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Laser beam machining—A review

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Abstract

Laser beam machining (LBM) is one of the most widely used thermal energy based non-contact type advance machining process which can be applied for almost whole range of materials. Laser beam is focussed for melting and vaporizing the unwanted material from the parent material. It is suitable for geometrically complex profile cutting and making miniature holes in sheetmetal. Among various type of lasers used for machining in industries, CO_2 and Nd:YAG lasers are most established. In recent years, researchers have explored a number of ways to improve the LBM process performance by analysing the different factors that affect the quality characteristics. The experimental and theoretical studies show that process performance can be improved considerably by proper selection of laser parameters, material parameters and operating parameters. This paper reviews the research work carried out so far in the area of LBM of different materials and shapes. It reports about the experimental and theoretical studies of LBM to improve the process performance. Several modelling and optimization techniques for the determination of optimum laser beam cutting condition have been critically examined. The last part of this paper discusses the LBM developments and outlines the trend for future research.

Keywords: Laser beam machining; Nd:YAG; CO_2; HAZ; Kerf; Modelling

Contents

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1. Introduction

Emergence of advanced engineering materials, stringent design requirements, intricate shape and unusual size of workpiece restrict the use of conventional machining methods. Hence, it was realized to develop some non-conventional machining methods known as advanced machining processes (AMPs). Nowadays many AMPs are being used in the industry such as; electro discharge machining, beam machining processes (Laser beam machining (LBM), electron beam machining, ion beam machining and plasma beam machining), electrochemical machining, chemical machining processes (chemical blanking, photochemical machining), ultrasonic machining (USM), and jet machining processes (abrasive jet machining, water jet machining, abrasive water jet machining), but these processes have their own limitations regarding workpiece material, shapes, etc. LBM is one of the AMPs which is used for shaping almost whole range of engineering materials. The laser beams are widely used for cutting, drilling, marking, welding, sintering and heat treatment. The laser is also used to perform turning as well as milling operations but major application of laser beam is mainly in cutting of metallic and non-metallic sheets.

This paper provides a review on the various research activities carried out in LBM process. The content of paper includes a brief introduction of laser and its development, different LBM configurations and LBM application for different category of materials. Major areas of LBM research have been discussed under the headings of experimental studies, modelling and optimization studies. In the last, the new challenges and future direction of LBM research have been discussed.

2. Laser beam machining (LBM)

This section provides the basic fundamentals of the LBM process and its variations.

2.1. Light and lasers

Planck has given the concept of *quanta* in 1900 and in 1920 it was well accepted that apart from wavelike characteristics of light it also shows particle nature while interacting with matters and exchange energy in the form of photons [1]. The initial foundation of laser theory was laid by Einstein who has given the concept of stimulated emission [2]. Townes and Shawlow (1957) produced the first laser known as Ruby Laser [1].

Laser (light amplification by stimulated emission of radiation) is a coherent and amplified beam of electromagnetic radiation. The key element in making a practical laser is the light amplification achieved by stimulated emission due to the incident photons of high energy. A laser comprises three principal components, namely, the lasing medium, means of exciting the lasing medium into its amplifying state (lasing energy source), and optical delivery/feed back system. Additional provisions of cooling the mirrors, guiding the beam and manipulating the target are also important. The laser medium may be a solid (e.g. Nd:YAG or neodymium doped yttrium–aluminium–garnet), liquid (dye) or gas (e.g. CO_2, He, Ne) [2].

Laser light differs from ordinary light because it has the photons of same frequency, wavelength and phase. Thus, unlike ordinary light laser beams are highly directional, have high power density and better focussing characteristics. These unique characteristics of laser beam are useful in processing of materials. Among different type of lasers, Nd:YAG and CO_2 are most widely used for LBM application. CO_2 lasers have wavelength of 10 μm in infrared region. It has high average beam power, better efficiency and good beam quality. It is suitable for fine cutting of sheet metal at high speed [3]. Nd:YAG lasers have low beam power but when operating in pulsed mode high peak powers enable it to machine even thicker materials. Also, shorter pulse duration suits for machining of thinner materials. Due to shorter wavelength (1 μm) it can be absorbed by high reflective materials which are difficult to machine by CO_2 lasers [4].

2.2. Principle of LBM

The mechanism of material removal during LBM includes different stages such as (i) melting, (ii) vaporization, and (iii) chemical degradation (chemical bonds are broken which causes the materials to degrade). When a high energy density laser bream is focussed on work surface the thermal energy is absorbed which heats and transforms the work volume into a molten, vaporized or chemically changed state that can easily be removed by flow of high pressure assist gas jet (which accelerates the transformed

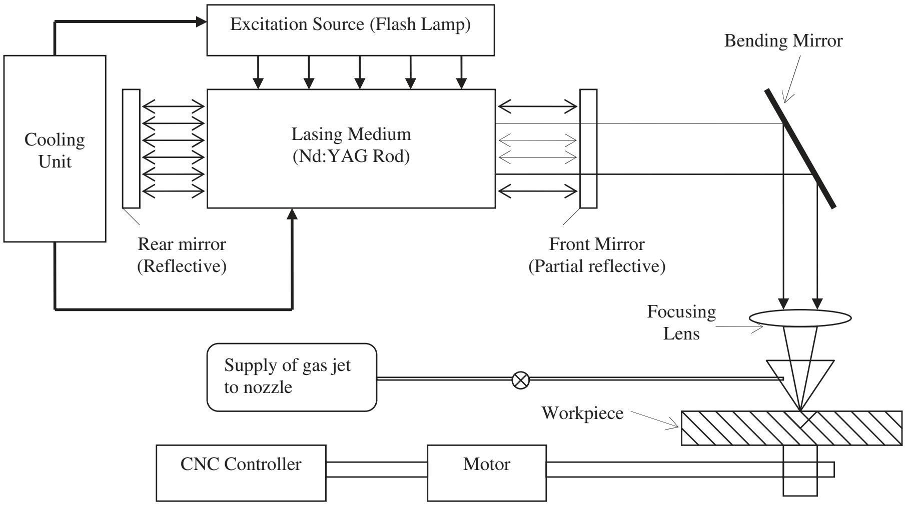

Fig. 1. Schematic of Nd:YAG laser beam cutting system.

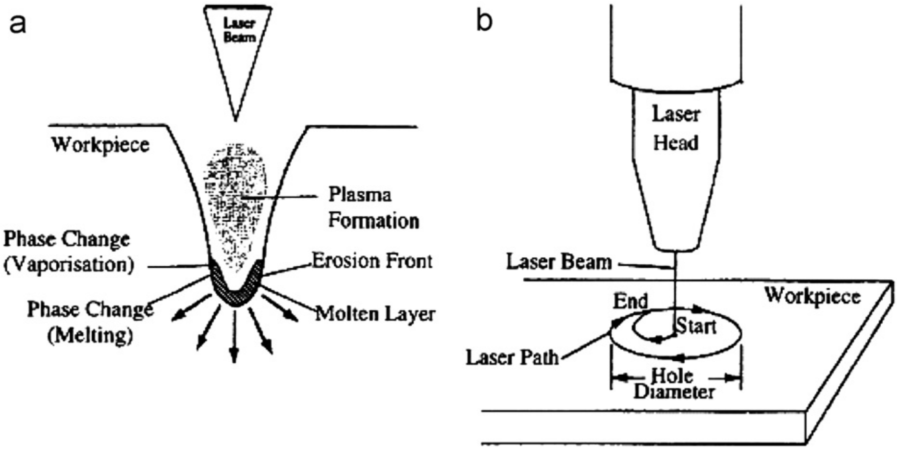

Fig. 2. Schematic of laser beam (a) percussion drilling and (b) trepan drilling [19].

material and ejects it from machining zone) [5]. The schematic of LBM has been shown in Fig. 1.

LBM is a thermal process. The effectiveness of this process depends on thermal properties and, to a certain extent, the optical properties rather than the mechanical properties of the material to be machined. Therefore, materials that exhibit a high degree of brittleness, or hardness, and have favourable thermal properties, such as low thermal diffusivity and conductivity, are particularly well suited for laser machining. Since energy transfer between the laser and the material occurs through irradiation, no cutting forces are generated by the laser, leading to the absence of mechanically induced material damage, tool wear and machine vibration. Moreover, the material removal rate (MRR) for laser machining is not limited by constraints such as maximum tool force, built-up edge formation or tool chatter. LBM is a flexible process. When combined with a multi-axis workpiece positioning system or robot, the laser beam can be used for drilling, cutting, grooving, welding and heat treating processes on a single machine [6].

2.3. LBM variations

The major LBM configurations are: drilling (1-D), cutting (2-D) and grooving, turning and milling (3-D), and micromachining of different workpiece materials. Laser beam drilling has become the accepted economical process for drilling thousands of closely spaced holes in structures. Two types of laser beam drilling exist: trepan and percussion laser beam drilling. Trepan drilling involves cutting around the circumference of the hole to be generated, whereas percussion drilling 'punches' directly through the workpiece material with no relative movement of the laser or workpiece (Fig. 2). The inherent advantage of laser percussion drilling process is the reduction in processing time [1]. Laser beam cutting and grooving operations have found applications in punching, cut-off and marking of metals, ceramics and plastics. Schematic of laser beam cutting is shown in Fig. 3. Laser beam cutting is superior to any cutting method conventional or non-conventional because of material versatility, no wear or change of tool, high material utilization and production flexibility and high accuracy and edge quality [5].

Laser beam turning and milling are 3-D operations and require two simultaneous laser beams to get desired profile in the workpiece (Fig. 4). The beams can be focussed at desired angles with the help of fibre optics. Laser milling allows the production of parts with complex shapes without expensive tooling. Laser milling is most suitable for machining parts with one-sided geometry or for partial machining of components from one side only. Complete laser milling of parts is also possible but difficulty in accurately re-positioning the work-part is a big challenge [6]. The researchers have proposed different mechanisms of material removal during laser milling. Tsai et al. [7] have proposed the laser milling of ceramics by fracture technique in which a focused laser beam is used to scribe the grooves on the work surface all around the machining zone and then a defocused laser beam is used for heating this zone. The heat induces the tensile stress and the stress concentration increases at the groove tip which results the fracture in the direction of groove cracks. Pham et al. [8] have studied the application of laser milling for rapid manufacturing of micro-parts of difficult to machine materials by using layer by layer material removal technique through chemical degradation. Qi et al. [9] have studied the laser milling of alumina ceramic and found that the milling quality was superior for laser milling in water but the efficiency was reduced as compared with laser milling in air.

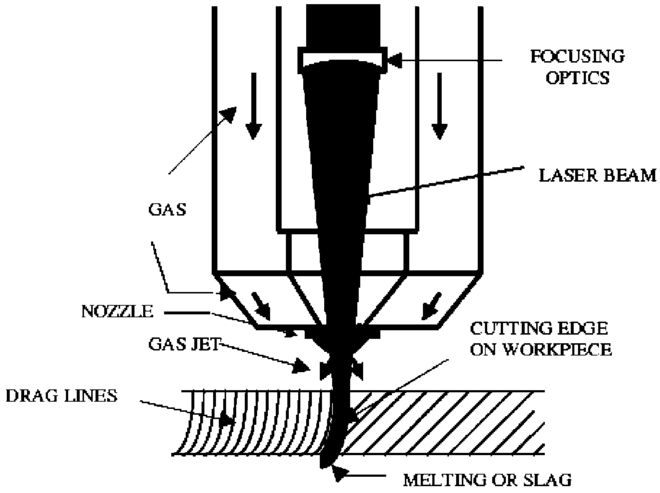

Fig. 3. Laser beam cutting.

Micromachining refers to machining of workpart or features having dimensions below 1 mm. Lasers are being used for micromachining operations with short pulses (pulse duration varies from microsecond to femtosecond) and very high frequencies (in kHz range). Pulsed Nd:YAG, and Excimer lasers are most commonly used for

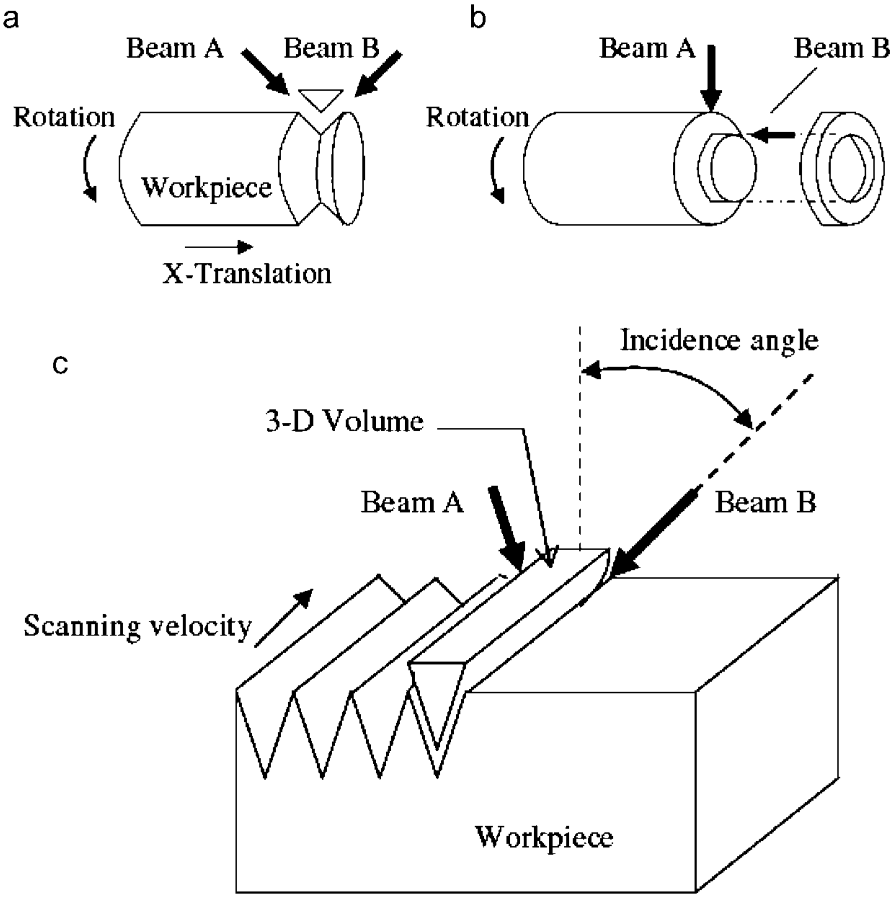

Fig. 4. Three-dimensional laser machining: (a) laser turning (helix removal); (b) laser turning (ring removal); and (c) laser milling [1].

micromachining applications in medical and electronic industries [4].

2.4. Laser-based hybrid/cross/assisted machining

Machining processes, which are combinations of two or more machining processes, have attracted special interest in the field of machining advanced engineering materials. These processes are developed to exploit the potential advantages and to restrict the disadvantages associated with an individual constituent process. Usually, the performance of hybrid machining process is better than the sum of their performance with the same parameter settings. In some of these processes, besides the performance from individual component processes, an additional contribution may also come from the interaction of the component processes [10]. Most of the hybrid machining processes has been developed by combining conventional or unconventional machining processes with LBM or USM. Laser and non-laser hybrid machining processes are becoming more popular in industries in recent time. Many attempts have been made to combine LBM with other machining processes. Some of them have been found very effective. Typical industrially developed hybrid machining processes of LBM are shown in Fig. 5.

The laser source of energy (thermal energy) is used for softening the workpiece material when it is combined with conventional machining processes such as turning, shaping and grinding. The hybrid machining processes developed with laser and non-laser conventional machining processes are shown in Fig. 6. In laser-assisted turning, the laser heat source is focussed on the un-machined section of the workpiece directly in front of the cutting tool. The addition of heat softens the surface layer of difficult-to-turn materials, so that ductile deformation takes place rather than brittle deformation during cutting. This process yields higher MRRs while maintaining workpiece surface quality and dimensional accuracy. It also substantially reduces the tool wear and cost of machining by reducing man and machine hours per part [11]. Lei et al. [12] have found that the laser-assisted turning (LAT) of silicon nitride ceramics economically reduces the surface roughness and tool wear in comparison to only conventional turning process. Wang et al. [13] have found that the LAT of alumina ceramic composite (Al_2O_3p/Al) has reduced the cutting force and tool wear by 30–50% and 20–30%, respectively, along with

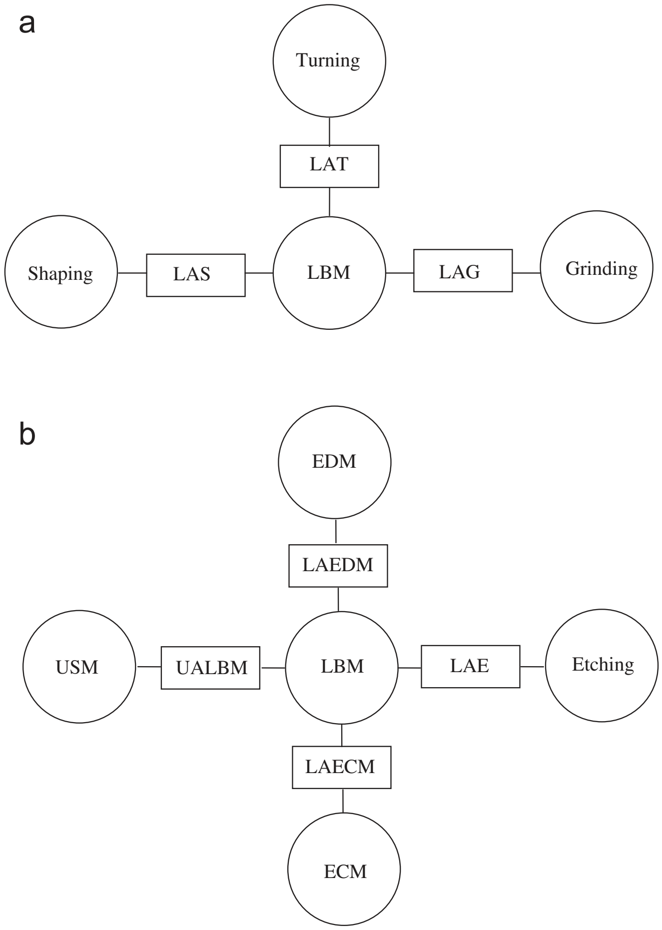

Fig. 5. Laser and non-laser hybrid (a) conventional and (b) unconventional machining processes. LAT, laser-assisted turning, LAS, laser-assisted shaping, LAG, laser-assisted grinding, LAEDM, laser-assisted EDM, LAECM, laser-assisted ECM, UALBM, ultrasonic-assisted LBM, LAE, laser-assisted etching.

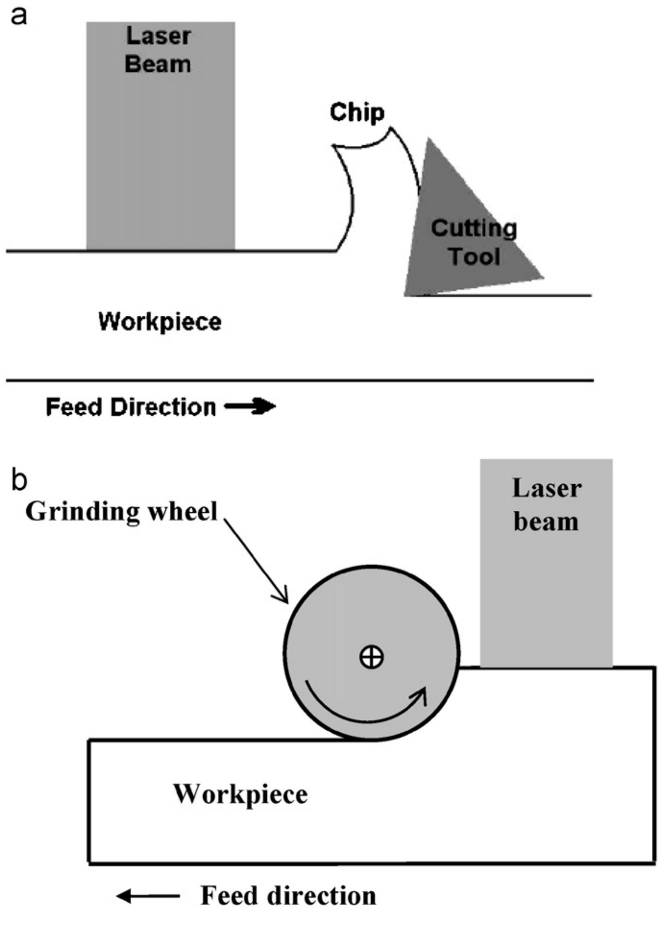

Fig. 6. Schematic of: (a) laser-assisted turning and (b) laser-assisted grinding.

the improved surface quality as compared with conventional turning. Chang and Kuo [14] have also found a reduction of 20–22% in cutting force with a better surface quality during laser-assisted planing of alumina ceramics. The thrust force in laser-assisted micro-grooving of steel has been found to be reduced by 17% as compared with conventional micro-grooving [15].

Hybridization of LBM with unconventional machining processes has also proven to be advantageous for improving the quality of machining. Ultrasonic-assisted LBM (UALBM), laser-assisted electrochemical machining (LAECM), laser-assisted electro-discharge machining (LAEDM), and laser-assisted etching (LAE) are the examples of laser hybrid machining processes. Zheng and Huang [16] found that both the aspect ratio (depth over diameter) and the wall surface finish of the micro-holes were improved by using the ultrasonic vibration-assisted laser drilling, compared to laser drilling without assistance of ultrasonic vibration. Yue et al. [17] have found the deeper holes with much smaller recast layer during ultrasonic-assisted laser drilling as compared with the laser drilling without ultrasonic aid. Laser-assisted seeding (a hybrid process of LBM and electro-less plating) process have proven to be superior than conventional electro-less plating during plating of blind micro-vias (micro-vertical interactions) of high aspect ratios in printed circuit boards (PCBs) [18]. In LAECM, the laser radiation accelerates the electrochemical dissolution and localizes the area of machining by few microns size which enables the better accuracy and productivity [19]. De Silva et al. [20] have found that LAECM of aluminium alloy and stainless steel have improved the MRR by 54% and 33%, respectively, as compared with electro-chemical machining alone. They also claimed that LAECM has improved the geometrical accuracy by 38%. Li and Achara [21] have found that chemical-assisted laser machining (laser machining within a salt solution) significantly reduces the heat-affected zone and recast layer along with higher MRR as compared with laser machining in air.

Li et al. [22] have applied the LBM and EDM sequentially for micro-drilling of fuel injection nozzles. They initially applied the laser drilling to produce the micro-holes and then EDM was used for rimming the drilled micro-holes. They claimed that this hybrid approach has eliminated the recast layer and heat affected zones (HAZs) typically associated with laser drilling. They also claimed that the hybrid process enabled 70% reduction in drilling time as compared with EDM drilling. Electro-chemical or chemical etching processes are combined with laser beam for localized etching to enable selective material removal. The use of LAE has improved the etched quality and etching rate of super-elastic micro-gripper prepared by cutting of nickel–titanium alloy [23].

2.5. *Remarks*

The conclusion that can be drawn from this section is that, the main strength of LBM process lies in its capability to machine almost all type materials in comparison to other widely used advanced machining method such as EDM, ECM and USM. In comparison to jet machining processes, it is quite suitable for cutting small and thin sheets with high cutting rates and can be applied to machine miniature objects unlike other jet machining processes such as water jet, and abrasive water jet machining methods. Though it is non-contact type advanced machining method with high flexibility but thermal nature of the process requires careful control of the laser beam to avoid any undesired thermal effect. Among different variations, only laser drilling and cutting are being used most widely while 3-D LBM operations are not fully developed and a lot of research work is required before they can be put for industrial use. Unlike other, non-conventional energy sources laser beam source of energy can also be used as assistance during conventional machining of difficult-to-machine materials. The laser hybrid machining processes have been found superior to a single non-conventional machining technique in various machining applications.

3. LBM applications

LBM has wide applications in the field of automobile sectors, aircraft industry, electronic industry, civil structures, nuclear sector and house appliances. Stainless steel, a distinguishable engineering material used in automobiles and house appliances, is ideally suitable for laser beam cutting [24,25]. Advanced high strength steels (AHSS) machined by laser beam have applications in car industry and boiler works [26]. Titanium alloy sheets used in aerospace industry to make forward compression section in jet engines are cut by lasers [27–29]. Aluminium alloys used in aeronautics are one of the most promising for laser machining implantation [30]. Also, aluminium alloy samples of slot antenna array can be directly fabricated on laser cutting system [31]. Cutting of complex geometry in metallic coronary stents (Fig. 7) for medical application is done by pulsed Nd:YAG laser beam cutting [32,33]. LBM is the most suitable and widely used process to machine nickel base superalloys, an important aerospace material [34–38]. Besides metals and alloys LBM is also used in different industrial applications to machine ceramic work materials successfully. Commercial piezoceramic discs are laser cut to provide complex shapes in RAINBOW actuators [39]. Cutting of commercially available ceramic tiles using diamond-saw, hydrodynamic or USM are time consuming and expensive in processing of particular shape. LBM can cut intricate shapes and thick sections in these tiles [40–42].

Short pulse Nd:YAG lasers are successfully used in electronic industry to cut QFN packages (semiconductor packages which are plastic encapsulated packages with copper lead frame substrates) [43–45]. The formation of vertical interconnections (vias) in PCB also makes use of laser beam for drilling [46–49]. Hard and brittle composite

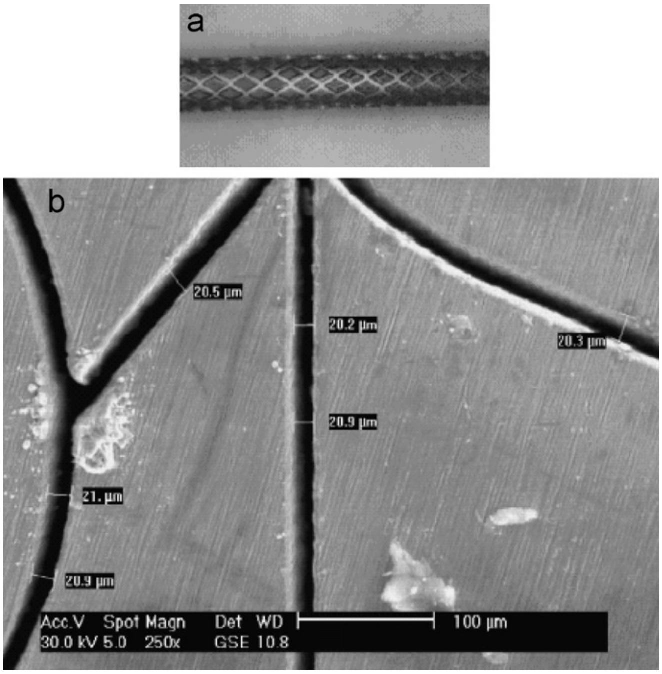

Fig. 7. (a) Pictorial view of laser generated metallic stent (b) SEM micrograph showing kerf width of laser cut metallic stent.

materials like marble, stone and concrete have wide applications in the field of civil structures. Refs. [50–53] have discussed the details of successful cutting of these materials by laser beam. Glasses used in optoelectronics are micromachined by laser beam as shown in Fig. 8 [54–56]. Smaller pieces of lace fabric (nylon 66) for lingerie are separated from main web by CO_2 laser cutting [57]. In the past few years CO_2 laser cutting of poly-hydroxy-butyrate (PHB) was used in the manufacturing of small medical devices such as temporary stents, bone plates, patches, nails and screws [58]. Surgeons in various medical fields have applied pulsed laser cutting of tissue for several years [59,60].

Latest generation Q-switched diode pumped solid state lasers (DPSSLs) can be used for industrial applications to produce 3-D intricate profiles by laser milling of a wide variety of materials including aerospace alloys, thermal barrier coatings, tool steels, diamond and diamond substitutes [61]. Werner et al. [62] have recently proposed the application of CO_2 laser milling in medical field for producing micro-cavities in bone and teeth tissues without damaging the soft tissues.

3.1. Remarks

The capability of LBM to cut complex shapes and drill micro size holes with close tolerances in wide variety of materials has opened a new door to industries. Nowadays, industries related to almost all manufacturing fields are adopting the LBM processes. Some unique applications of LBM involves cutting of stainless steel pipes with high cutting rates and at less cost than diamond saw cutting, cutting complex shapes in car doors, cutting QFN packages in electronic industries, producing cooling holes in turbine engines in aircraft industry, micro-fabrication of vias in PCB. The coronary stents used in medical field are micromachined by LBM. Unlike other thermal energy based processes such as EDM and ECM it provides lesser HAZ that makes it suitable for micromachining applications.

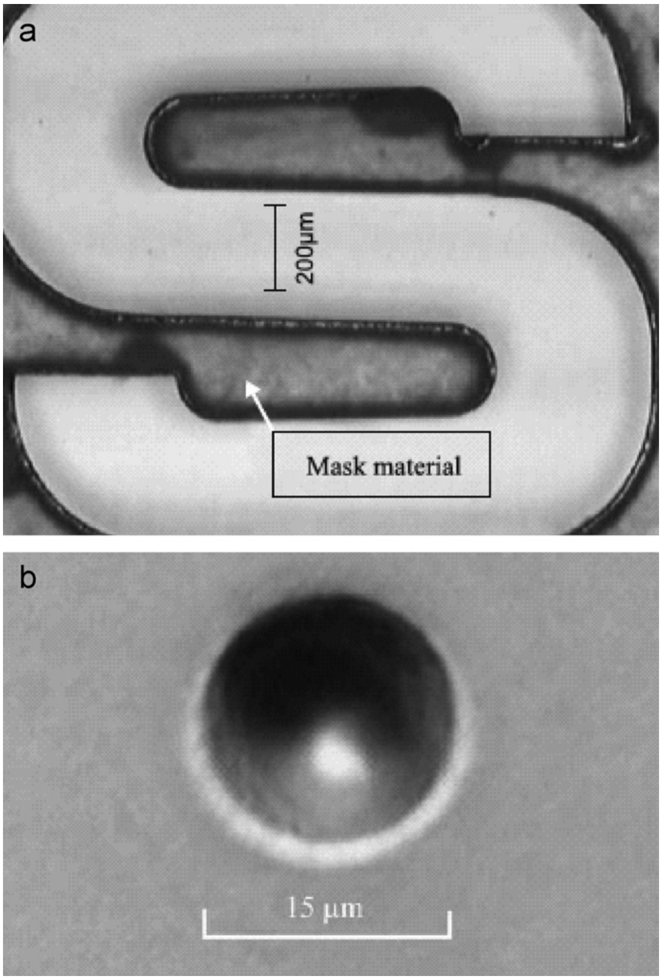

Fig. 8. Laser micro-machining application of glass sample: (a) complex features and (b) spherical cavity with a diameter of 15 µm and central depth of 4.5 µm.

4. Major areas of LBM research: state-of-the-art

The research work carried out in the area of LBM can be divided in three parts namely experimental studies, modelling studies and optimization studies.

4.1. Experimental studies

Experimental studies on LBM by researchers show the effect of process input parameters such as laser power, type and pressure of assist gas, cutting material thickness and its composition, cutting speed and mode of operation (continuous or pulsed mode) on process performance. The

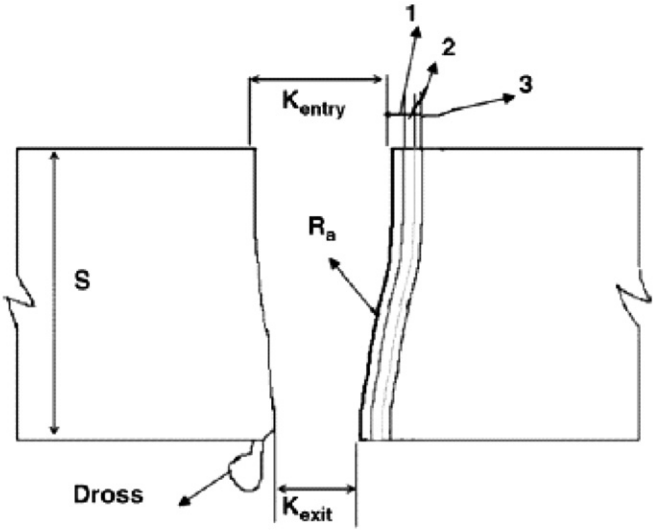

Fig. 9. Schematic illustration of various cut quality attributes of interest [21]. *K*entry: kerf width at entry side; *K*exit: kerf width at exit side; *R*a: surface roughness; *S*: thickness of material; 1: oxidized layer; 2: recast layer; and 3: heat affected zone (HAZ).

quality characteristics (or process performance) of interest in LBM are MRR, machined geometry (kerf width, hole diameter, taper), surface quality (surface roughness, surface morphology), metallurgical characteristics (recast layer, heat affected zone, dross inclusion) and mechanical properties (hardness, strength, etc.). The important quality characteristics related to laser cutting of sheets are shown in Fig. 9.

4.1.1. Material removal rate (MRR)

Voisey et al. [63] have studied the melt ejection phenomena in metals (aluminium, nickel, titanium, mild steel, tungsten, copper and zinc) by conducting Nd:YAG laser drilling experiments at different power densities. It was found that MRR first increases and then decreases after a critical value with increasing power density for all metals tested. The critical value was found as type of metal dependent. Some investigators have used machining speed and/or machining time to represent the MRR. Cutting speed of continuous wave (CW) and pulsed Nd:YAG laser beam was compared in [64] for cutting bare and coated metal plates (0.8–2.0 mm thick) of car frame using oxygen assist gas. The cutting speed obtained was more in case of CW laser, bare metal and thinner plate and the highest cutting speed recorded was 5 m/min at an optimum oxygen pressure of 3 bar. Experimental study [65] for cutting stainless steel sheets (up to 2 cm thick) from a long distance (1 m) without using any assist gas was performed in pulsed mode taking pulse frequency (100–200 Hz), peak power (2–5 kW) and cutting velocity (0.05–0.5 m/min) as process variables. The study reveals that low pulse frequencies and high peak powers were found to be favourable for higher cutting speeds. The experimental study of micromachining of sapphire (381 μm) and silicon (533 μm) wafers show that the MRR increases with beam energy density irrespective of machining speed (Fig. 10) [66]. The MRR of mullite-alumina ceramic during laser cutting was increased by proper selection of off-axis nozzle angle (optimum value 45°) and distance between the impinging point of the gas jet and the laser beam front (optimum value 3 mm) [67]. Experimental study by Lau et al. [68] shows that compressed air removes more material in comparison to argon inert gas during laser cutting of carbon fibre composites. The effect of pulse intensity (kW) on depth of cut or MRR during pulsed Nd:YAG laser cutting shows increasing effect for all metal matrix composites, carbon fibre composites and ceramic composites [69]. The MRR during laser machining of concretes shows increasing trend with both laser power and scan speed [53].

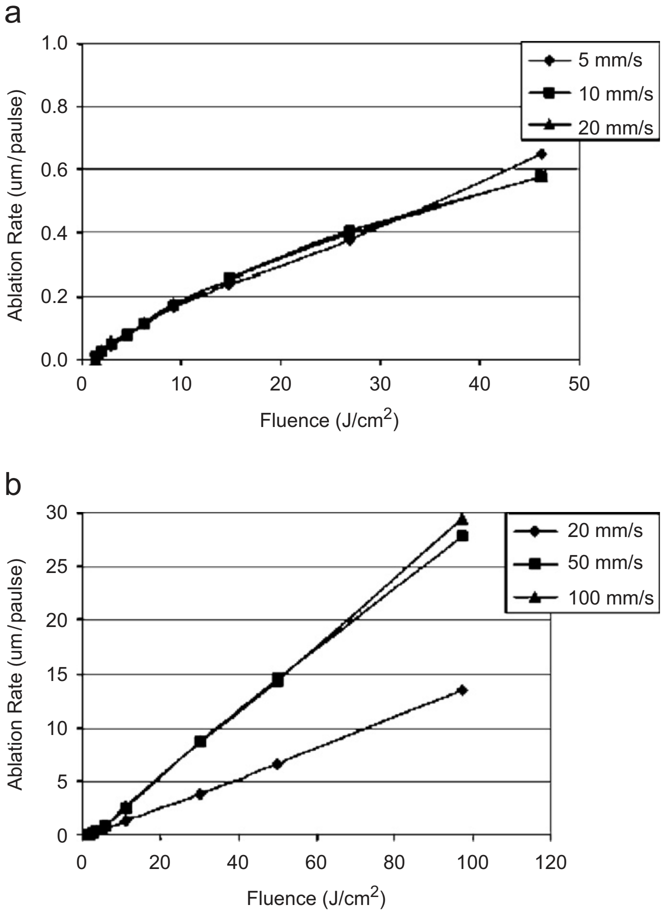

Fig. 10. The ablation rates (material removal rates) of laser micromachining vs. laser fluences (energy densities) for (a) sapphire wafer and (b) silicon wafer, with different cutting speeds.

4.1.2. Machined geometry

Two important parameters of LBM, which decide the quality of machining, are cut width/ hole diameter and taper formation. Due to converging–diverging shape of laser beam (Fig. 11), tapers always exist on laser machined components but it can be minimized up to acceptable range. Smaller kerf width or hole diameter reduces the taper. Chen [70] has examined the kerf width for three

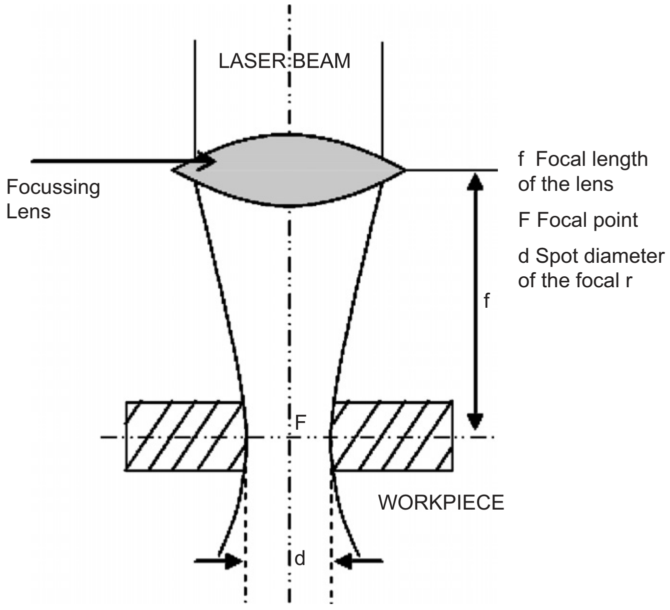

Fig. 11. Schematic of beam profile.

different assist gases oxygen, nitrogen and argon at high pressure (up to 10 bar) and found that kerf width increases with increasing laser power and decreasing the cutting speed during CO_2 laser cutting of 3 mm thick mild steel sheet. He also observed that oxygen or air gives wider kerf while use of inert gas gives the smallest kerf. Ghany et al. [24] have observed the same variation of kerf width with cutting speed, power and type of gas and pressure as above during experimental study of Nd:YAG laser cutting of 1.2 mm thick austenitic stainless steel sheet. They have also found that on increasing frequency the kerf width decreases. The same effect of laser power and cutting speed on kerf width during CO_2 laser cutting of steel sheets of different thicknesses was observed by other researchers also [26,71–73]. Refs. [74,75] also show the same variation of kerf width with laser power and cutting speed during CO_2 laser cutting of different fibre composites.

Karatas et al. [76] found that the kerf width reduces to minimum when the focus setting is kept on the workpiece surface for thin sheets (1.5 mm) and inside the workpiece for thicker sheets (3.5 mm) during hot rolled and pickled (HSLA) steel cutting using CO_2 laser. Laser cutting of metallic coated sheet steels (1 mm thick) show that a particular combination of laser–lens–metal gives same kerf width irrespective of variations in process parameters [77]. Thawari et al. [37] have performed Nd:YAG laser cutting experiment on 1 mm thick sheet of nickel-based superalloy and found that on increasing the spot overlap (which is a function of pulse frequency and cutting speed) the kerf width increases. They also observed that shorter pulse duration yields lower taper kerf compared to a longer duration pulse.

Bandyopadhyay et al. [34] have investigated the effect of material type and its thickness on hole taper during Nd:YAG laser drilling of titanium alloy and nickel alloy sheets of different thicknesses. The results show that the hole entry diameter and taper angle are different for different materials and increases with decreasing thickness. Taper angle decreases with increasing pulse frequency while pulse energy shows no significant effect on hole taper. Nd:YAG laser drilling of fibre-glass composites (7 mm thick) show that setting of focal plane position w.r.t. workpiece surface for minimum hole taper depends on material thickness [78]. CO_2 and Nd:YAG laser drilling of polyester foils and glass fibre reinforced epoxy laminates give larger hole diameter at increased laser power [79].

4.1.3. Surface roughness

Surface roughness is an effective parameter representing the quality of machined surface. Ref. [24] shows that surface roughness value reduces on increasing cutting speed and frequency, and decreasing the laser power and gas pressure. Also nitrogen gives better surface finish than oxygen. In Ref. [70] surface roughness value was found to be reduced on increasing pressure in case of nitrogen and argon but air gives poor surface beyond 6 bar pressure. Also, surface finish was better at higher speeds. Ref. [71] shows that the laser power and cutting speed has a major effect on surface roughness as well as striation (periodic lines appearing on the cut surface) frequency (Fig. 12). They have shown that at optimum feed rate, the surface roughness is minimum and laser power has a small effect on surface roughness but no effect on striation frequency. Chen [80] has not found the good surface finish up to 6 bar pressure (of inert gas) during CO_2 laser cutting of 3 mm thick mild steel. Ref. [37] shows that surface finish improves on increasing the spot overlap. Recently, Li et al. [81] have proposed the specific cutting conditions for striation free laser cutting of 2 mm thick mild steel sheet.

Micromachining of 0.5 mm thick NdFeB ceramic (magnetic material) using pulsed Nd:YAG laser gives better surface finish in water as compared to air [82]. The experimental investigations on pulsed Nd:YAG laser

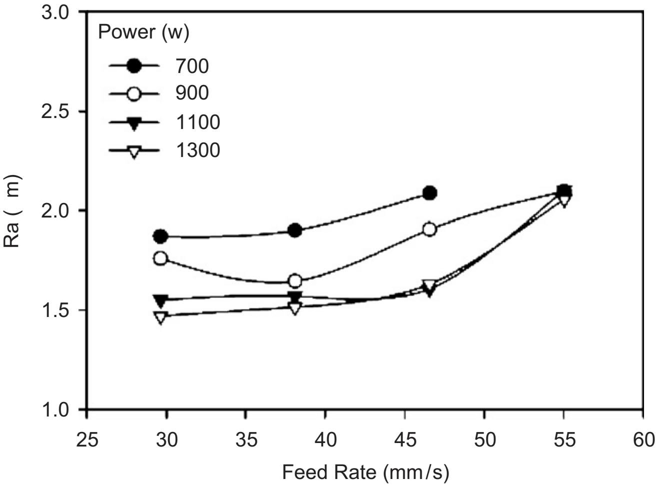

Fig. 12. Variation of surface roughness with laser power and feed rate (cutting speed) during CO_2 laser cutting of 1.27 mm steel sheet.

cutting of 2.15 mm thick silicon nitride ceramic sheet using air as assist gas show that the optimum value of surface roughness falls in the middle range of operating parameters pulse frequency (6–8.5 Hz), lamp current (22–27 amp) and cutting speed (17–22 mm/s) [83]. Laser cutting of thick (1–10 mm) alumina ceramic substrates through controlled fracture using two synchronized laser beams, focused Nd:YAG (for scribing the groove crack) and defocused CO_2 (to induce thermal stresses) show that surface finish obtained at 60 W laser power (for both Nd:YAG and CO_2) and 1 mm/s cutting speed was much better than conventional laser cutting [84]. The surface roughness of thick ceramic tiles during CO_2 laser cutting is mainly affected by ratio of power to cutting speed, material composition and thickness, gas type and its pressure [40,41]. Use of nitrogen assist gas and lesser power intensities reduce the surface roughness [74]. Pulsed mode CO_2 laser cutting gives better surface finish than CW mode [75].

4.1.4. Metallurgical characteristics

The change in metallurgical characteristics of laser machined workparts is mainly governed by HAZ. Therefore, it is required to minimize the HAZ during LBM by controlling various factors. Decreasing power and increasing feed rate generally led to a decrease in HAZ [71]. Wang et al. [85] also found the same effect of power and cutting speed on HAZ during CO_2 laser cutting of coated sheet steels. They also observed that increased oxygen pressure increases the HAZ. Pulsed laser cutting of titanium and titanium alloy sheets show that minimum HAZ can be obtained at medium pulse energy, high pulse frequency, high cutting speed and at high pressure of argon assist gas, while use of oxygen assist gas gave maximum HAZ in comparison to nitrogen and argon [27,29]. The microstructural study of CO_2 laser machined aluminium alloy show that HAZ increases as the depth of hole drilling increases [30]. Low material thickness and pulse energy gives smaller HAZ while pulse frequency has no significant effect on HAZ for laser cutting of thick sheets of nickel base superalloy [34]. Zhang et al. [86] have investigated that the pulsed laser cutting using low wavelength laser with low pulse width gives less HAZ in comparison to high wavelength laser with high pulse width. Effect of beam angle during Nd:YAG laser drilling of TBC nickel superalloys show that on increasing the beam angle to surface decreases the HAZ, recast and oxide layer thickness up to 60° after that it remains almost constant (Fig. 13) [38].

Pulsed Nd:YAG laser cutting of ceramic sheet show that HAZ increases with increase in pulse energy and feed rate but decrease very little when pulse frequency increases [87]. The cut quality of mullite-alumina ceramic composite of 4 mm thick was evaluated during experimental investigations on pulsed Nd:YAG laser cutting and it was found that pulse frequency and cutting speed have significant effect on HAZ area while assist gas pressure has no relevant effect. Also, it was found that cutting speed is a function of power and gas pressure [88]. HAZ in laser cutting of carbon fibre composites was found more in comparison to EDM [68].

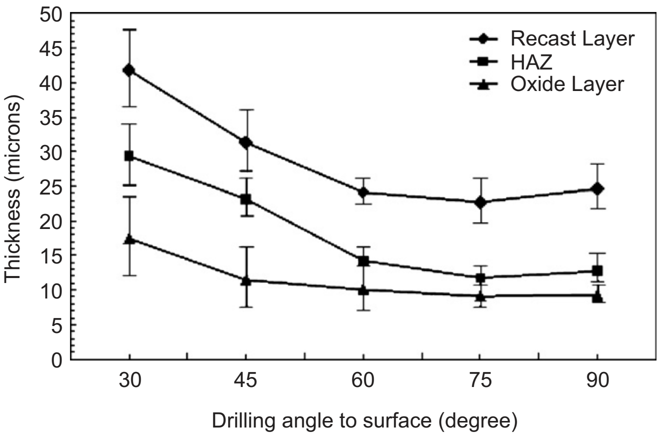

Fig. 13. Mean thickness of recast layer, HAZ and oxide layer for different drilling angles.

Since most of the materials removed during LBM are by melt ejection, the melt part which is not removed from cavity is resolidified and a recast layer results on side walls and also at bottom of cavity. This recast zone has entirely different property as compared to parent material. Therefore, aim is always to remove or minimize the recast layer. Many researchers have found the effect of parameters on recast layer and tried to minimize it. The observation of recast layer in thick titanium and nickel base alloys during laser drilling show thicker layer at hole entry side. Also, parameters effect show that on increasing the pulse frequency and pulse energy recast layer reduces while increases with material thickness [34]. Effect of beam angle on recast layer was found to be same as of HAZ [38]. A specially designed nozzle was used for laser cutting of thick ceramic plates at an optimum angle and distance from work surface to completely remove the recast layer [67].

4.1.5. Mechanical properties

Researchers have also studied the mechanical properties of laser machined workparts and found that thermal damages and crack formation affect the strength of materials. Zhang et al. [87] have found that the mean value of flexural strength reduced to 40% of original material after laser cut. Also, laser micromachining of silicon wafers shows that breaking limit after laser cutting is reduced [89]. The hardness of titanium alloy sheet in heat-affected zone was increased by 10% after laser cutting and the crack formation was found to be more by using oxygen or nitrogen assist gas in comparison to argon inert gas [27]. Cosp et al. [42] have found optimum cutting conditions for laser cutting of fine porcelain stoneware to avoid crack formation.

4.1.6. Remarks

The experimental results discussed above show that the effect of process parameters on process performance are not showing a fixed pattern in different operating ranges. In such cases more scientific experimental study is needed in different range of operating parameters for the prediction of process behaviour. In many experimental results discussed so far, the optimum range of process parameters have been found based on variation of one factor at a time but simultaneous effect of variation of more than one parameters at a time have not been studied in a comprehensive way. Here, it can be concluded that a comprehensive scientific methodology based study is needed for LBM of different advanced engineering materials with all possible input parameters as well as single or multiple performance measure.

4.2. Modelling and optimization studies

Modelling in LBM helps us to get a better understanding of this complex process. Modelling studies are the scientific ways to study the system behaviours. A mathematical model of a system is the relationship between input and output parameters in terms of mathematical equations. On the basis of their origin, models can be divided in three categories e.g. experimental or empirical models, analytical models, and artificial intelligence (AI) based models. Complexity in machining dynamics has forced researchers to find optimal or near optimal machining conditions with discrete and continuous parameters spaces with multi-model, differentiable or non-differentiable objective function or responses finding optimal solutions by a suitable optimization technique based on objective function formulated from model is a critical and difficult task and hence, a large number of techniques has been developed by researchers to solve these type of parameter optimization problems.

The literature related to modelling and optimization of LBM is mainly using statistical design of experiments (DOE) such as Taguchi method and response surface method. Several analytical methods based on different solution methodologies, such as exact solution and numerical solution, have also been examined related to LBM. Few researchers concentrated on modelling and optimization of laser beam cutting through AI based techniques such as artificial neural network (ANN) and fuzzy logic (FL).

4.2.1. Experimental methods

This is basically useful for modelling a new type or complicated system. This is experiment based modelling technique in which the performance of a system is measured by varying the input parameters (important factors that are supposed to affect the process performance) in a certain range. Mathematical model is developed using the set of input and output parameters in different experimental runs. Curve fitting techniques such as regression analysis method may be applied to develop a polynomial relationship [$y_i = f(x_j)$] between input factors and quality characteristic. No assumptions are taken to develop these models and model gives real solution valid for limited range of input conditions.

For developing these models, accuracy of measuring instruments and experimentation is of utmost importance. The accuracy of experimentation can be increased by using the scientific experimental design techniques. Designed experiments approach is superior from unplanned approach because it is a systematic and scientific way of planning the experiments, collection and analysis of data with limited use of available resources. *Factorial design* (FD), *Response surface methodology* (RSM) with *central composite design* (CCD) and *Taguchi robust design methodology* (TRDM) are the most widely used experimental design techniques in material processing methods.

In FD, important factors and their levels decide the number of experimental runs. In general l^k runs are required for k factors each at level l. The minimum number of level taken is 2. The number of experimental runs can be reduced by using fractional FD technique in which some interactions are aliased with main factors. After matrix experimentation statistical techniques are used for data analysis in order to decide the individual factor effects, interaction effects (if any) and their significance on process performance [90].

In RSM, the experiments are performed using CCD matrix (for first-order response model FD matrix can be used but due to lack-of-fit first-order-response model is avoided generally) to develop a second order response model as

$$\begin{aligned} Y = {} & b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_{11} X_1^2 + b_{22} X_2^2 \\ & + b_{12} X_1 X_2 + \cdots + b_{n-1,n} X_{n-1} X_n, \end{aligned} \tag{1}$$

where Y is response and X_i are different factors. The regression coefficients b_i can be computed by least-square method. Significance of factors and their interactions can be computed using statistical analysis. Using above response model optimum value of response and optimal setting of parameters can be computed [91].

In TRDM, the level of controllable factors (process parameters) is selected in such a way to nullify the effect of uncontrollable or noise factors in order to make the process robust or insensitive to noise factors (uncontrollable factors). Taguchi has suggested that a loss will always occur for any deviation from desired value (even in tolerance limit). Based on this principle a quality loss function is calculated for each quality characteristic after performing the experiments as per Taguchi's standard orthogonal array (OA) matrix for selected factors and their levels. The quality loss function may be of three types such as *nominal-the-best, lower-the-better* and *higher-the-better* type depending upon the nature of quality characteristics:

$$\text{Lower-the-better}: L_{\text{LB}} = 1/n\Sigma(y_i^2), \tag{2}$$

$$\text{Higher-the-better}: L_{\text{HB}} = 1/n\Sigma(y_i^2), \tag{3}$$

$$\text{Nominal-the-better}: L_{\text{NB}} = 1/n\Sigma(y_i - M)^2, \tag{4}$$

where y_i is the ith experiment response, n is total no. of experiments at the same level and M is the target value of response.

Signal-to-noise (S/N) *ratio* for each quality characteristic is calculated and aim is always to maximize the S/N ratio:

$$\eta_i = -10\log(L_i), \tag{5}$$

where L_i is the ith experiment quality loss and η_i is the S/N ratio for ith experiment.

Parameter levels corresponding to highest S/N ratios are selected as optimum parameter levels. Statistical analysis tool such as analysis of variance (ANOVA) is used to determine the significance of factors/interactions. The verification experiment is done to confirm the improvement in process performance [92].

Literature related to LBM shows that most of the experiments on LBM have been performed without using DOE approach. Only few researchers have applied the DOE approach during LBM.

Mathew et al. [93] performed parametric studies on pulsed Nd:YAG laser cutting of fibre reinforced plastic composite sheet (2 mm thick). A CCD with uniform precision was used for experimental design and a second-order response surface model for HAZ and kerf taper was developed. The input process parameters were cutting speed, pulse energy, pulse duration, pulse repetition rate and gas pressure. Ghoreishi et al. [94] applied CCD and RSM to analyse the effect of parameters on hole taper and circularity of stainless steel 304 sheet (2.5 mm thick) and the results were compared with that of mild steel sheet. The variable parameters taken to develop the response model for hole diameter and hole taper are: peak power, pulse width, pulse frequency, no. of pulses, assist gas (oxygen) pressure, and focal plane position. Kuar et al. [95] have also applied CCD and RSM to develop mathematical model for HAZ and taper during micro-drilling of Zirconia (ZrO_2) ceramic sheet (1 mm thick) using Q-switched Nd:YAG laser beam system.

Tam et al. [96] applied Taguchi method to study the laser cutting process for 4.5 mm thick mild steel sheet using Rofin Sinar RS500 laser. The S/N ratio of overall figure-of-merit (FOM) is considered as quality function. FOM function integrates weighted effects of quality characteristics (kerf width, surface roughness, micro-hardness, slope of cut edge and HAZ) and cost components (cutting speed, oxygen pressure and beam power). Lim et al. [97] have applied the same approach for the study of the surface roughness obtained during high speed laser cutting of stainless steel sheets. Li et al. [45] have also applied Taguchi's robust design methodology to study the width of cut and HAZ during laser cutting of QFN (quad flat no-lead) packages using a DPSSL system. The cutting parameters taken are: laser current, laser frequency and cutting speed.

Tam et al. [98] used Taguchi approach to determine the drilling time during Nd:YAG deep hole drilling of 25 mm thick Inconel 718 (Ni-based superalloy). The variable parameters taken in study are: pulse energy, pulse duration, pulse shape, focal position, and oxygen pressure. Same approach was applied [35] during laser drilling of aerospace material (3.6 mm thick thermal barrier coated Rene80 substrate) to determine the effect of factors on recast layer and micro-crack formation. Masmiati et al. [99] have also applied the Taguchi methodology to study the effects of no. of pulses, nozzle standoff distance, assist gas pressure and nozzle diameter on MRR, hole taper and spatter thickness. Same approach was also applied to study the laser micro-engraving of photo-masks taking beam expansion ratio, focal length, power, pulse frequency and engraving speed as variables [100].

Yilbas [101] applied the FD approach for parametric study of laser hole drilling for three metals namely stainless steel, nickel and titanium by varying pulse length (1.5–2.5 ms), focus setting (50.5–52 mm), energy (15–21 J) and material thickness (0.5–1.25 mm) using Nd:YAG laser. The quality characteristics considered were mean hole diameter and taper. Same approach was also used by Almeida et al. [28] to determine the effects of pulse energy, overlapping rate and type of assist gas on the surface roughness and dross formation (edge irregularity) during Nd:YAG laser cutting of pure titanium and titanium alloy (Ti–6Al–4V).

Chen et al. [102] have used a *hybrid approach* to study non-vertical laser cutting process. FD method was used for experimentation and ANN was used for the optimization of the process parameters.

4.2.2. Analytical methods

Analytical models are the mathematical models based on basic laws and principles, of a manufacturing process. These models can be divided in three categories, e.g. exact solution based model, numerical solution based model, and stochastic solution based model. Exact solution based models are normally based on some hypothetical assumptions and sometimes they may not give the real solution. Numerical models are complex mathematical models widely used in engineering sciences but solution is based on numerical methods such as finite difference method (FDM), finite element method (FEM), boundary element method (BEM), etc. Stochastic model is probabilistic in nature, i.e. for a range of inputs possibility of output falls in a range and most appropriate solution is very difficult. In LBM, there are so many analytical models which predict the system behaviour in different operating conditions.

4.2.2.1. Exact solution based. Aloke et al. [103] have formulated a mathematical model for the calculation of the size of hole and cut-out disc of varying radii in steel plates in order to estimate the dimensional accuracy of laser cut holes. The model included the assumption that the layer adjacent to hole is plastically deformed and contains residual stresses up to the yield strength. Espostto et al. [104] have developed an analytical model to predict the kerf width during laser cutting of steels. Yilbas [105] has developed a kerf width model using scaling laws for oxygen-assisted laser cutting of mild steel. Contribution of high temperature oxidation reaction in cutting was accommodated in the analysis. The kerf width predicted by developed model with variable cutting speed and laser power for 1 and 2 mm thick mild steel sheets are shown in Fig. 14. These results were found true at low cutting speeds when compared with experimental results. Kaebernick et al. [106] have predicted a 3-D analytical model of kerf width for pulsed laser cutting of metals including oxygen reaction with the molten metal. The model is based on infinitesimal point heat sources, representing the effect of laser beam on the surface inside the cutting zone. Sheng et al. [107] have established a theoretical model for kerf width as a function of erosion front size. The resonant frequency of pressure waves generated by flow of co-axial gas jet was used to determine the size of erosion front. Cenna et al. [108] have developed a model which predicts the cut quality parameters such as kerf width at inlet and exit, angle of cut surfaces and energy transmitted through the cut kerf for laser cutting of fibre reinforced plastic composites. Siekman [109] have developed a theoretical model for finding cut-width with beam power during CO_2 laser cutting of thin carbon films assuming equal reflectivity of film and substrate. They assumed that the laser energy is absorbed through the entire thickness of the material. Li et al. [110] have developed the lumped parameter mathematical model for the determination of the cutting capability of laser beam with rectangular spot. In their model, they have assumed that the entire region, whose temperature is above than the melting temperature, is removed by an assist gas jet to generate the kerf.

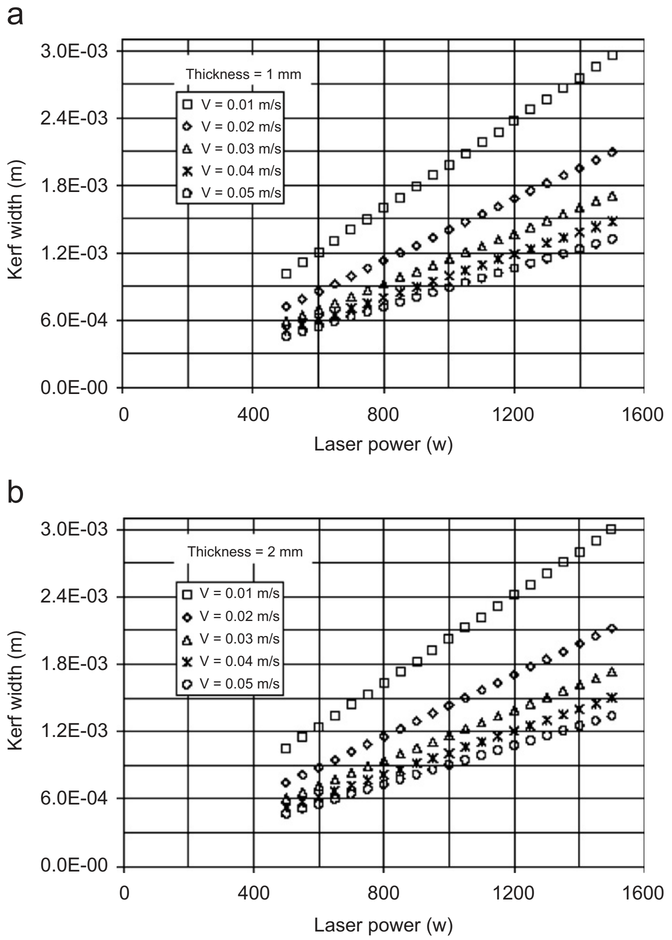

Fig. 14. Kerf width with laser output power at various cutting speeds for (a) 1 mm thick and (b) 2 mm thick mild steel sheet.

Tani et al. [111] have developed a mathematical model for the evaluation of the melt film thickness in laser cutting of steels. They have used energy balance equation for the calculation of kerf geometry, and mass and force balance for the calculation of velocity and thickness of the melt film in the kerf. They have predicted the dross adhesion by means of melt film geometry and ejection speed (Fig. 15). Yilbas et al. [112] have developed a theoretical model for the prediction of melting layer thickness during CO_2 laser cutting of 0.8–2.0 mm thick mild steel sheet considering effects of momentum and gas–liquid interface shear stress caused by assisting gas jet. Zhou et al. [113] have developed a theoretical model for the estimation of depth of cut in terms of material properties and cutting speed for non-metallic materials using low power CO_2 laser. Jiang et al.

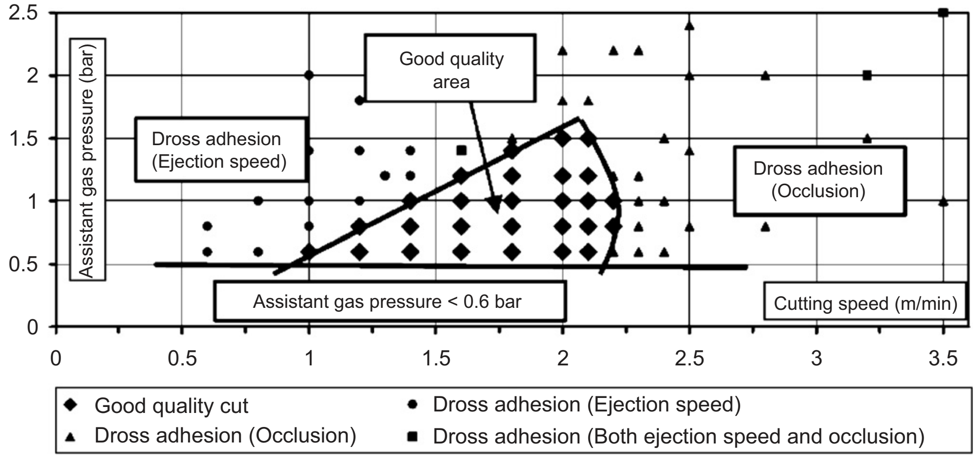

Fig. 15. Prediction of dross adhesion by means of melt film geometry and ejection speed: feasibility area (3 mm mild steel sheet, 2 kW power).

[114] have developed a theoretical model for the prediction depth of machining in sheetmetal due to pulsed Nd:YAG laser.

Berrie et al. [115] have developed theoretical models for the determination of MRR during CO_2 laser cutting and drilling of perspex. Their model is based on heat balance and the Gaussian mode of heat propagation. Caprino et al. [116] have developed a thermal model for the prediction of maximum laser cutting speed during laser cutting of fibre reinforced plastic composites. They assumed that no melting takes place in HAZ, and material is removed by an instantaneous evaporative process when vaporization temperature is reached. Graaf et al. [117] have utilized power, mass and impulse balance equations to model the laser cutting process of metal laminates in order to predict the cutting speed and corresponding damage depth. Lim et al. [118] have developed analytical model for the determination of laser cutting speed using energy flux balance equation. They assumed that cutting occurs due to melt ejection only. Black [119] has compared the theoretically predicted optimum cutting speeds with experimentally derived data during laser beam cutting of decorative ceramic tile. They found difference between theoretical and experimental results.

A 2-D analytical model is reported in Ref. [120] for the study of formation of molten layer. Authors have applied the mass, momentum and energy balance equations to predict the melt film thickness, its displacement and velocity, amount of laser energy absorbed, and cutting front temperature. Striation and dross formation during LBM has been analysed by means of an analytical model [121] based on mass, force and energy balances. Here 3-D geometry of the cutting front, and temperature fields of the melt film have been evaluated. Pietro et al. [122] have developed a theoretical model for the determination of surface roughness over a mild steel workpiece. Man et al. [123] have theoretically analysed the effect of shape and dimensions of nozzle tip on dynamic characteristics of gas jets that finally affect the cut quality of high-pressure gas laser cutting process.

4.2.2.2. Numerical solution based. Exact solution based theoretical studies does not provide the real solution that is why most of the analytical models developed today use numerical approaches such as finite difference, finite element and BEMs, for finding the solutions. Prusa et al. [124] have developed a numerical model for the calculation of heat conduction losses, cutting speed and temperature distribution in HAZ in laser cutting of thick materials. Li et al. [125] have developed a finite element based thermal model for the prediction of transient temperature and stress distribution in thin alumina ceramics using CO_2 laser. Modest [126] has developed a 3-D heat conduction model for the prediction of transient temperature distribution inside a thick solid that is irradiated by a moving laser source. He has considered the changing shape of a groove carved into it by evaporation of material. He has also developed another 2-D stress model for the prediction of thermal stresses during pulsed laser drilling of ceramics [127]. Roy et al. [128] have developed a 3-D heat conduction model for the prediction of temperature distribution inside the solid and the shape of groove formed by partial evaporation of a semi-infinite body using a moving laser with a Gaussian beam profile.

Bang et al. [129] have developed a 3-D thermal model for the study of beam guiding effects during laser machining of ceramics due to multiple reflections in the groove for two extreme cases, purely specular and purely diffuse reflections. Sheng et al. [130] have developed 2-D finite element model of internal temperature distribution to study the HAZ during laser cutting of 304 stainless steel. Yilbas et al. [131] have developed a heat transfer model for CO_2 laser cutting of metals. In their model, they have considered the oxidation effect and cooling effect due to assist gas (oxygen) jet. Yu [132] has presented a finite element based numerical model for laser beam cutting considering changing boundary and loading conditions as well as phase changes. Lee et al. [133] have predicted the HAZ and cutting profile of laser-deburred parts using FEM. Tsai et al. [134] have used FEM software ANSYS to analyse the temperature and stress distributions in laser cutting of ceramics with controlled fracture. Pietro et al. [135] have developed a 2-D transient model to investigate the effect of various CNC table speeds on the resulting cutting front temperature. Coelho et al. [136] have developed a 3-D temperature distribution model for laser cutting of thin thermoplastic films. Paek et al. [137] have developed a thermal model to describe the temperature profile and thermal stress propagation for laser drilled holes in high-purity fired alumina ceramic considering a continuous, distributed, and moving heat source.

Yue et al. [138] have developed a theoretical model based on FEM to determine the shape of ultrasonic aided laser drilled holes and thickness of the recast layer. Cheng et al. [139] have developed a 3-D finite difference based heat flow model for the prediction of hole shape and size in carbon fibre composites during laser drilling. Ho et al. [140] have developed a 1-D thermal model for the prediction of erosion depth in ceramics during pulsed Nd:YAG laser drilling considering the absorption of plasma plume formed on the surface of the ceramics. Han et al. [141] have developed a 3-D mathematical model to analyse the effects of convection and surface deformation on the heat transfer and melt pool shape. Zhang et al. [142] have developed an axisymmetric numerical model considering laser beam distribution and its coupling with the target material for the simulation of micro-scale cavity formation during ultraviolet (UV) laser micromachining of copper.

Turchetta et al. [143] have developed a linear model to predict the shape and geometry of kerf for cutting natural stones with CO_2 laser. Pietro et al. [144] have developed a 3-D transient heat transfer model for the prediction of kerf geometry considering the exothermic reaction energy. Kim et al. [145] have developed a 2-D FEM based heat transfer model for both steady state and transient conditions. The performance of metal removal was discussed in terms of shape and size of the groove formed. Kim [146] developed an unsteady convective heat transfer model using BEM considering moving continuous Gaussian laser beam for the prediction of groove shape, groove depth, temperature and flux distribution. He has also developed a 3-D FEM based steady state heat transfer model for the prediction of groove shapes and temperature distributions during evaporative laser cutting [147].

An axisymmetric model was developed by Modest [148] for the study of effects of multiple, specular reflections on hole quality and drilling rate during evaporative drilling with nanosecond laser pulses. Yilbas et al. [25] have developed a 1-D heat transfer model for the prediction of penetration speed during CO_2 laser cutting in stainless steel workpieces. Kim [149] has developed a 2-D time dependent boundary element based model analysis of evaporative material removal process using a high energy Gaussian laser beam. Kim et al. [150] have developed a FEM based unsteady heat transfer model for the prediction of amount of material removal and groove smoothness during evaporative cutting with a Gaussian wave pulsed laser. Hong et al. [151] have developed a 2-D mathematical model for prediction of kerf shape during pulsed laser evaporative cutting of silicon nitride ceramics. They have used energy conservation equation to develop the mathematical model. Pan et al. [152] have developed a FEM based model for the prediction of dynamic behaviour of silicon-based micro-structure of high aspect ratio which was fabricated by using Nd:YAG laser micromachining. Gross et al. [153] have analysed the effect of assist gas velocity on heat transfer in their 3-D simulation model. Mai et al. [154] have developed a finite volume method based numerical model for the evaluation of gas pressure distribution around a substrate subjected to supersonic impinging jet in laser cutting.

4.2.3. *Artificial intelligence (AI) methods*

AI is implemented in engineering problems through the development of expert systems, FL systems, and ANN systems for the prediction of process behaviour. An expert system is an interactive intelligent program with an expert-like performance for solving a particular type of problem using knowledge base, inference engine and user interface. Model developed based on FL deals with linguistic variables rather than operating on crisp values. ANN models are able to learn, adapt to changes and mimic human thought process with little human interactions [155].

The structure and function of ANN are similar to the way biological nervous systems work such as brain. ANNs are composed of a large number of highly interconnected, simple and adaptable processing units which can acquire, store and utilize experimental knowledge throughout learning. The two main functions of an ANN are: (i) the architecture of the network, which generally dictates what type of problems can be dealt with; (ii) the method of learning of training algorithm: supervised learning or unsupervised learning. The most common type of ANNs that have been used in the literature has been found as feedforward ANNs trained with back propagation algorithm [156].

Yousef et al. [156] have proposed a neural network model to predict the level of pulse energy needed to create a dent or crater with the desired depth and diameter during laser micromachining process. Chen et al. [102] have also applied the ANN approach to predict the cut kerf quality in terms of dross adherence during non-vertical laser cutting of 1 mm thick mild steel sheets. They used FD experiments to reduce the number of experiments during training session.

4.2.4. *Remarks*

The experimental modelling based studies used in LBM process have similar goals but with different approaches. For developing the model the experimental input/output results have been used to show the relationship between process parameters and quality characteristics by fitting a first or second-order regression model using least square fit. Only difference lies in performing the experiments. The different DOE techniques applied for experimentation have their own advantages and disadvantages. Unlike, experimental study of one factor variation at a time the DOE based studies show the interaction effect among various process parameters by simultaneously varying more than one process parameters. The most of the results obtained in this section show quite different trend of parameter effect when varied simultaneously in comparison to that of one parameter variation at a time. The FD method has all possible parameter combinations but the large number of runs is a cumbersome job. The RSM is mainly the model formulation procedure and investigate how important factors affect the response of an experiment. The TM is more of a factor-screening procedure to determine the significance of each factor.

Analytical models are the best tools for preliminary study of the process performance of a complex process like LBM. In most of the LBM studies the exact solution based and numerical solution based analytical models have been developed. The literature available does not show the LBM study based on stochastic solution. Most of the exact solution based models discussed above have better predicted on geometrical characteristics and MRR but the prediction of HAZ was far away from real solution. The numerical solution based studies have concentrated on thermal models but assumptions are taken in liberal way for developing the models. Some researchers have approached in better way for predicting the performance behaviour in case of CW-LBM but in case of pulsed-LBM no right approach has been adopted.

Regression analysis is not useful for precisely describing the non-linear complex relationship between process parameters and performance characteristics. ANN techniques are an alternative when regression techniques fail to provide an adequate model. Though in recent years these techniques are widely being applied in different fields of manufacturing. Only two researchers have applied ANN based technique in LBM.

5. Future directions of LBM research

The major research areas in LBM are discussed in previous sections. Researchers have contributed in different directions but due to complex nature of the process a lot of works are still required to be done. Most of the published works are related to laser cutting followed by drilling and micromachining but 3-D LBM like turning and milling are still awaiting for industrial use. The control of two or more laser beams at different angles simultaneously is not an easy task during 3-D machining. Thickness of material is another constraint during LBM which can be reduced by improving the beam quality. At present, the use of LBM is limited up to complex profile cutting in sheet metals but due to emergence of advanced engineering materials, need is to develop it for cutting of difficult-to-cut materials. So, these developments in LBM can be an area of future research.

Most of the experimental works presented in LBM are aimed to study the effect of parameter variations on quality characteristics. Only few researchers have used the scientific methods under the umbrella of DOE for the study of LBM process. Unplanned experimental study includes a lot of undesired factors which affect the performance variations and finally leads to unreliable results. Further, researchers have excluded many important factors such as beam spot diameter, thermal conductivity and reflectivity of workpiece material and the interaction effects among various factors during study which otherwise would affect the performance characteristics differently. In the same way, during theoretical study authors have taken a number of hypothetical assumptions to simplify the problems of LBM which otherwise could be incorporated in their models to enhance the reliability and applicability of the model. Thus, it is desirable to develop the models with no or very few assumptions to get the real solution of the LBM problems quantitatively.

The optimization of process variables is a major area of research in LBM. Most of the literature available in this area shows that researchers have concentrated on a single quality characteristic as objective during optimization of LBM. Optimum value of process parameters for one quality characteristic may deteriorate other quality characteristics and hence the overall quality. No literature is available on multi-objective optimization of LBM process and present authors found it as the main direction of future research. Also, various experimental tools used for optimization (such as Taguchi method and RSM) can be integrated together to incorporate the advantages of both simultaneously. Only one literature available so far shows hybrid approach (integration of FD and ANN) for optimization of process variables and more work is required to be done in this area.

LBM being a thermal process induces many adverse effects in workpiece material which in turn affects the mechanical properties also. The most of the performance characteristics discussed by various researchers relate to geometrical, metallurgical and surface qualities such as: surface roughness, taper formation and HAZ. Fatigue strength, micro-hardness, and residual stresses are also important performance measures which are required to be improved. So, improvement of mechanical properties during LBM is a research area of interest.

6. Conclusions

The work presented here is an overview of recent developments of LBM and future research directions. From above discussion it can be concluded that:

1. LBM is a powerful machining method for cutting complex profiles and drilling holes in wide range of workpiece materials. However, the main disadvantage of this process is low energy efficiency from production rate point of view and converging diverging shape of beam profile from quality and accuracy point of view.
2. Apart from cutting and drilling, LBM is also suitable for precise machining of micro-parts. The micro-holes of very small diameters (up to 5 μm) with high aspect ratio (more than 20) can be drilled accurately using nanosecond frequency tripled lasers. Cutting of thin foils (up to 4 μm) has been done successfully with micro-range kerf width.
3. The performance of LBM mainly depends on laser parameters (e.g. laser power, wavelength, mode of operation), material parameters (e.g. type, thickness) and process parameters (e.g. feed rate, focal plane position, frequency, energy, pulse duration, assist gas type and pressure). The important performance characteristics of interest for LBM study are HAZ, kerf or hole taper, surface roughness, recast layer, dross adherence and formation of micro-cracks.
4. The laser beam cutting process is characterized by large number of process parameters that determines efficiency, economy and quality of whole process and hence, researchers have tried to optimize the process through experiment based, analytical, and AI based modelling and optimization techniques for finding optimal and near optimal process parameters but modelling and optimization of laser beam cutting with multi-objective, and with hybrid approach are nonexistent in the literature.
5. The two extreme application areas such as machining of thick materials and machining of micro-parts need considerable research work.

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