences of grain coarsening due to heat flow beyond the thin surface wetted region (Fig. 1.8c) [46]. A detailed XRD analysis of the bent zone revealed that, while phase aggregate remained the same, lattice strain due to thermal effect led to measurable broadening of peaks [46].

Besides microstructure, laser bending affects microhardness in different zones depending on the laser parameters adopted. Figure 1.9 shows the variation of microhardness with distance at different regions of laser bent steel (lased with a power of 54.3×10^7 W/m^2, scan speed of 5,000 mm/min). Microhardness increases to 250 VHN as compared to 190 VHN of the substrate at the inner bent zone. The microhardness further increases after multiple passes (275 VHN after 40 passes) possibly due to recrystallization and grain refinement effect. The sudden rise in hardness immediately after the melt zone is attributed to the formation of $Cr_{23}C_6$ precipitates along the zone near to the solid–liquid interface [46].

Subsequent grain coarsening in the heat affected zone reduces the hardness considerably resulting in a sudden drop in microhardness (Fig. 1.9). On the other hand, microhardness of the outer bent zone (reverse side of the irradiated zone) is marginally increased due to working effect (as also evident from Fig. 1.9). The microhardness of melt zone and outer zone along the centerline of the bent sheet is, however, found to vary with laser parameters. Increase in the number of passes increases the microhardness of the irradiated zone due to microstructural refinement [46]. On the other hand, the hardness of the outer bent region increases with increased number of passes

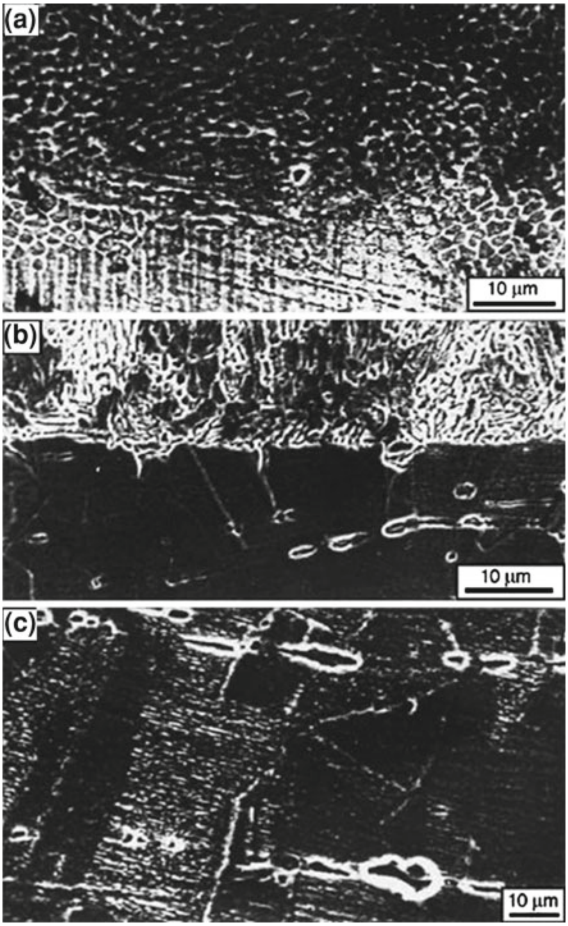

Fig. 1.8 Scanning electron micrographs of the (**a**) irradiated region, i.e., inner side of bending, (**b**) solid–liquid interface, and (**c**) heat affected of laser bent AISI 304 stainless steel irradiated with a power density of 19.6×10^7 W/m^2, scan speed of 4,000 mm/min and 10 number of passes [46]

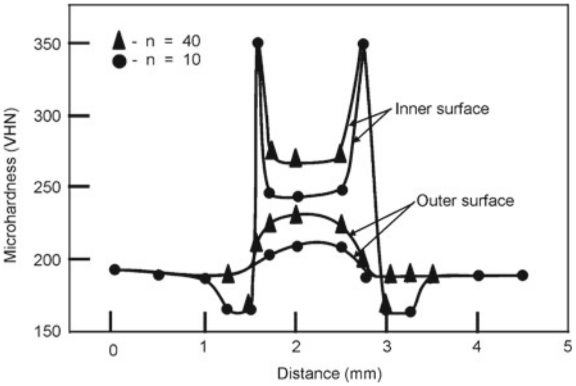

Fig. 1.9 Distribution of microhardness along the length of laser bent AISI 304 stainless steel (sheet thickness of 0.9 mm, lased with a power of 54.3×10^7 W/cm^2, scan speed of 5,000 mm/min) [46]

mainly because of a larger degree of deformation induced at greater thermal stress developed due to repeated irradiation. Hence, laser bending is a unique technique of bending of sheet metals with an improved mechanical property at the centerline of laser bending.

Is case of materials which undergo phase transformation, the phase transformation stress should also be taken into account. Wang et al. [47] studied the bending of St C45 steel (C: 0.08, Si: 0.3–0.1, Mn: < 0.4, $P :< 0.025$, $S :< 0.025$) by a continuous wave CO_2 laser and observed that the final deformation angle was found to depend on a combined action of thermal strain and phase transformation strain. Bending of tube is primarily achieved through thickening of the scanned region instead of thinning of the un-scanned region, and the scanned region assumes a slightly protruded shape [48]. The importance of the process lies on bending of metal matrix composite and difficult to bend materials. Laser assisted bending has been studied in Ti and its alloys [49–56]. Magee et al. [50–52] studied the influence of process variables on laser bending of $\alpha + \beta$ Ti alloy (Ti–6Al–4V) using a continuous wave CO_2 laser. Blake et al. [53, 54] studied the effect of beam divergence, feed rate, laser power, and pulse width on the angle and range in laser assisted bending of Ti–6Al–4V and Ti–15V–3Cr–3Sn–3Al using a 400-W pulsed Nd-YAG and 50 W desktop CO_2 laser. Similarly, Maher et al. [55] and Hatayama and Osawa [56] investigated the effect of process variables on the bending behavior of pure Ti. Marya and Edwards [39] studied the interactions between process variables, materials properties, and residual angular distortions (bending angle) during laser assisted bending of Ti–6Al–2Sn–4Zr–2Mo and Ti–15V–3Al–3Cr–3Sn alloys.

Okuda et al. [57] studied the deformation mechanism of Mg alloy by finite element modeling. Chan et al. [58] compared the deformation behavior of chromium sheet having limited room temperature ductility subjected to roll compression and laser bending technique. In roll compression test, a bending angle of 90° was achieved without fracture at a temperature of 100°C. However, the maximum bending angle achieved by non-contact laser bending was 23.5° and the same was found to increase with increase in applied power density and number of irradiation.

The deformation behavior of SiCp reinforced 6,092 aluminum matrix composite using a 2 kW Nd:YAG laser was studied by Liu et al. [59]. Figure 1.10 shows the variation of bending angle as a function of (a) laser scanning velocity at laser powers of 500 W and (b) applied power at an average scan speed of 5 mm/s. It is evident that the bending angle decreases with increase in scan speed because of the decrease in interaction time between the laser beam and composite. On the other hand, the bending angle increases with increase in applied power. However, when the applied power is above 700 W, there is no more increase in the bending angle. Under a suitable condition for bending, a linear relationship between the bending angle and the number of irradiation passes was observed. Ramos et al. [60] investigated the microstructures of Alclad 2024–T3 Al–Cu alloy following bending by a CO_2 laser. It was observed that the irradiated zone experienced different stages of thermal annealing including recovery (sub-grain formation), recrystallization, and grain growth depending on the deposited thermal energy. Recrystallized zone suffered partial melting at the grain

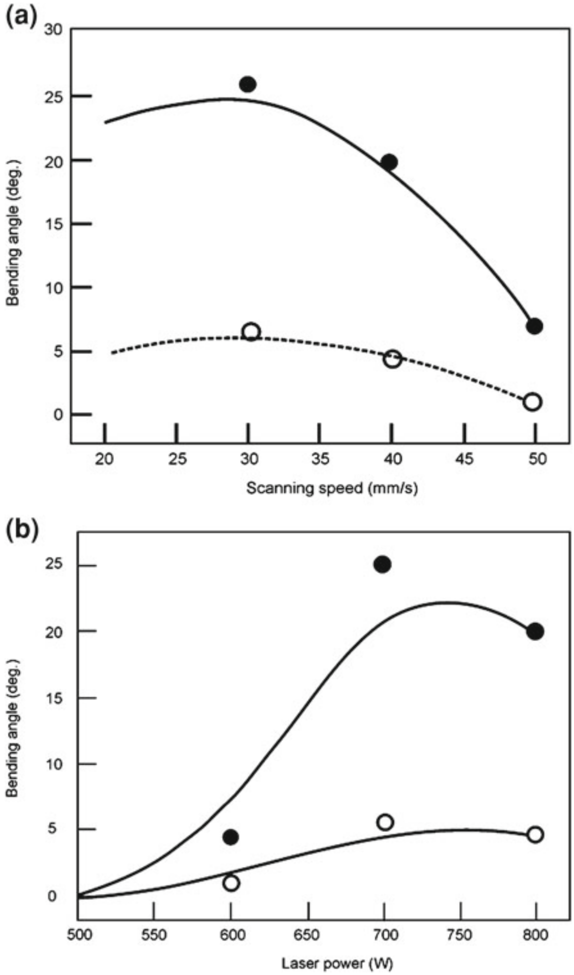

Fig. 1.10 Variation of bending angle as a function of (**a**) scanning speed at an applied power of 800 W, and (**b**) applied power at a scan speed of 40 mm/min for laser bent SiC dispersed 6092Al matrix composite lased with a continuous wave Nd:YAG laser [59]

boundary corners or triple points leading to precipitation along grain boundaries on cooling.

In spite of its poor room temperature ductility, Ti_3 Al-based intermetallic alloy was reported to be laser bent by Yet Chan and Liang [49] primarily due to the differential degree of thermal expansion of the intermetallic across the thickness. A linear relationship between laser bending angle and line energy was observed when the line energy was between 1 and 5 J/mm^2. Significant changes in microstructures were observed in the alloy after bending without formation of cracks or voids. The hardness profile and microstructure of the deformed specimen revealed that there was a steep temperature gradient across the thickness and the laser bending mechanism was related to that gradient.