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Introduction to Laser Material Processing

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Abstract

A laser is an instrument that produces light by means of optical amplification, which relies on the stimulated emission of electromagnetic radiation. Because of this, lasers are used for a wide range of purposes, from simple everyday tasks to the most complex ones, for entirely commercial or solely scientific reasons, and everything from lifesaving to life-threatening reasons. High-power lasers can process materials, performing a variety of manufacturing tasks, and producing severe heating. Intentionally excluding the range of laser applications in fields such as biomedical technology and metrology, the current contribution gives a general idea of the use of high-power lasers exclusively for material processing in engineering applications. The manufacturing methods discussed can be broadly categorized into four main groups: surface engineering, joining, machining, and laser-assisted forming. Each section lists a thorough update of the literature, scientific problems, and technological advancements, in addition to going over the extent and underlying principles of these processes. The basics of laser–matter interaction, classification of laser material processing, and a quick overview of many types of lasers and their broad applications were given at the outset. Correlating the qualities with the material's microstructure, composition, and processing factors is the main emphasis of the entire conversation.

***Keywords*:** Surface engineering, microstructure, machining, joining, forming, laser, engineering materials

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1.1 Introduction

A laser is a machine that utilizes optical amplification based on the stimulation of electromagnetic radiation to create light. With a precise dimension, spatial distribution and spot size on a particular substrate, a laser may provide focused power ranging from very low (mW) to high (1–100 kW) through any intervening medium [1–8]. Applications for lasers are numerous and include printers, pointers, spectroscopy, meteorology, surgery, and invisible surveillance. The crucial characteristics allow and support the use of lasers in such a broad range of applications: monochromaticity, minimal divergence, and high continuous or pulsed power density.

To enable various forms of ultrafast, innovative, and cost-effective material processing that set themselves apart from their traditional factors in terms of productivity, efficiency, and quality, the discussion is limited in this contribution to laser material processing, which entails concentrated laser heating of components. The overview of industrial lasers, their applications, and the categorization of lasers will be given before delving into the present state of various laser material processing. Additionally covered would be the physics of laser–matter interaction and the laser principle. Lastly, a thorough review of the various forms of laser material processing would be provided, along with a focus on the relevant scientific and technological aspects. Machining, surface engineering, forming, and joining are the four categories into which the field of laser-assisted material processing has been separated for ease of use. Below is a summary of each procedure, along with the most recent and upcoming developments in that field of laser material processing research and development.

1.2 Applications of Commercially Available Lasers

Einstein established the fundamentals of laser theory. Maiman [9] received the Nobel Prize in 1960 for creating the first functional ruby laser. Later, several new lasers with improved durability and dependability were created, including dye lasers and gas lasers. A solid, liquid, or gaseous laser medium may be used, depending on the desired laser type and wavelength. It is common practice to name various laser types based on the physical characteristics or state of the active medium. Thus, solid state, liquid, gas, glass, or semiconductor lasers are available. Ion lasers, excimer lasers, neutral atom lasers, and molecular lasers are further subcategories of gas-based lasers. Solid state or glass lasers, semiconductor or diode lasers, dye or liquid lasers, neutral or atomic gas lasers, ion lasers, and molecular gas lasers are a few examples of commonly available commercial lasers. The lasers that are currently on the market have wavelengths that span a broad spectrum, from soft X-ray to far infrared [10].

1.3 Material Processing Using Laser–Matter Interaction

Through the controlled use of laser energy, material processing employing laser–matter interaction is a flexible and extremely accurate technique used in a variety of sectors to shape, change, or analyze materials. Depending on the material type and laser characteristics, a laser beam's interaction with a material can cause a variety of physical changes by transferring energy to the material's surface or volume. Cutting, welding, engraving, ablation, and surface hardening are just a few of the processes that can result from these interactions, and they provide several benefits over conventional techniques. The capacity to accurately adjust the laser pulse's energy, strength, and duration is essential for laser-material interaction. This control is perfect for processing delicate or high-precision components since it allows for the development of extremely precise, detailed results with little heat damage to the surrounding material. For instance, lasers can be used to precisely cut metals, fuse disparate materials, or even alter the surface characteristics of materials like ceramics and polymers to improve their resistance to corrosion or wear [11]. In sectors where high precision and little material waste are essential, like aerospace, automotive, electronics, and medical device manufacture, laser processing is particularly helpful. Complex shapes and elaborate designs that would be challenging or impossible to accomplish with traditional methods are made possible by the ability to focus the laser beam to a tiny spot size, which enables micro-level alterations. Furthermore, because laser processing is non-contact, it lessens wear on machinery and tools, which lowers maintenance costs and extends the life of equipment. All things considered, laser-matter interaction material processing has emerged as a vital method that provides efficiency, accuracy, and diversity for a variety of uses.

1.4 Engineering Materials Processed by Laser

Laser applications for material processing fall into two main categories: those that need little energy or power and only produce minor microstructural changes in a small volume or area without changing states, and those that need a significant amount of energy to induce phase transformation from one state to a large volume or area. The first group covers processes like polymer curing, semiconductor annealing, and marking or scribing integrated circuit substrates, among others. Laser cutting, cladding, surface hardening, and welding are all involved in the second category of applications. In the first category, power utilization is comparatively low, whereas in the second category, it is greater because the processes entail one or more phase changes in a brief period. Almost all laser types can operate in both continuous wave (CW) and pulsed modes if the energy density and interaction time are used for the specified wavelength.

For material processing, four types of beam profiles are frequently utilized: top hat, square (or rectangular), multimode, and Gaussian. Because a Gaussian beam is a "sharp tool," which evaporates and melts the substrate deeply, making it more appropriate for welding and cutting applications than surface treatment. On the other hand, for surface engineering, multimode, top hat, and square profiles—also known as "blunt tools"—are recommended. The process of modifying an input beam to create an output beam with the required irradiance or spatial profile is known as beam shaping. The quality of laser microprocessing, welding, and hardening is significantly influenced by beam shaping [12–14]. Three general categories can be used to group beam shaping techniques. Aperturing is the first and most basic type of beam shaping. It is accomplished by using an aperture to let some beam power through while the remainder of the beam is either absorbed or reflected. The main disadvantage of aperturing is a significant amount of power loss. In the second kind, an input beam is efficiently and precisely converted into the desired output beam using a field mapper. A single-mode Gaussian beam could be converted into a beam with uniform irradiance using this method. Homogenizing or integrating the beam is the third type of laser beam shaping. With this method, a variety of lenses or facets can split the input beam. For various material processing applications, different beam shaping techniques may be employed. During welding, an elliptical beam can be exploited for either preheating or post-heating. Stripes, rectangles, and lines are typically utilized for heat treatment and hardening processes. A dual-beam (twin-spot) setup is employed, applying one spot for welding and the other for preheating or post-heating. It was found that using a double focus (twin-spot) technique when welding aluminum may reduce porosity and spatter. Additionally, altering the beam's shape can alter the weld penetration profiles. To create a unique power distribution for joining disparate materials, such as alloys of stainless steel, Inconel, and aluminum, Hammond *et al.* [15] employed diffractive optical elements. It was discovered that applying a defocused laser beam during the hybrid laser–gas metal arc welding process increased the weld pool's spreading and enhanced its fatigue life [16].

1.5 Laser-Assisted Forming

Producing final goods with the appropriate dimensions, shape, geometry, design, and properties is one of the main objectives of material processing. Producing completed parts straight from raw materials without the need for complex intermediate steps is made possible by laser material processing [17]. Rapid prototyping/manufacturing, reclamation/repairing, and laser-assisted bending are some of the most prominent and effective examples of the various forms of laser-assisted forming processes currently in use. These procedures set themselves apart from other laser material processing techniques by claiming to be able to produce a finished or semifinished product in a single step rather than assisting with any additional intermediate processing stages like surface engineering, joining, or machining. We will refer to all these laser-assisted variations of traditional manufacturing techniques as laser forming for the sake of conciseness. Techniques for laser-assisted manufacturing, including direct laser manufacturing and laser bending, will be covered in detail in this section.

1.6 Laser-Assisted Bending

Thermal residual stresses created by laser-assisted heating are used to change the curvature of sheet metal without the need for mechanical forces from outside sources [18–21]. To obtain more precise and effective metal forming, laser-assisted bending is an innovative production technique that blends the accuracy of laser technology with conventional bending processes. This technique involves using a powerful laser to heat a specific area of the material, thereby softening it and reducing its resistance to deformation. This localized heating facilitates more precise bending, particularly in thicker sections or hard metals that are difficult to manipulate using conventional methods. A substantial benefit of laser-assisted bending is its ability to enhance the accuracy and precision of bends, especially for materials with intricate shapes that may be prone to hardening, distortion, or cracking. By concentrating the heat at the bending point, the laser helps preserve the material's integrity and minimizes the force needed during the bending process. Furthermore, this method allows the creation of clean, sharp bends with minimal risk of damaging the workpiece, thereby improving production quality and efficiency. Industries such as electronics manufacturing, automotive, and aerospace, which require high precision and tight tolerances, greatly benefit from the advantages of laser-assisted bending. The laser represents an ideal choice for complex or delicate applications due to its precise control over energy and heat distribution. This technique not only enhances production efficiency but also reduces energy consumption and minimizes tool wear, rendering it a cost-effective solution for both small and large manufacturing enterprises [22–30].

1.6.1 Bending Ferrous Metals and Alloys with Laser Assistance

A significant advancement in metalworking is the capability to bend ferrous metals and their alloys using laser technology, which merges traditional bending techniques with the precision offered by lasers. This approach enhances the malleability of the material and reduces its hardness by selectively heating the area to be bent with a high-powered laser. By meticulously controlling the laser's temperature, the bending process becomes more manageable, minimizing the risk of material distortion or cracking and enabling sharper, more precise bends. Laser assistance alleviates some challenges associated with ferrous metals, such as steel and iron, which typically exhibit greater resistance to deformation due to their inherent strength and hardness. The localized heating from the laser diminishes the forces required for bending, thereby lowering the likelihood of issues like work hardening, which can render the material brittle and susceptible to failure. This technique is particularly advantageous when bending larger sections or complex shapes, where conventional methods may fall short in achieving the desired accuracy. Additionally, since the laser focuses solely on the area being processed, it helps reduce tool wear, leading to less frequent tool replacements, extended equipment lifespan, and decreased maintenance costs. The ability to finely tune the laser parameters also enhances accuracy and repeatability, making this method suitable for high-volume production with minimal defects [31–38]. As industries strive for greater manufacturing efficiency and precision, laser-assisted bending of ferrous metals has emerged as a powerful technique for achieving exceptional metal forming outcomes.

1.6.2 Bending of Non-Ferrous Metals and Alloys with Laser Assistance

An innovative approach to enhancing the efficiency and quality of metal forming is the laser-assisted bending of non-ferrous metals and alloys. This technique integrates traditional bending methods with the precision offered by laser technology. It involves the localized heating of the material using a high-powered laser, creating a temperature gradient that softens the metal at the point of contact. This localized heating reduces the material's resistance to deformation, allowing for more precise and controlled bending without the necessity for excessive mechanical force. The laser-assisted bending method presents several advantages over conventional techniques, particularly for non-ferrous metals such as copper, titanium, and aluminum, which are known for their high sensitivity to heat and lower melting points [39–47]. By pre-softening the material with laser heat, this method facilitates sharper and more accurate bends, minimizes the risk of distortion or fracture, and reduces the need for extensive post-processing. This technique is especially beneficial for components with thin walls and intricate geometries, where traditional bending methods may lead to imperfections.

1.7 Laser Rapid Prototyping

An advanced manufacturing technique known as laser rapid prototyping (LRP) utilizes laser technology to swiftly create precise prototypes of complex components or products. This method serves as an essential resource across various sectors, such as consumer electronics, healthcare, and aerospace, allowing designers and engineers to evaluate and refine their concepts before proceeding to full-scale production. By selectively melting or sintering materials like metals, polymers, or ceramics with lasers, LRP produces highly accurate and detailed prototypes while minimizing material waste. One of the primary advantages of LRP is its speed; prototypes can be generated within a few hours, significantly reducing the time required to transition from idea to functional prototype. Additionally, the precision of laser systems ensures that the prototypes closely match the specifications of the final product, enabling effective testing and optimization. This rapid feedback mechanism accelerates the product development process, leading to shorter innovation cycles and improved product quality. A flexible method for creating prototypes of different sizes, shapes, and purposes, LRP also provides the ability to deal with a broad variety of materials and design complexity. It is anticipated to become more significant in contemporary manufacturing as the technology develops, giving producers the capacity to swiftly adjust to shifting consumer needs and create superior, customized goods with previously unheard-of efficiency [48–50].

1.7.1 Fast Production of Ferrous Components with Laser Assistance

Iron and steel have been the subject of several studies on laser-assisted rapid manufacturing; 108–120 Iron, Cr–V tool steel, and 97Al–3Fe were all subjected to direct laser sintering. The impact of process variables on sintering behavior was examined. Diode lasers and CW CO_2 lasers have been used to study the impact of process parameters on the clad height and surface quality of AISI 316L stainless steel that has been directly laser deposited [51]. The range of grain sizes, from the largest to the smallest, was used to gauge homogeneity. It was discovered that as scan speed increased, the range of grain size and microporosity shrank to almost nothing [52]. Along the wall height, the microhardness is consistent across the cross-section, with a slightly higher value close to the substrate and a lower value in the middle. The microstructure refinement brought on by a high quenching rate from the underlying substrate is the primary cause of the slightly higher microhardness value close to the substrate region. A thorough microstructural analysis reveals that the coarsening of grains causes a decrease in average microhardness when a higher power density is applied. Similarly, applying a faster scan speed raises the fabricated layer's average microhardness. As scan speed increases, less energy is used during melting because of the shorter interaction time. This refines the grains and raises the average microhardness.

1.7.2 Rapid Production of Non-Ferrous Components with Laser Assistance

Because of its special blend of low density and high compressive strength, metallic foam is growing in popularity [53]. Because of its lightweight nature and potential for a wide range of structural uses in the automotive, aerospace, and related industries, aluminum foam has attracted particular attention. However, the use of aluminum foam on a larger scale is restricted by its manufacturing processes [54]. Tang *et al.* [55] performed specific laser sintering on an alloy based on copper [56]. Similar research on the rapid manufacturing of Cu and its alloys using laser assistance has been documented elsewhere. Ti and its alloys are frequently utilized in biomedical implants and aerospace components. Using selective laser sintering, Arcella and Froes [57], and Abbott and Arcella [58] tried to create fully dense and quickly solidified Ti–6Al–4V components. TiAl alloy was created by Srivastava *et al.* [59, 60] using a VFA 600 WCO_2 laser unit and gas-atomized Ti48Al2Mn2Nb powder as feedstock. The microstructure turned out extremely fine and heterogeneous. Improvements in microstructural and compositional homogeneity were observed following a post-heat treatment. The Co–Cr–Mo superalloy was created for bioimplants with enhanced biocompatibility. Superalloys based on Ni and Co were created using the direct laser metal deposition method [61–65].

1.7.3 Summary and Future Scope

Numerous direct or single-step, contactless, and innovative techniques for creating complete components and polymeric origins are available with laser forming. While bending is limited to dimensional adjustments, laser-assisted direct manufacturing procedures involve the continuous, layer-by-layer, or sequential addition of material. Direct manufacturing, quick prototyping, and bending are among the options provided by laser forming. Because laser bending can achieve high precision and production rates without the use of mechanical forces, it is appealing to both the automotive and aerospace industries. Laser bending, which mainly relies on “temperature gradient” and “buckling” mechanisms, is frequently used to customize the curvature of metals and alloys based on titanium, iron, and aluminum. Even though the method is used commercially in production, some basic concepts must be fully comprehended, especially in relation to the exact mechanism of laser bending.

Rapid prototyping and laser assisted manufacturing are two important laser forming techniques that have been commercialized for a variety of uses. The ability to directly (one step) manufacture round or square sections, and more complex geometry using the same machine and fixture is the primary driver of interest in these methods. Layers are typically used to create solid portions. As a result, the weakest point continues to be the interfaces between successive layers. Predicting the stresses produced at the solid object’s corners and edges, as well as its compositional distribution and surface roughness or contour, calls for further research.

1.8 Laser Joining

In the manufacturing process known as laser joining, materials are fused or bonded together using a laser beam. This technology is frequently used for joining metals, polymers, ceramics, and other materials, having various advantages such as precision, little thermal distortion, and the ability to join dissimilar materials. Usually, a high-intensity laser is focused into the area that needs to be connected, causing localized melting of the material. The substance creates a solid bond when it cools. When strong, long-lasting connectors are needed, laser joining is frequently utilized in sectors like electronics, medical device production, automotive, and aerospace [66, 67]. Welding, brazing, soldering, and micro welding are all included in laser joining. A laser source that can give a high-power density with accuracy, dependability, and overall economy is necessary for material joining. As a result, the most widely utilized lasers for joining are pulsed or CW Nd:YAG or CO_2 lasers (rarely ruby lasers), and more recently, diode lasers. These papers were chosen mainly to highlight new developments and list the unsolved problems with employing lasers as a material joining technique. Only electron beam welding can equal the incredibly high precision, variety, and productivity of laser joining, which can be used on both inorganic and organic materials, as well as similar and dissimilar materials. Furthermore, unlike electron beam welding, which requires vacuum processing, laser-assisted joining can be completed in an environment (with the right shielding).

1.9 Laser Welding

Among the laser joining processes, laser welding is the most significant operation due to the sheer volume and scope of work, as well as advancements over the years. Depending on the beam's power, configuration, and concentration on the workpiece, there are two basic types of laser welding: conduction welding and keyhole or penetration welding.

One of the cutting-edge fusion welding techniques is laser beam welding (LBW). The joining procedure is completed by applying a high-energy laser beam to the selected gap, which provides the heat needed to melt and fill the edges. It should be mentioned that the LBW's apparatus and operation techniques differ from those of traditional fusion welding. Compared to traditional welding techniques, LBW produces a thin and deep junction while using a significantly smaller amount of heat input from the workpieces. When the molten area is too big, too small, or too much of the material evaporates, the joint fails. The evaporation of alloying materials and the thermal gradient of the processes causing the crack formation are used to examine the quality of the weld [68–74]. Porosity results when the weld area's volume and scale are out of proportion. Constant laser radiation absorption and even heat distribution throughout the workpieces are necessary to achieve equilibrium between heat input and output. At the beam focal point, the buildup of hot fumes frequently obstructs the laser beam's route to the weld pool. Under specific circumstances, these heated vapors have the potential to form a plasma cloud that absorbs and disperses the beam with significant effect. The initial phase of LBW research involves identifying the variables influencing the process's repeatability, welding area, molten pool, heating/cooling balance, and strategies for controlling these variables.

1.10 Laser Brazing

Using a high-intensity laser beam to heat and melt a filler material—usually a metal alloy—laser brazing is a specialized metalworking process that joins two or more base materials. In brazing, the filler material is melted at a lower temperature than the melting temperatures of the base metals, as opposed to typical welding, which melts and fuses the base materials themselves. By keeping the base metals solid, this technique avoids distortion or damage that can happen with greater heat applications. When high precision and minimal thermal impact on adjacent areas are essential, the focused beam of a laser provides precise control over the heating process, allowing for meticulous energy delivery. The initial steps in this process involve selecting the appropriate filler material and positioning the components to be joined. Once the laser melts the filler, it flows into the joint through capillary action, and as it cools and solidifies, it bonds the materials together. This technique is commonly utilized in industries such as electronics, automotive, and aerospace, where strong, durable connections are required without compromising the integrity of the base materials. One of the primary advantages of laser brazing is its ability to create joints with enhanced mechanical properties, including strength, resistance to corrosion, and durability. Additionally, the precision of the laser minimizes distortion and reduces heat-affected zones (HAZs), particularly when working with thin materials or intricate shapes. Laser brazing is also more rapid and efficient than traditional brazing methods, as the concentrated energy of the laser can swiftly heat the filler material, thereby reducing processing time. However, this method does have its challenges, such as the need for highly accurate equipment and careful selection of filler materials. The cost of the necessary laser technology and the expertise required to operate it may also limit its adoption, particularly among smaller businesses. Despite these challenges, laser brazing remains a highly effective joining technique for applications that demand strength, precision, and minimal heat impact, making it an integral part of advanced manufacturing processes.

1.11 Laser Soldering

The package density is increasing significantly, and solder junction sizes are drastically lowering due to the trends of electronic device miniaturization, multifunctionality and light weight. Because of its unique benefits—non-contact heating, rapid heating, local heating, and rapid cooling—laser soldering technique is frequently used to connect electronic components and printed circuit boards (PCBs). The strength and dependability of the connection between the PCB and electronic components are always significantly influenced by solder alloys. Because of its exceptional solderability and dependability, SnAgCu is the recommended lead-free solder to replace SnPb solder in applications involving electronic components and PCBs. Solder compositions, element additives, substrate orientation, and reaction temperature or process factors are known to have a significant impact on the microstructure of solder junctions.

According to Zeng, the primary determinant of bonding strength during laser soldering is the scanning speed or soldering duration [75]. Numerous calculation models based on different assumptions have been recommended, and numerical simulation technology is being used more in the study of laser soldering of electronic components. The mechanical properties of solder connections on Micro-USB connectors may be enhanced by the right laser soldering parameters and power, according to Zeng's 3D transient heat transfer model of the Micro-USB package, which was proposed to optimize the laser soldering process parameters [76].

1.12 Laser Tissue Joining

An extremely accurate and minimally invasive substitute for conventional techniques like sutures, staples, or clamps is laser tissue joining, a cutting-edge medical technology that uses concentrated laser light to fuse or bond biological tissues together. The initial phase entails directing a concentrated laser beam onto the tissue, which absorbs the energy and converts it into heat. This localized heating causes the denaturation of tissue proteins, such as collagen, leading to the adhesion of adjacent tissue surfaces. The precision of the laser allows for controlled coagulation of the tissue, often resulting in seamless fusion without significantly damaging surrounding structures. One of the primary benefits of laser tissue joining is its ability to perform this intricate procedure with minimal invasiveness. This characteristic makes it particularly advantageous for high-precision operations, including microsurgery and ocular procedures like LASIK. Additionally, this method typically promotes quicker healing and reduces scarring compared to conventional techniques, as it generally inflicts less stress on the tissue and lowers the risk of infection. Laser tissue joining has proven valuable in various medical fields, including vascular surgery, where it can effectively seal arteries or blood vessels, and tissue engineering, where it aids in the development of artificial tissues or organs [77].

1.12.1 Summary and Future Scope

Future studies will primarily focus on bonding (e.g. metallic to covalent) and combining materials with different mechanical (hardness and strength) and physical (melting point, density, and diffusivity) qualities. In addition to welding, efforts must be made to create practical localized joining techniques like brazing and sintering to produce more complex and varied final products. In addition to cladding, reclaiming, and refurbishing old and worn components, laser-assisted welding could be expanded to create functionally and compositionally categorized surfaces with customized configuration and microstructure.

1.13 Laser Machining

A high-energy laser beam is used in laser machining, a sophisticated non-contact material processing method, to precisely cut, drill, engrave, or ablate materials. Because it can process a variety of materials, including composites, metals, and ceramics, with little mechanical stress or tool wear, it is widely employed in industries including aerospace, electronics, and medical manufacturing. Laser machining is the controlled removal of material from a specified area or spot on the workpiece's surface or bulk at a predetermined pace using simultaneous laser-induced melting and evaporation. Laser machining results in a component's size or dimension being reduced if dimensions or volume are added during laser shaping or joining.

Up to a certain depth or dimension, laser machining may accomplish nearly every kind of traditional machining operation, including drilling, cutting, cleaning, marking, and scribing. Regardless of the material's hardness and physical/chemical characteristics, laser machining can be used to cut metals, ceramics, polymers, and composites. With minimal HAZ, the entire procedure may be fully automated at great speed and accuracy while maintaining crisp, clean edges. The scope and versatility of laser machining will be discussed in this section, along with the latest developments and unresolved problems with employing lasers as a non-contact tool for engineering solids machining.

1.14 Laser Cutting

A concentrated laser beam is used in laser cutting. It is a high-precision manufacturing technique to cut different materials, such as composites, polymers, ceramics, and wood. The capacity of this non-contact technology to provide precise, intricate, and clean cuts with little material waste makes it popular in sectors including electronics, automotive, aerospace, and manufacturing. In laser cutting, a powerful laser beam—produced by CO_2, fiber, or Nd:YAG lasers, for example—is focused onto the surface of the material. A jet of assist gas (such as oxygen, nitrogen, or air) helps remove the molten material after the laser warms, melts, or vaporizes the material, resulting in a clean and accurate cut. Three primary types of the process can be distinguished: sublimation cutting, in which material is directly vaporized into gas without melting; flame cutting, which uses oxygen to create an exothermic reaction and increase cutting efficiency; and fusion cutting, in which an inert gas helps expel molten material. The literature has documented successful research projects on laser-assisted machining of engineered materials, including non-metallic and metallic ones [78]. Airframe manufacturing uses titanium alloys that have been cut in an inert atmosphere. Aluminum alloys offer comparable benefits when it comes to laser cutting. Another significant application for laser cutting is the cutting of radioactive materials. In the die board, gift, craft, and trophy industries, among others, cutting wood up to one inch thick may be helpful.

1.15 Laser Drilling

A high-intensity laser beam is used in laser drilling, a sophisticated non-contact machining technique, to precisely drill holes in a variety of materials by melting, vaporizing, or ablation. Because it can drill very small to relatively large holes with high accuracy and little material distortion, it is widely used in industries like aerospace, automotive, electronics, and medical device manufacturing. Depending on the material's characteristics and the necessary hole specifications, the procedure can be carried out using a variety of laser sources, including CO_2, Fiber, and Nd:YAG lasers. Single-pulse drilling, which uses a single laser pulse to drill a hole in thin materials; percussion drilling, which applies multiple laser pulses at the same spot to gradually deepen the hole; trepanning, which entails drilling a small hole first and then enlarging it by moving the laser in a circular pattern; and helical drilling, which uses a spiral motion of the laser beam to achieve precise depth control, are different methods of laser drilling. Furthermore, laser drilling can create the cooling holes in turbine blades for aeronautical applications, as well as the micro-holes needed in fuel injector nozzles and electronic components. To get the best results, though, issues including material reflectivity, thermal damage, and the trade-off between hole quality and drilling speed must be properly handled. Notwithstanding these difficulties, laser drilling is still a popular option for sectors needing accurate, quick, and non-invasive hole production, making it a crucial piece of technology in contemporary manufacturing. In contrast, a Nd:YAG laser can outperform all other techniques by creating a hole in four seconds [79].

1.16 Laser Micromachining

High-precision laser beams are used in laser micromachining, a sophisticated material processing method, to produce incredibly tiny and complex features on a variety of materials, such as metals, ceramics, polymers, semiconductors, and composites. This technology is crucial for sectors like electronics, aerospace, medical devices, and microelectronics to fabricate micro-scale structures with great accuracy, little thermal damage, and remarkable repeatability. Laser micromachining is a non-contact technique that guarantees low material distortion and excellent finishes, in contrast to traditional machining techniques that could result in mechanical wear and tool deterioration. Numerous laser micromachining processes exist, including laser cutting, drilling, engraving, and micro-scale surface shaping. Laser micro-cutting is perfect for producing microelectronics, stents, and precision components because it can create tiny geometries, thin slits, and complex patterns in sensitive materials. High-aspect-ratio holes with diameters as small as a few microns can be created by laser micro-drilling, and these holes are frequently found in medical devices, aircraft turbine blades, and fuel injectors. Laser micro-engraving is also used to add fine lettering, QR codes, and identification markers to small parts without putting them under mechanical stress [80].

The application of ultrafast lasers, such as femtosecond and picosecond lasers, which function at incredibly short pulse durations, is one of the most important developments in laser micromachining. To prevent thermal damage and ensure accurate machining of heat-sensitive materials, including glass, polymers, and biological tissues, these lasers enable "cold ablation," which removes material without producing excessive heat. This has proved very helpful in the development of micro-electromechanical systems, optical components, and microfluidic devices. High precision, excellent surface quality, less material waste, and the capacity to treat a broad range of materials with intricate geometries are some benefits of laser micromachining. Additionally, the efficiency and uniformity of production are improved by its interoperability with automation and computer-controlled systems. Laser micromachining is anticipated to be a key component of next-generation manufacturing, facilitating advancements in medical technology, microelectronics, and sophisticated engineering applications as industries continue to seek highly functional, downsized components.

1.17 Laser Cleaning

High-intensity laser beams are used in laser cleaning, a cutting-edge, non-contact, and eco-friendly surface treatment method, to eliminate impurities, rust, oxides, paint, coatings, grease, and other undesirable elements from a variety of materials. Because of its accuracy, effectiveness, and capacity to clean without causing harm to the underlying material. This procedure has become widely used in sectors like manufacturing, electronics, automotive, aerospace, and cultural heritage restoration. Laser cleaning offers a dry and environmentally safe substitute for conventional cleaning techniques that depend on abrasive materials, chemicals, or solvents, greatly lowering waste and environmental risks.

In the first stage, the ionization of the atoms vaporized off the surface results in the formation of a plasma plume, which prevents contact between the beam and the surface. When the radiation ends, the surface's brief compression turns into tension, which causes the oxidized layer to spallate. When the laser beam strikes the workpiece at an oblique or glancing angle of incidence as opposed to direct or perpendicular irradiation of the surface, cleaning efficiency can be significantly increased in terms of both area and energy. Pulsed laser irradiation of oxidized metallic surfaces in an electrolytic cell under appropriate voltage circumstances has been shown by Tsunemi *et al.* [81] to be a unique method for the efficient removal of oxide layers. Schmidt *et al.* [82] used a 120 W CW diode laser to investigate the output parameters by eliminating white chlorinated rubber coatings from concrete surfaces that are tinted with titanium white. Using the oxygen process gas flow, multiple coating layers that were roughly 0.3 mm thick were eliminated.

1.18 Laser Marking

Materials that are glassy, polymeric, or metallic can be marked using lasers, which emit heat. Compared to traditional marking methods, laser ablation is quick, affordable, and environmentally benign, making it a viable option for direct marking on polymers or plastics. Using a 532 nm laser pulse, it is helpful for dry etching, non-contact, and printing of polyethylene plastics in addition to imprinting a mark or design on a surface for identification purposes. Similarly, soda lime and borosilicate glasses can be manipulated to microcrack or shatter under laser irradiation. A CO_2 laser marking system can cut, heat, or mark a variety of surfaces using a scanning flexible wave guide. Recently, an argon ion laser (514 nm) has been used in a photothermal deposition technique to create permanent markings of different colors on a variety of plastic and ceramic substrates.

There have been recent attempts to create a dual laser writing method where a longer-wavelength laser efficiently enhances the marking process with an unmodulated short-wavelength red laser. The dual-beam writing strategy may reduce the recorded mark length variability and the mark breadth in addition to improving the thermal efficiency of the laser marking process itself. These improvements, when combined with the short wavelength read spot's higher resolution, may enhance writing or marking performance overall.

1.19 Laser Scribing

In the microelectronics sector, laser scribing is widely utilized for ceramic machining. The quantity of debris generated and the size of the HAZ—the smaller the better for both—are used to assess the superiority of scribing, especially for alumina substrates and silicon chips. Excimer laser is used to drill high aspect ratio with straight-walled *via* holes into aluminum nitride, either with or without a metallization layer applied to the *via* walls. A popular method for producing high-quality micromachining of a variety of materials with the least amount of damage and the greatest amount of precision is laser micromachining, which uses ultrashort laser pulses to create micrometer-sized structures on the surface of solid materials. With a possible range of applications in thin film deposition, surface micromachining, and 3D internal waveguide construction, the approach has been in use for over a decade.

1.19.1 Summary and Future Scope

With laser machining, a material must be carefully removed by vaporizing it within a small area with the least amount of heating and damage to the surrounding area. While removing a controlled quantity of materials, the procedure can take various forms, such as drilling, cutting, marking, scribing, or cleaning. It is difficult to remove material by all these processes while preserving accuracy and precision and causing no harm to the environment. Here, the laser's exact spatial and temporal resolution is unquestionably advantageous. The most recent developments currently depend on choosing the right wavelength, employing several beams, permitting oblique or angled incidence, and gradually eliminating material. In a series of steps, several beams can enhance cut thickness, clear debris or vapor, decrease thermal shock, and preheat. Lasers may be used to machine a wide range of materials, including diamond and human and animal tissues. A different material is used when cutting soft organics or animal tissues than when reshaping ultrahard diamond tools or machining silicon wafers. However, the operation's success depends on selecting the right laser strength and wavelength. Nowadays, laser machining frequently uses many lasers for the same operation due to the variety of materials, geometries, and conditions that may be handled. The additional issues with enhancing the cut quality include the use of sophisticated optics and improved sample stage control. Increasing the capacity to machine bigger sections, curved surfaces, and different/heterogeneous materials are some of the problems of the future. In a similar vein, evaluating material damage requires closer supervision and tracking of microstructural alterations and damage throughout the incision. It would be necessary to interface a large database with the hardware to develop intelligent machines that could machine a variety of materials. The main benefit of laser machining is its fully automated operation, which offers both speed and accuracy. Therefore, more work is required to simulate laser machining processes and validate the expected outcomes through appropriate experimentation.

1.20 Laser Manufacturing Techniques

Laser manufacturing techniques have become integral to modern industrial production. These methods are vital across various sectors, including heavy machinery, electronics, automotive, aerospace, and healthcare, and encompass processes such as laser cutting, welding, drilling, marking, engraving, surface treatment, and additive manufacturing. Among these, laser cutting stands out for its ability to create precise cuts and intricate designs with minimal material waste. This technique achieves flawless edges and high accuracy by melting, burning, or vaporizing materials like metals, polymers, ceramics, and composites using intense laser beams. Similarly, laser welding is an efficient joining technique that produces robust, precise, and distortion-free welds, making it ideal for applications in microelectronics, medical device manufacturing, and automotive assembly. Laser drilling is another essential technique for creating small, high-aspect-ratio holes in challenging materials, such as PCBs, turbine blades, and biomedical implants. Additionally, laser marking and engraving provide permanent, high-contrast markings for branding, security, and traceability, commonly used in the production of consumer goods, medical devices, and electronic components. Surface treatment methods, including laser hardening, cladding, and texturing, enhance a material's mechanical properties by improving wear resistance, corrosion protection, and surface aesthetics. Various industries, including aerospace, biomedical, and tooling, heavily rely on these techniques. Furthermore, advancements in laser-based additive manufacturing, such as direct metal laser sintering and selective laser melting, have revolutionized production by enabling the creation of complex, lightweight, and customizable components while minimizing material waste. The integration of automation, artificial intelligence, and robotics with laser technology has further optimized production processes, enhancing their speed, consistency, and flexibility. As the demand for high-precision, sustainable, and cost-effective manufacturing continues to rise, laser-based methods are evolving accordingly. They play a crucial role in the advancement of smart factories and the principles of Industry 4.0.

Laser material processing has developed advanced manufacturing by providing efficient, precise, and different techniques for cleaning, scribing, marking, drilling, welding, and surface treatment. It is a non-contact material processing technique that improves precision, accuracy, and lowers the mechanical wear. Generally utilized laser types are fiber, diode, CO_2, and Nd: YAG lasers, which are used for specific applications based on their compatibility, wavelength, and power with various materials. One noteworthy application is laser drilling, which creates small holes in difficult materials such as superalloys and ceramics. These holes are necessary to fabricate turbine blades, electronic components, and medical implants. Moreover, laser engraving and marking methods can create high-contrast identification marks on different materials, including polymers and metals, which are needed for branding, security coding, and traceability. Surface treatment methods such as cladding, texturing, and laser hardening improve the material's resistance to wear and corrosion while also upgrading its aesthetic appeal. These procedures are frequently employed in the production of biomedical implants, tools, and decorative items. Furthermore, developments in ultrafast lasers have made it possible to process fragile materials like polymers, semiconductors, and glass with precision without creating heat damage. The consistency, efficiency, and customization of manufacturing have been further improved by the combination of artificial intelligence, automation, and robots with laser processing. By facilitating complex geometries and minimizing material waste, additive manufacturing—specifically, laser-based 3D printing—has revolutionized production and prototyping. It is predicted that laser technology will become even more significant in Industry 5.0, high-precision manufacturing, and smart factories as it develops further, stimulating advancements in a variety of fields.

1.21 Conclusion

This article provided a summary of the principles of lasers, their interaction with matter, and their use in material processing, which is broken down into four main areas: surface engineering, forming, joining, and machining. The early twentieth century saw the invention of the laser. Almost 40 years ago, commercial high-power lasers were created that could provide sufficient power density for material processing that involved heating, melting, and vaporizing all engineering solids. However, using lasers to process materials only gained popularity in the 1980s and beyond. However, the initial research and experiments quickly evolved into a wide range of uses, all the way up to large-scale commercial production. The scientific community quickly became very interested in understanding the microstructure and phase evolution, the impact of process factors on material behavior, and the relationship between microstructure and characteristics due to the success in engineering applications. The ability of lasers to create microstructures, such as amorphous and extended solid solutions, by ultrarapid cooling due to self-quenching, in addition to producing intense localized heating, has sparked a great deal of scientific interest in the development of metastable aggregates with improved properties, increased performance, and longer component life. Even though the thermal profile or laser-induced heating decreases exponentially with depth, large components of nearly any desired size and geometry can now be created to the ability to combine laser technology with contemporary engineering techniques. Nowadays, lasers are used to create graded aggregates with regulated porosity, content, and microstructure, as well as to seal surface porosities on coated and welded goods.

In addition to drilling, the same material can be machined, marked, or scribed with the same equipment and space. Despite the benefit of completely automated processing at a very high speed and productivity, the quality and dimensional correctness of these holes are unparalleled. The walls of the holes are entirely vertical, and the bulk workpiece is undistorted. It is also feasible to have holes with threads, steps, or a tapering inclination. Round rims, flat turbine blades, thin filter, cigarette papers, and other materials can all be perforated similarly and precisely. Almost any solid can have micro holes made with laser drilling with extremely high precision and tight tolerance. Although transformation hardening is mostly used on steels and cast irons, non-ferrous metals and alloys can also have hard, wear-resistant surfaces due to the ultrafine grain structure created by surface melting and the ensuing fast cooling. In semiconductor wafers and films, controlled laser irradiation can result in localized heating, holes, and *via* drilling, annealing, even metallization, and doping.

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