INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING-GREEN TECHNOLOGY Vol. 4, No. 3, pp. 307-322

REVIEW PAPER

DOI: 10.1007/s40684-017-0037-7
ISSN 2288-6206 (Print) / 2198-0810 (Online)

Lasers in Additive Manufacturing: A Review

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KEYWORDS: Laser manufacturing, Additive manufacturing, Selective laser sintering, Selective laser melting, Direct metal laser sintering

In recent years, additive manufacturing, also known as three-dimensional (3D) printing, has emerged as an environmentally friendly green manufacturing technology which brings great benefits, such as energy saving, less material consumption, and efficient production. These advantages are attributed to the successive material deposition at designated target areas by delivering the energy on it. In this regard, lasers are the most effective energy source in additive manufacturing since the laser beam can transfer a large amount of energy into micro-scale focal region instantaneously to solidify or cure materials in air, therefore enabling high-precision and high-throughput manufacturing for a wide range of materials. In this paper, we introduce laser-based additive manufacturing methods and review the types of lasers widely used in 3D printing machines. Important laser parameters relevant to additive manufacturing will be analyzed and general guidelines for selecting suitable lasers for additive manufacturing will be provided. Discussion on future prospects of laser technologies for additive manufacturing will be finally covered.

Manuscript received: January 25, 2017 / Revised: March 16, 2017 / Accepted: May 21, 2017

1. Introduction

Additive manufacturing (also known 3D printing) based on layer-by-layer construction has great potential in enabling customizable production for end users without multiple supply chains so is attracting significant attention today. Additive manufacturing has numbers of advantages over traditional subtractive manufacturing, such as the production of complex objects with a minimal lead time and less material waste without subsequent part assembly process.[1-4] Optimal designs that can be realized only in additive manufacturing, such as lightweight hollow objects or molds with internal cooling paths, can greatly save the raw materials without unexpected quality degradation. Furthermore, the end-use production without multiple chains and printed lightweight structures can save overall production energy and fuel, especially for aircraft and automobiles, which is also followed by cutting down on carbon and greenhouse gasses.[5-9]

Although additive manufacturing has attracted much attentions as an alternative technology and already been applied to various field, further improvements are, however, still needed to extend the scope of applications in terms of printable materials, printing precision, and throughput.[10,11] The additive manufacturing process generally consists of 3D modeling, digital data processing, 3D object construction, and post-processing.[12] Among these processes, final products' performances are usually dominated by the 3D object construction process, such as vat photopolymerization, material extrusion, powder bed fusion, and directed energy deposition.[13] During the material deposition, the energy should be efficiently transferred to the material at a designated position to be melted, softened, or cured. Then, the repetitive layer-by-layer deposition process leads to the construction of the part. For example, in the material extrusion, the heat energy is transferred to the printing material through a nozzle by heat conduction, enabling the material to flow through the nozzle to the target location. The slow energy transfer due to the heat conduction across the limited contact area and the extrusion of molten material through a small nozzle leads to low manufacturing throughput compared to other methods. For the high printing resolution and high-quality surface finish, the extrusion requires the maintenance of the constant pressure of molten materials.

To circumvent these deposition-related issues, the energy can be directly transferred to material which is placed at the desired position in advance. The most frequently used energy source to do so is the laser because the high-intensity laser beams irradiated onto the printing material can be efficiently absorbed without any transfer medium. The laser energy leads to either photochemical reaction curing the material instantly[18] or photothermal reaction (e.g. thermal sintering or melting),[19-21] as shown in Fig. 1. As lasers generate spatially coherent light contrary to incoherent sources, such as thermal lamps or light emitting diodes (LEDs), the laser beams propagate without critical

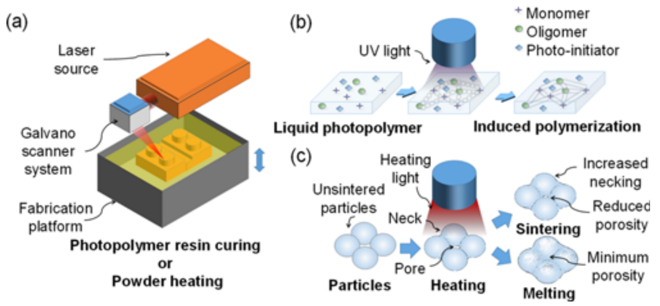

Fig. 1 Laser-Based additive manufacturing for material curing or heating: (a) Schematic of general 3D printing machines, (b) UV curing process, (c) Heating process for sintering or melting

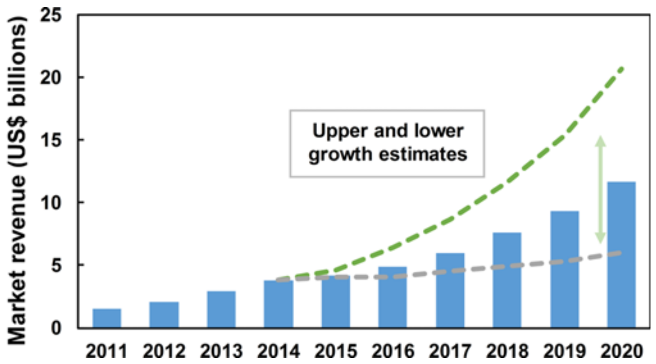

Fig. 2 Future expected growth of additive manufacturing industry[14]

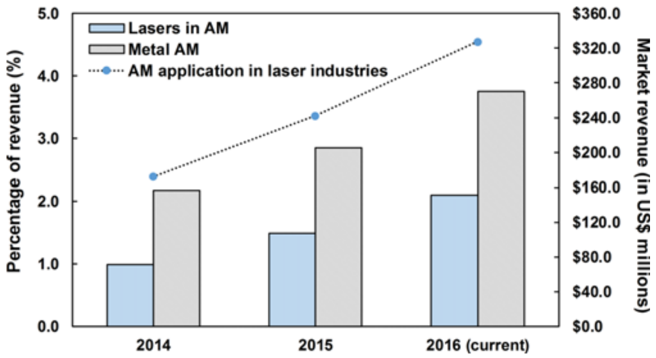

Fig. 3 Proportion of lasers in additive manufacturing with respect to total laser revenue (Dashed line, Primary axis),[15] market revenue of lasers in additive manufacturing (Blue bars, Secondary axis),[16] and estimated market revenue of metal additive manufacturing (Shaded bars, Secondary axis)[17]

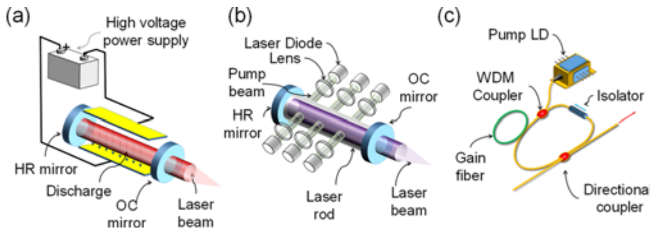

Fig. 4 Laser schematics with different gain materials: (a) Gas laser, (b) Solid-State laser, (c) Rare-Earth-Doped fiber laser (OC mirror: Output coupling mirror, HR mirror: High reflectivity mirror)

beam divergence or power loss over long distances, and also can be focused into small spots, so they can provide the improved precision and throughput in 3D part construction.[22]

The advantages of additive manufacturing in creating high complexity components at a low cost have enabled its explosive growth over the past 30 years. By being an integral part of the so-called fourth industrial revolution, the size of the global additive manufacturing market stands at around $ 4.2 billion today, up from just $ 0.25 billion in the mid-1990s.[14] The market has averaged an impressive annual growth (CAGR) of 25.4% since the 1990s[23] and this growth is set to continue with the lower bounds of market growth predicted to US $ 12.1 billion up to over $ 20 billion at the end of 2020 as shown in Fig. 2.[14,24] The most recent data from the past two years on the overall laser industry also supports this increasing trend as shown in Fig. 3. Furthermore, market revenues of lasers in additive manufacturing have been increasing steadily with impressive year-on-year growth rates, 50.7% from 2014-2015 and forecasted for 41.1% growth from 2015-2016.[16] This strong year-on-year growth, which is the largest percentage growth relative to other laser categories, underpins the steadily growing market share of lasers in additive manufacturing in total market revenues (an increase of about 1% of total market revenue annually).

Strong market revenues for lasers in additive manufacturing would be driven in large part by the growth in metal additive manufacturing, which makes extensive use of ytterbium-doped fiber lasers (Yb-fiber lasers) in Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM) machines. For example, market revenue for metal additive manufacturing is expected to grow at an average CAGR of 31.5% from 2015 to 2020, reaching a market size of $ 0.78 billion from $0.16 billion in 2014.[17] The values in Fig. 3 for the market revenue of metal additive manufacturing are estimated from this CAGR. Reviewing the fundamentals of lasers in additive manufacturing is, therefore, essential to understanding the growing impact of laser-based additive manufacturing on the industry.

To understand the impact of laser-based additive manufacturing, this review will discuss basic principles of the lasers used in additive manufacturing, critical laser parameters that affect manufacturing performance, and representative laser-based additive manufacturing methods. We firstly begin with presenting a brief introduction to basic laser principles and then different types of lasers used in commercial 3D printing machines, such as CO_2 lasers, Nd:YAG lasers, Yb-fiber lasers, and excimer lasers will be analyzed in the second section. To provide a better understanding of the influence of laser parameters on manufacturing, the relationship between the manufacturing performance and critical laser parameters, such as wavelength, power or energy, pulse duration, and spot size, will be explained in the third section. In the fourth section, we will bring together the topics in the last two sections for in-depth discussion on laser-based additive manufacturing methods, such as stereolithography (SLA), selective laser sintering (SLS), selective laser melting (SLM), and laser engineered net shaping (LENS) in terms of their respective laser sources.

Table 1 Representative lasers for additive manufacturing and those specifications[25]

Laser	CO_2 laser	Nd:YAG laser	Yb-fiber laser	Excimer laser
Application	SLA, SLM, SLS, LENS	SLM, SLS, LENS	SLM, SLS, LENS	SLA
Operation wavelength	9.4 & 10.6 μm	1.06 μm	1.07 μm	193, 248, 308 nm (ArF, KrF, XeCl respectively)
Efficiency	5-20 %	Lamp pump: 1-3 %, Diode pump: 10-20 %	10-30 %	1-4 %
Output power (CW)	Up to 20 kW	Up to 16 kW	Up to 10 kW	Average power 300 W
Pump source	Electrical discharge	Flashlamp or laser diode	Laser diode	Excimer recombination via electrical discharge
Operation mode	CW & Pulse	CW & Pulse	CW & Pulse	Pulse
Pulse duration	Hundreds ns-tens μs	Few ns-tens ms	Tens ns-tens ms	Tens ns
Beam quality factor (mm·mrad)	3-5	0.4-20	0.3-4	160 × 20 (Vertical × Horizontal)
Fiber delivery	Not possible	Possible	Possible	Specially designed fiber necessary
Maintenance periods	2000 hrs	200 hrs (Lamp life) 10,000 hrs (Diode life)	Maintenance free (25,000 hrs)	10^{8-9} pulses (Thyratron life)

2. Lasers in Additive Manufacturing Methods

A laser generally consists of a gain medium, a pumping energy source, and an optical resonator. The gain medium placed inside the optical resonator amplifies the light beam by stimulated emission using the external energy supplied by a pumping source. Lasers are usually classified by the gain medium in use - solid state, gas, excimer, dye, fiber or semiconductor ones. The representative lasers used in additive manufacturing include gas, solid state, and fiber lasers as shown in Fig. 4. This section covers CO_2 laser, Nd:YAG laser, Yb-fiber laser, and excimer laser as the representative lasers because of their widespread use in additive manufacturing and many other precision manufacturing applications. The detailed specifications of each laser are summarized in Table 1.[25]

2.1 CO_2 Laser

The CO_2 laser is one of the earliest gas lasers, developed in 1964.[26] The laser consists of a discharge tube, an electric pump source, and several optics, such as mirrors, windows, and lenses, for constructing an optical resonator (See Fig. 5). In CO_2 lasers, the gas state gain medium, CO_2, fills the discharge tube and is electrically pumped by a DC or AC current to induce the population inversion for lasing.[27] CO_2 lasers can generate infrared output wavelength from 9.0 to 11.0 μm; 10.6 μm is the most widely used wavelength in additive manufacturing. Because of the infrared wavelength emission, special materials are used for the optical components, silver or gold for mirrors and germanium or zinc selenide for windows and lenses.[28] Compared to other continuous wavelength lasers, CO_2 lasers provide high efficiency (5-20%) and high output power (0.1-20 kW) so they are extensively used in material processing, e.g. cutting, drilling, welding, and surface modification.[25,29] An electrically pumped gas discharge tube is installed between two reflectors, a high reflectivity mirror at one end, and a partially reflecting mirror (so-called output coupler) at the other end. A heat dissipation device such as a water jacket to cool the electrodes would be included for high power operation over several kilowatts in addition. The simplicity of the system brings a low cost, highly reliability, and system compactness, which are the main reasons that

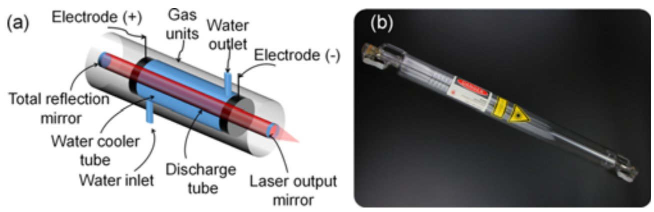

Fig. 5 CO_2 laser: (a) Schematic of a CO_2 laser, (b) Commercial CO_2 laser discharge tube (Adapted from MASTER LASER™ with permission)

CO_2 lasers are the workhorse of precision manufacturing. However, their output power is relatively non-stable because of thermal expansion and contraction of the laser structure due to the heat generated in the process of energy pumping to a large volume CO_2 gas. The instability can also arise from the gas turbulences in the gas-assisted heat diffusion process.[30-32] In high power operation, overall optics should be checked for fatigue every 2,000 hours.[33] Long infrared operation wavelength results in several limitations. In manufacturing for metal parts, the CO_2 laser provides limited throughput due to low light absorption coefficient in the in the infrared region. Furthermore, CO_2 lasers require the use of free-space bulk reflective optics for beam delivery due to lack of optical fibers delivering the wavelength range. Therefore, in order to work with a wider range of materials or take advantage of fiber-based beam delivery, other types of lasers have to be considered.

2.2 Nd:YAG Solid-State Laser

Nd:YAG lasers (neodymium-doped yttrium aluminum garnet laser; $Nd^{3+}:Y_3Al_5O_{12}$ laser) are a type of solid-state laser using rod-shaped Nd:YAG crystals as a solid gain medium.[34] Nd:YAG lasers, along with CO_2 lasers, are the two most commonly used high-power lasers in the industry. In Nd:YAG lasers, the gain medium is optically pumped along the radial direction by a flash lamp or pumped by an 808 nm laser diode in the axial direction, to produce a near infrared (NIR) output wavelength of a 1064 nm,[28] as shown in Fig. 6. At this operating wavelength, the light beam can be delivered by flexible optical fibers,

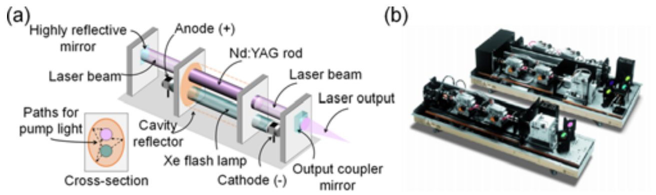

Fig. 6 Nd:YAG laser: (a) Schematic of a Nd:YAG laser, (b) Commercial Nd:YAG lasers (Adapted from Spectra-Physics with permission)

which is one of the noticeable advantages over the CO_2 laser, in terms of system compactness and higher delivery efficiency.[32] Nd:YAG lasers can be operated both in continuous mode (with the crystals doped with low concentrations) and in pulsed mode (with highly-doped crystals). The output power reaches up to a few kW in continuous mode and up to 20 kW in peak power (pulse energy up to 120 J) in pulsed mode.[25]

Conventional Nd:YAG lasers are generally optically pumped by Xenon flash lamps; they suffer from relatively low electrical-to-optical power conversion efficiency. This low power efficiency results in a low beam quality because most of the unabsorbed energy is dissipated as heat; thermal heating of the optical elements induces unexpected thermal lensing and birefringence effects, causing poor beam quality.[35] The short lifetime of the flash lamp had been also a weakness. These disadvantages can be overcome by applying diode lasers as the pump sources instead (they are called as diode-pumped solid-state (DPSS) lasers).[36,37] Thanks to the higher electrical-to-optical power conversion efficiency of the laser diodes and selective excitation of the gain medium, the laser's overall power efficiency can be boosted up by ~5 times compared to lamp-pumped lasers.[38] In additive manufacturing, Nd:YAG lasers are being replaced by more compact and efficient Yb-fiber lasers. However, the ubiquity and accessibility of Nd:YAG lasers still make them be heavily used in research works for parametric study[39-41] or optimizing manufacturing parameters.[42-44] Recently, $Nd:YVO_4$ lasers have also attracted much attention as another alternative to Nd:YAG lasers because it has wider absorption band, lower operating threshold, and higher efficiency than Nd:YAG lasers.[45,46] $Nd:YVO_4$ lasers work with the same principles as Nd:YAG lasers with a central wavelength of 1064 nm, and are primarily used in SLA[47] as a source of UV light by third harmonic generation (355 nm) to selectively cure photopolymer resins.[48,49]

2.3 Yb-Doped Fiber Laser

A fiber laser is a laser in which the active gain medium is a rare-earth doped optical fiber. In the early years after the first development of fiber lasers, fiber lasers had limited performances in terms of output power and pulse energy compared to bulk lasers. However, fiber lasers have become the most promising laser source as the alternative to conventional bulk lasers thanks to their progressive developments over the past few decades. Among the various rare-earth doped gain fibers, Yb-fibers are most suitable for high power generation because of high quantum efficiency (-94%) (See Fig. 7).[50-52]

This high efficiency is the very reason why Yb-fiber laser are widely used in material processing and have mostly replaced Nd:YAG lasers in additive manufacturing.[53,54] They are pumped by the laser diodes

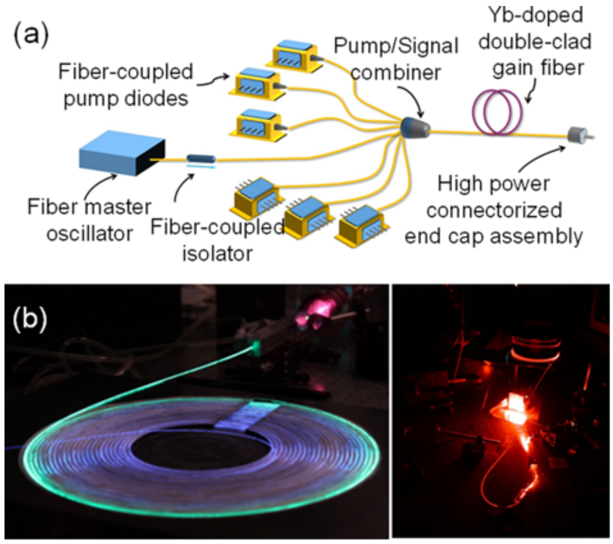

Fig. 7 Yb-fiber laser: (a) Schematic of a Yb-fiber laser, (b) Commercial Yb-fiber lasers under operation (Adapted from optoelectronics research centre (ORC), finland with permission)

in 950-980 nm wavelength and produce near-infrared laser beams in 1030 -1070 nm output wavelength. Other advantages, due to the fiber-based gain medium and optical components, are the high electrical-to-optical efficiency (-25%), excellent beam quality, robustness against environmental disturbances, and system compactness.[25] Yb-fiber lasers also have some limitations due to the light propagation inside the fiber. In the case of bulk lasers, the light propagates through the air, which has a minor influence as a light guiding medium. In contrast, when the light propagates through the optical fiber, the guided light is strongly affected by the guiding medium, the optical fiber, especially on its nonlinear properties. The optical nonlinear effect induced by the high peak power, such as self-focusing, self-phase modulation, Kerr lens effect, and Raman effects can limit the laser performances.[55-58] The unexpected polarization change by fiber bending, vibration, and temperature variation can also be detrimental to the laser output.[59] For higher environmental stability, polarization-maintaining (PM) optical fibers are recommended as the gain and light guiding medium.

2.4 Excimer Gas Laser

Excimer lasers use 'excimers' as the gain medium and are pumped by pulsed electrical discharge to produce nanosecond pulses in ultraviolet (UV) region. Excimer is an abbreviation of the excited dimer, which are gas mixtures containing a noble gas (e.g. argon, krypton, or xenon), a halogen (e.g. fluorine or chlorine), and a buffer gas (typically neon or helium). Among various excimer lasers with wide operation wavelengths ranging from 157 to 351 nm (dependent on the gas mixture), ArF, KrF, and XeCl lasers generating 193, 248, and 308 nm wavelength beams, are the most popular excimer lasers in manufacturing applications.[60] An excimer laser also consists of a pump source, a gain medium, and an optical resonator; the gain medium is pumped by electrical current in the same fashion as other gas lasers (e.g. CO_2) as shown in Fig. 8. Excimer lasers can be operated only in pulsed mode, which produce pulses with a repetition rate of few kHz

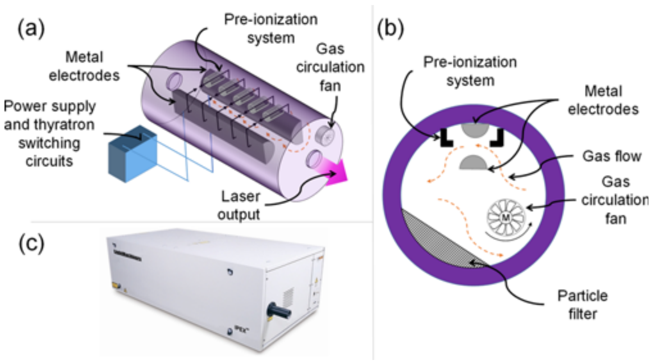

Fig. 8 Excimer laser: (a) Schematic of an excimer laser, (b) Cross section of a laser resonator, (c) Commercial excimer laser (Adapted from Light Machinery with permission)

and average output power between a few and hundreds of watts. Generation of UV pulsed light is of great importance in manufacturing applications because most optical materials have a high absorptivity around UV region.[61-64] However, relatively poor beam quality, tricky maintenance, and extremely high running cost make the excimer lasers impractical in additive manufacturing machines.[65,66] Thus, frequency-tripled Nd:YVO_4 lasers are preferred choice instead to produce laser beams in the UV range.[67]

3. Critical Laser Parameters in Additive Manufacturing

Lasers can be specified with several parameters such as average power, power stability, central wavelength, spectral bandwidth, beam diameter, beam quality, pulse energy, pulse duration, and repetition rate. Because the importance of parameters varies with target applications, classifying the critical laser parameters in additive manufacturing and understanding how they affect the manufacturing performance can provide deeper insights into laser systems used in additive manufacturing. In most additive manufacturing technologies, critical laser parameters are related to light-material interaction based on thermal processes. In this section, the representative critical parameters are explained in four different domains: wavelength domain (operating wavelength), power domain (average power, pulse energy, and intensity), time domain (pulse duration), and spatial domain (beam quality and focused spot size). Because all of these parameters are closely related to each other, each parameter will be repeatedly referred in other sections.

3.1 Operating Wavelength

The operating wavelength of the laser is the most important parameter to be considered in additive manufacturing because different materials interact with different laser wavelengths. Table 2 shows the absorptivity of various materials in a loose powder state at the operating wavelength of Nd:YAG and CO_2 lasers. In laser-based additive manufacturing, a high material absorption at the laser wavelength is desired since the target material should efficiently interact with the incident laser light; high absorptivity generally leads to high manufacturing throughput.[73-76] For metal powders, the shorter the wavelength, the better the light absorptivity. Therefore, Nd:YAG or Yb-fiber lasers with 1064 nm operating wavelength exhibit a higher throughput than CO_2 laser with a 10.6 μm operating wavelength in metal printing. Conversely, polymeric materials, which are one of the most important materials used in additive manufacturing, have much higher absorptivity at 10.6 μm than 1064 nm, which explains the extensive use of CO_2 lasers with polymers (See Fig. 9). The operating wavelength is also related to focusability, which determines the ultimate manufacturing resolution. The minimum focused spot size is proportional to wavelength due to the optical diffraction limit, making CO_2 lasers unsuitable for micro/nano-scale manufacturing.[77]

Table 2 Absorptivity of various materials in a loose powder state at the operating wavelength of Nd:YAG and CO_2 lasers[68,69]

Material	Nd:YAG laser (1.06 μm)	CO_2 laser (10.6 μm)
Metals (%)		
Cu	59	26
Fe	64	45
Sn	66	23
Ti	77	59
Pb	79	-
Ceramics (%)		
ZnO	2	94
Al_2O_3	3	96
SiO_2	4	96
SnO	5	95
CuO	11	76
SiC	78	66
Cr_3C_2	81	70
TiC	82	46
WC	82	48
Polymers (%)		
Polytetrafluoroethylene	5	73
Polymethylacrylate	6	75
Epoxypolyether-based polymer	9	94
Mixtures (%)		
Cu-10Al (wt%)	63	32
Fe-3C-3Cr-12V + 10Ti (wt%)	65	39
Fe-0.6C-4Cr-2Mo-1Si + 15TiC (wt%)	71	42
Fe-1C-14Cr-10Mn-6Ti+66TiC (wt%)	79	44

3.2 Average Power, Pulse Energy, and Intensity

Lasers are one of the energy sources used to transfer the energy to printing materials. Therefore, the laser intensity, defined as the laser power per unit area is strongly related to the process throughput. Firstly, the laser intensity must exceed a certain energy threshold to cause the target material to reach the required conditions for in-situ solidification, sintering or melting.[78,79] For the materials in powder or wire form, this condition is related to the temperature for sintering or melting point, where the intensity is related to curing or solidification for photopolymer resins. In contrast to the most polymers with relatively low sintering or melting temperature, some materials, such as ceramics, have an extremely high melting point (zirconium diboride: -

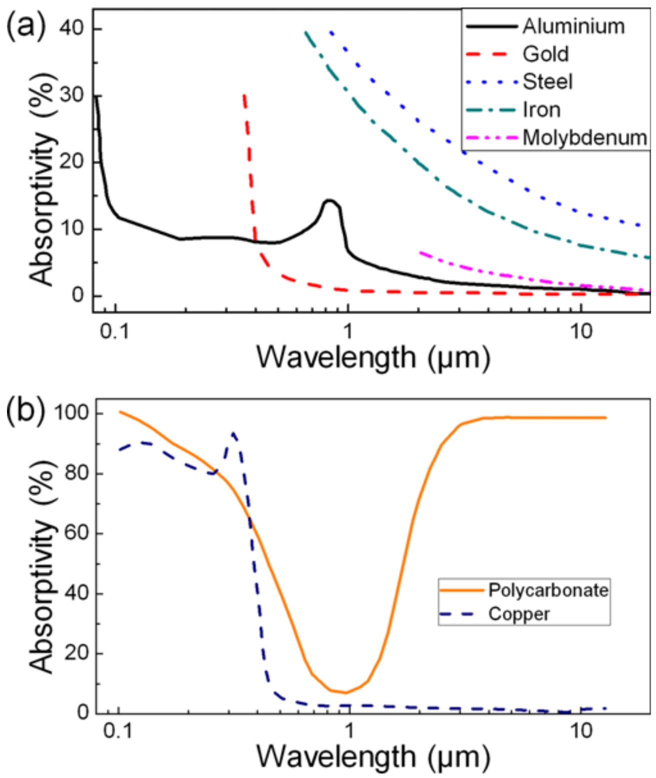

Fig. 9 Light absorptivity at different wavelengths of (a) various metals and (b) polycarbonate and copper[70,71]

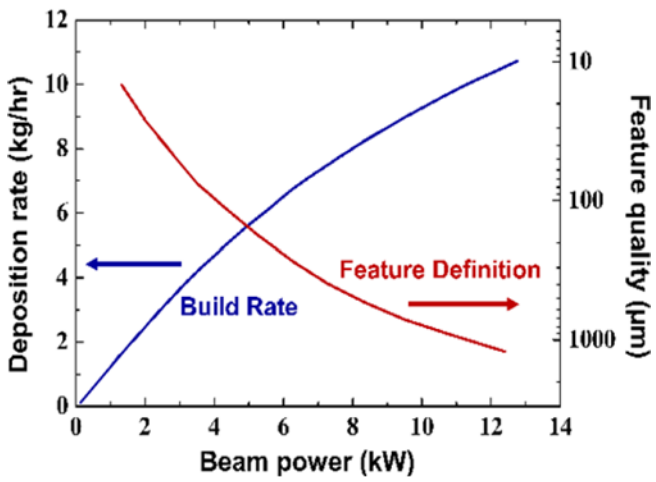

Fig. 10 Relationship between build rate, power, and feature definition in additive manufacturing of metals[72]

3245ºC),[80] which require very high intensities. In addition, the materials having a high reflectivity or a high thermal diffusivity such as aluminum or copper also require high intensities to overcome the slow temperature increase. Once the laser intensity is higher than the manufacturing threshold, higher intensities can improve the build rate. Fig. 10 describes the relationship between the build rate, power, and feature quality in additive manufacturing of metals.[38] Although the build rate can be increased by using a higher power laser, the feature quality fabricated at a high build rate could worsen.[81] Therefore, the beam power should be carefully chosen over the threshold energy of the material by considering both the build rate and the feature quality.[82]

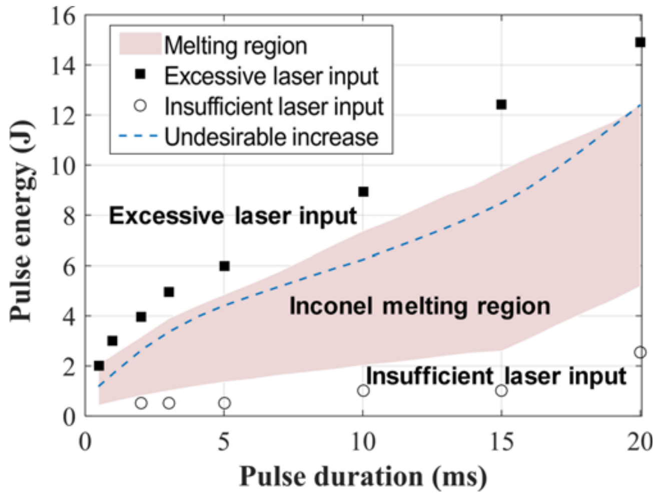

Fig. 11 Pulse energy versus pulse duration for melting region of Inconel 625[83]

Focused intensity of the laser beam is proportional not only to the average power but also to the focused spot size which is ultimately determined by the operating wavelength. For example, while the CO_2 laser and Yb-fiber laser have the same average power, the intensity of Yb-fiber laser can be hundreds of times higher than CO_2 laser because the focused intensity is inversely proportional to the square of the laser wavelength. It is because the laser beam from Yb-fiber laser can be focused to the much smaller area than CO_2 laser due to the shorter wavelength and higher beam quality of Yb-fiber lasers.

3.3 Pulse Duration

Laser operation modes can be classified into a continuous mode or pulsed mode in the time domain. In the continuous mode, the output power remains as constant independent of time; whereas in the pulsed mode, lasers emit output power only within a short pulse duration at a fixed repetition rate. Most lasers covered in this review can be operated in both modes except for excimer lasers, which are only operated in pulsed mode. The pulsed mode can be achieved by Q-switching, mode-locking, or pulsed pumping; the pulsed mode provides a much higher peak power than the continuous mode. For example, a Nd:YAG laser with a pulse duration of several ns produces the pulses with hundreds of MW peak powers, which can melt most of the target materials within a millisecond exposure time. Thus, in laser-based manufacturing, the pulsed mode can give several advantages over continuous mode. The light pulses with a high peak power can increase the temperature of material instantaneously with minor thermal energy dissipation to surrounding material, which makes it easier to reach the threshold energy required for the machining. Conversely, in the continuous wave mode, the same average power would be diffused to the surrounding materials, which makes it difficult to reach the threshold energies. The fundamental is the same in additive manufacturing. As an example, the relationship between the melting condition, pulse energy, and pulse durations when processing Inconel 625 based on SLM using a Nd:YAG pulsed laser is shown in Fig. 11. In the SLM, the material irradiated by the laser beam should be sufficiently heated so as to be fully melted.

Along pulse duration requires a large pulse energy for melting the metal powders. In general, for laser pulse durations from continuous wave to tens of picoseconds, the light-material interaction can be explained through the heat diffusion and the threshold of light energy for manufacturing follows the square root of the laser pulse duration.[25]

3.4 Beam Quality and Focused Spot Size

Beam quality and focused spot size are the laser parameters in the spatial domain, which should be considered to improve the manufacturing precision. To define beam quality, ‘Beam Parameter Product (BPP)’ is generally used in additive manufacturing, which is the product of beam radius (measured at the beam waist) and the half-angle of beam divergence (measured in the far field) with the units of mm·mrad (millimeters times milliradians). Because the low BPP means high energy confinement, BPP is closely correlated to the power density and affects the manufacturing resolution. The factor depends on the gain medium, pumping source, resonator structure, and operating wavelength. The operating wavelength, in particular, determines the lower limit of BPP, which is λ/π, defined as the diffraction-limit. For example, the minimum BPP of a 1064 nm Nd:YAG laser beam is about 0.339 mm·mrad. Ideally, the minimum BPP can be attained when the beam profile is in perfect Gaussian shape; however, the perfect Gaussian beam cannot exist in the real world because of the refractive index gradients, imperfect optical surfaces, and other perturbing influences. The M^2 factor (or beam quality factor) is also used as a simpler way to define the beam quality regardless of the laser wavelength. The M^2 factor is defined as the BPP divided by λ/π, which would equal to one if the laser beam is the perfect Gaussian one.

The beam qualities of CO_2 lasers, Nd:YAG lasers, and Yb:YAG lasers are shown in Fig. 12. The solid lines in Fig. 12 exhibit the relationship between BPP and M^2 factors determined by the diffraction limit at the operating wavelengths. Conventional CO_2 lasers have the BPP values of 3-5, which is similar to those of diode-pumped Nd:YAG lasers, although the diffraction-limit of CO_2 lasers is 10 times higher than that of Nd:YAG lasers. It is worth noting that CO_2 lasers have relatively low BPP and an M^2 factor approaching unity, due to the simple optical structure and stable electrical pumping method. Yb-fiber lasers provide an almost perfect Gaussian-shaped beam. The excellent beam quality of Yb-fiber lasers is attributed to the light propagation through the optical fiber; when the laser beam propagates through the fiber, higher order spatial modes are filtered out due to the limited mode-field diameter of the optical fiber so a single or limited numbers of spatial modes remain inside. In contrast, excimer lasers exhibit relatively poor beam quality including high-order spatial modes and high beam divergence. In addition, their output beam is shaped as rectangular and has asymmetric angular divergence in X and Y axes.

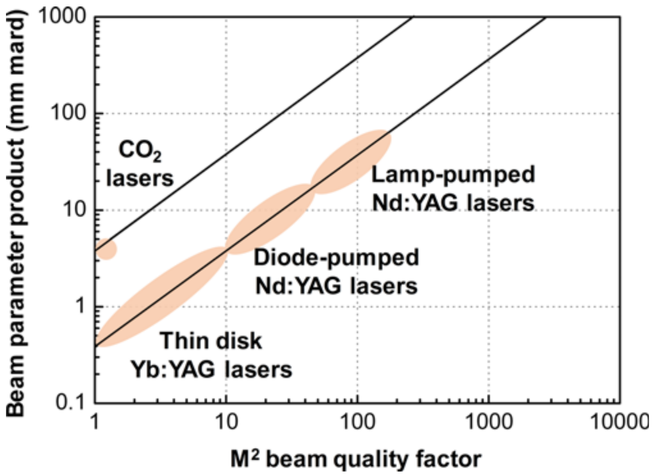

Fig. 12 Beam parameter product and M^2 values of various laser types[84]

4. Laser-Based Additive Manufacturing Technologies

Representative laser-based additive manufacturing processes will be discussed in this section; SLA, SLS, SLM, and LENS. According to the classification of ‘ASTM F42 – Additive Manufacturing’ defined by American Society and Testing and Materials (ASTM), SLA is classified as a vat photopolymerization process; SLS and SLM are classified under powder bed fusion; LENS is classified under directed energy deposition. These processes utilize a different type of lasers and material deposition methods to achieve layer-by-layer manufacturing.[85]

4.1 Stereolithography (SLA)

SLA is one of the earliest additive manufacturing methods, first patented by Chuck Hull in 1984.[86] SLA is a process which makes the use of selective photopolymerization by focusing an ultraviolet (UV) laser light onto a vat of photosensitive polymer resin. The laser beam traces a well-defined outline across a layer of resin to be cured before the cured layer is lowered. The next layer of uncured resin is then cured on top of the previous layer. This process is repeated until the desired 3D structure or part is achieved.[86-90]

UV is an important wavelength for many chemical processes including the polymerization. Polymerization in SLA can be radical or cationic-based. In radical polymerization, the photoinitiator absorbs the incident photons and in return produces free radicals which start the polymerization reaction. For higher efficiency, the operating wavelength of the laser source, therefore, has to be matched to the high absorption wavelength range of the photo-initiators, which is usually in the UV wavelength.[91,92] Cationic polymerization uses acid containing group anions of very low nucleophilicity. Upon UV irradiation, reactive species are produced which initiate the polymerization reaction. In the early days of SLA, the commercialized resins were mainly acrylic-based but the newer resins used today are mostly epoxy-based instead, since epoxy-based resins provide better mechanical properties and less shrinkage.[93,94] Commercial SLA systems utilize Nd:YVO_4 diode-pumped solid-state lasers having a 1064 nm central wavelength, whose wavelength is then converted into 355 nm via third harmonic generation process.[95]

For curing of photosensitive resins, critical laser exposure (E_c) has to be above a certain threshold value. For some of the classical resins, these values fall between 4.3 and 7.6 mJ/cm^2.[96] The cured line for the resin resembles that of a parabolic shape when a Gaussian laser source is used. Layer thickness generally decreases if scanning speed increases or spot size decreases. These two factors heavily affect E_c, which in turn affects the polymerization of the resins. The relationship between

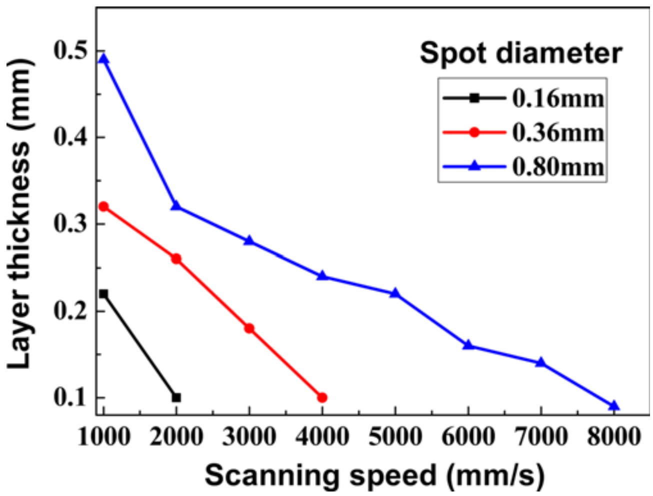

Fig. 13 Layer thickness versus scanning speed of different spots under same laser power in SLA[97]

the layer thickness and scanning speed with respect to different spot diameters is shown in Fig. 13. Therefore, the layer thickness can be adjusted through the control of those two parameters.

While most SLA machines employ the laser output radiation in the UV range, sometimes other wavelengths outside the UV range are also employed. An SLA technique using infrared lasers as an energy source is called infrared (IR) SLA.[98-100] IR SLA utilizes a thermal-initiated process instead of the usual UV-initiated polymerization process. A CO_2 laser is commonly used to provide the thermal energy for thermal sensitive resins such as epoxy-based resins.[101]

Micro-stereolithography (μSL) is another technique, which is derived from the conventional SLA process. μSL is used to produce small complex objects with micron resolution.[102-104] μSL is based on the same principle of applying an energy source to photo-cure the photosensitive polymer. Generally, a smaller beam spot size is required and the laser energy irradiated on the resin is precisely controlled such that it is close to the critical energy for polymerization.[105] A highly absorbing reactive media and neutral absorbers can be used. This helps to form a thinner polymerized layer and therefore much better lateral resolution is achieved.[90]

4.2 Selective Laser Sintering (SLS)

SLS was developed and patented by Carl R. Deckard in the mid-1980s.[106] It is an additive manufacturing process that allows the building of complex parts and structures through the solidification of multiple layers of powders on stacked top. A high power laser is used for the process and the laser power provides the thermal energy required for the powder sintering. A beam deflection system (e.g. Galvano scanner) is used to focus the laser beam to the desired position in order to scan each layer. A new layer of powder is then deposited on top of the solidified materials and the process is repeated until the desired 3D part is achieved. The sintering between the powder particles occurs when the temperature is raised above the melting point of the metal or the softening point of polymers. In some cases, binder materials (commonly found in metal SLS) are added as a sacrificial material to improve sintering processes for the materials having a high melting point or to allow the sintering of larger sized powder particles. The binder material, having a low melting temperature, melts and flows into the small pores formed by the non-molten particles.[108-110]

CO_2 and Yb-fiber lasers are commonly used in SLS processes, depending on the type of material.[111-117] CO_2 lasers with a few tens to hundreds of Watts average power are generally used in SLS machines because polymers have a high absorptivity at the operating wavelength. They can also be used for the sintering of oxide ceramics and composite.[118] Laser sintering of metal powders, however, requires Nd:YAG lasers or more commonly Yb-fiber lasers, which generate a laser beam with 1064 nm wavelength, which is closer to the high absorptivity range for metal powders. This metal based SLS process is also called Direct Metal Laser Sintering (DMLS) to differentiate from polymer based SLS.[119] Besides metal powders, Nd:YAG and Yb-fiber lasers are also used in the sintering of carbide ceramics.[107] Other than the operating wavelength, a number of laser parameters also influence the mechanical property and geometry of SLS printed parts. Laser power and scanning speed are the primary parameters affecting the sintering process.[120] The laser power determines the amount of photon energy per unit time being irradiated on the sintering area while the scanning speed determines the time duration for the target sintering area exposed to the laser beam. These two factors determine the total energy density being absorbed by powders, which in turn affects the quality of the sintered part. When the absorbed energy density is too low, the sintering can be incomplete so the resulting sintered part will be fragile for handling. However, when the absorbed energy density is too high, the sintered part would either be damaged by the excess laser energy, or uneven melting within the part would occur, creating inhomogeneity in the printed part. Laser energies in excess of the material's decomposition energy could even lead to material vaporization. Optimum processing parameters vary with the type of target material used in SLS. The efficiency of the material sintering depending on the energy density can be expressed by a processing window graph. The processing windows for stainless steel-Cu sintered by CO_2 and Nd:YAG lasers are shown in Fig. 14. Stainless steel-Cu has different energy absorption rate at CO_2 and Nd:YAG lasers' wavelengths, which causes the different processing window. With a Nd:YAG laser, stainless steel-Cu has a larger process region in which laser sintering can take place, compared to the case using a CO_2 laser. As the energy density increases, the layer thickness of the sintered material generally increases; this increase is because more energy is transferred per unit area of the fusion area. A higher degree of sintering results in more powder particles fused together to produce a deeper layer thickness. The average density and module strength generally increase with an increase in energy density.[121]

4.3 Selective Laser Melting (SLM)

SLM is a process where a laser beam is incident on metal powder bed to produces 3D objects, categorized under powder bed fusion technologies. Similar to SLS, the repeated process of laser processing and powder spreading builds the object layer by layer into the desired geometry. In SLM, a relatively higher powered laser fully melts each layer of metal powder instead of sintering the powder.[122] Whereas the material used in SLS includes various polymers as well as metals, SLM can only be used with certain metals such as stainless steel, tool steel,

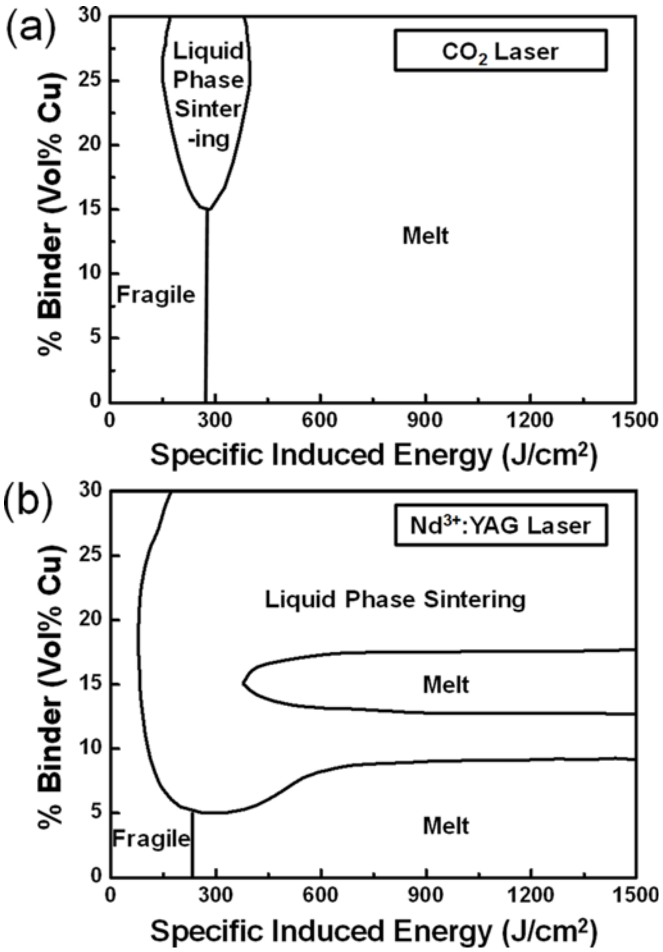

Fig. 14 Processing window for stainless steel-Cu sintered by (a) CO_2 and (b) Nd:YAG laser[107]

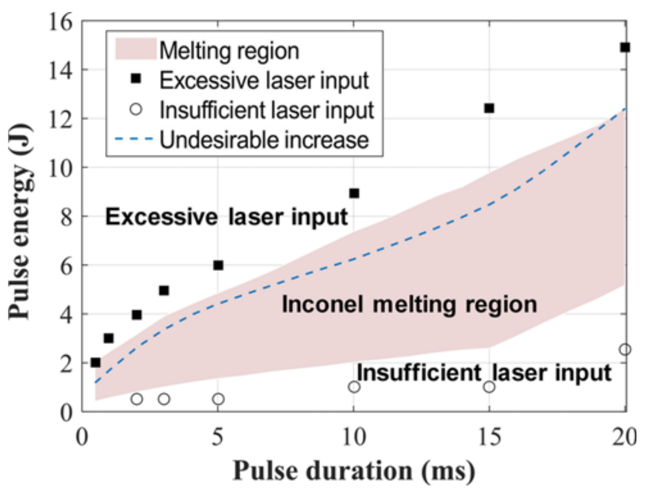

Fig. 15 Variation of absorption of Ni-alloy I metal powder with Nd:YAG laser processing time[68]

titanium, cobalt-chromium and aluminum parts. The laser beam is directed to the specified position or coordinates through the use of Galvano-scanners in a similar manner to SLS machines.

The key difference between SLM and SLS is the bonding process between particles.[123] SLM involves complete melting and solidification of powder particles, which results in improved microstructural and

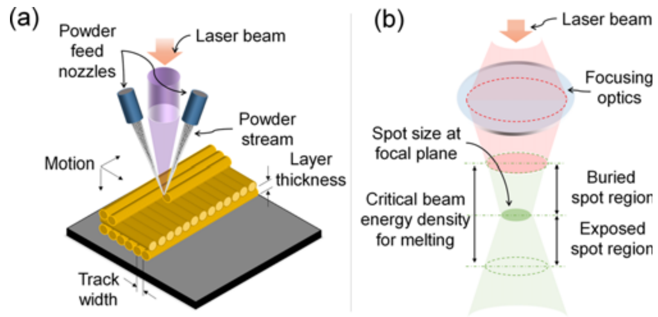

Fig. 16 Schematic of a typical LENS process: (a) LENS system and (b) Laser focusing area[124]

mechanical properties but at the same time suffers from instability when the material is transformed from solid to liquid and vice-versa.[125] Laser parameters such as wavelength, repetition rate, pulse duration and pulse energy greatly affect the melting and solidification process, and therefore to the printed object's properties. Laser parameters need to be optimized according to the properties of the metal powders such as particle size, shape, and absorptivity to achieve good scanning stabilities and part porosity.[126] Most importantly, the absorptivity is very sensitive to the experimental conditions; for example, the absorptivity of Ni-alloy I powder was measured with respect to the time at different laser power density as shown in Fig. 15. Nd:YAG laser at 1.06 μm wavelength was used for the experiment with power intensity of 100 W/cm^2 and 250 W/cm^2. At both intensities, the absorptivity rises rapidly due to the drastic changes in the powder thermo-physical properties. At 100 W/cm^2, the powders were sintered by the surface melting and the particles were rearranged during the processing; thus the absorptivity was saturated at the heat balance point. Meanwhile, at 250 W/cm^2, the prolonged heating induces pronounced melting of particles, followed by the decrease in absorptivity because of the drastic reduction in porosity.

In SLM process, Nd:YAG and Yb-fiber lasers which provide shorter wavelength than CO_2 lasers are preferred because metal particles usually have higher absorptivity at shorter optical wavelengths.[122] Lasers having improved beam quality can exhibit higher manufacturing precision, such as thin disc laser and fiber lasers.[127] Therefore, most commercial SLM machines today utilize Yb-fiber lasers as the light source, moving away from less efficient CO_2 lasers. The combination of multiple lasers in a single printing machine has also been introduced to improve SLM's part quality and printing speed.[128]

4.4 Laser Engineered Net Shaping (LENS)

LENS is a type of additive manufacturing process categorized under the directed energy deposition by the ASTM. Occasionally this process is also referred other terminology, such as Directed Light Fabrication (DLF), Direct Metal Deposition (DMD), 3D laser cladding, Laser-Based Metal Deposition (LBMD), Laser Freeform Fabrication (LFF), laser direct casting, laser cast, laser consolidation, laser form and others.[127,129,130] A schematic of a typical LENS process is shown in Fig. 16. In LENS, print materials are dispensed into the molten pool through the nozzles in either powder or wire form at a controlled rate where the high power laser beam is focused onto. Normally, the whole dispenser

Table 3 Lasers in various commercial 3D printing machines

Company	System	Process	Power	Laser type
		Photopolymer resins		
3D Systems	ProX series	SLA	up to 1.45 W	Nd:YVO_4 laser
CTC	Riverbase 500	SLA	300-500 mW	Nd:YVO_4 laser
		Polymer powders		
3D Systems	sPro series	SLS	30-230 W	CO_2 laser
EOS	EOSINT P series	SLS	50 W	CO_2 laser
		Metal powders		
3D Systems	ProX DMP series	DMP/SLM	500-1000 W	Yb-fiber laser
SLM Solutions	SLM HL series	SLM	400-1000 W	Yb-fiber laser
Optomec	LENS series	LENS/DMD	400-1000 W	Yb-fiber laser
EOS	EOS M series	DMLS	200-400 W	Yb-fiber laser
Matsuura	LUMEX Avance series	DMLS/ Milling	400-1000 W	Yb-fiber laser
Concept laser	LaserCUSING series	SLM	100-1000 W	Yb-fiber laser
		Metal wire		
Irepa laser	EasyCLAD MAGIC LF6000	LC	750-4000 W	Yb-fiber laser
Huffman	H series	LC	400 W	Yb-fiber laser

and laser focusing module are mounted on a multi-axis robotic arm to be moved through the same path.[131,132] Thanks to the system flexibility, LENS can also be used to repair and add material to existing large scale objects.

When the laser beam is focused to a smaller spot at the focal plane as shown in Fig. 16(b), there is a range of the laser beam in the depth direction (near to the focal plane) with sufficient energy density for melting the powders. This region is known as the 'critical beam energy density region' and depending on the position of the substrate to the focal plane, this region is further separated into the 'buried spot region' and 'exposed spot region'. Focal plane positioning, scanning rate, laser power, and feed rate are the critical parameters determining the height and volume of deposit in the melt pool. The thickness of the melt pool should match with the minimum layer thickness of the LENS system. Without a consistent melt pool, the deposition will suffer from the non-uniform thickness of the melt pool between different layers, so the substrate could be shifted out of the exposed spot.[132] Since LENS systems use robotic arms with high degrees of freedom for positioning, Yb-fiber lasers, enabling highly flexible laser beam delivery, are most widely used nowadays.

4.5 Lasers in Commercial Additive Manufacturing Machines

Knowing the types of lasers used in additive manufacturing are of importance in understanding the state-of-the-art of laser-based additive manufacturing. Table 3 summarizes the various lasers used in different commercial additive manufacturing machines. For various additive manufacturing processes, Yb-fiber lasers are exclusively used by all major additive manufacturing companies today, which are an improvement over earlier Nd:YAG lasers. CO_2 lasers are generally used in SLS of polymer powders while photopolymer resins are cured in-situ by frequency-tripled Nd:YVO_4 lasers. New technologies are also being developed and adapted for various applications. Research into newer laser technologies for SLA includes He-Cd lasers (wavelength 325 nm) and Argon excimer lasers with wavelength of 364 nm, while the application of femtosecond lasers are increasingly being investigated as a means of printing the materials with high melting temperature[133,134] or high thermal diffusivity.[135,136]

5. Conclusion and Future Prospects

This review provides a comprehensive review of various types of lasers used in laser-based additive manufacturing, including their operating principles, optical configurations, and comparative analysis of their respective advantages and limitations. CO_2 and Nd:YAG lasers have long been the industrial workhorses for not only additive manufacturing but also various laser-based manufacturing techniques because of their high-performance ratings and cost-effectiveness. Yb-fiber lasers are increasingly replacing Nd:YAG lasers as the alternatives due to their all round progressive developments on higher average power, high system stability, high-level parametric tunability, and low maintenance costs. In spite of relatively low beam quality and higher cost, excimer lasers can be used in additive manufacturing requiring high power UV laser beams for various research purposes. To understand the manufacturing performances such as printable material, precision, and throughput in laser-based additive manufacturing, light-matter interaction with different operating wavelengths, light power, pulse duration, and beam quality were considered. The laser source for additive manufacturing must be selected in accordance with target performances. The review and analysis presented in this paper showed that future of additive manufacturing will maintain strong relevance with laser technologies. Hence, it is envisaged that laser-based additive manufacturing would continue to replace traditional subtractive manufacturing technologies, support traditional manufacturing technologies to improve their performances (called as hybrid manufacturing) or create novel industries that have not been possible with conventional manufacturing technologies.

ACKNOWLEDGEMENT

This work was supported by Singapore National Research Foundation (NRF-NRFF2015-02), Singapore Ministry of Education under its Tier 1 Grant (RG 180/16), and research collaboration agreement by Panasonic Factory Solutions Asia Pacific (PFSAP) and

Singapore Centre for 3D Printing (SC3DP) (RCA-15/027). We thank David A. Belforte, Chief Editor of Industrial Laser Solutions, who provided expertise in understanding trends in lasers used in additive manufacturing that greatly assisted this research. We also thank MASTER LASER™ for use of their copyrighted image of the CO_2 laser discharge tube (Fig. 5 (b)), Spectra-Physics for use of their copyrighted image of the Quanta-Ray Nd:YAG laser (Fig. 6 (b)), Optoelectronics Research Centre (ORC), Finland for use of their copyrighted image of the Yb-fiber laser (Fig. 7 (b)), and LightMachinery for use of their copyrighted image of the IPEXTM-840 / 860 industrial excimer laser (Fig. 8 (c)). Commercial rights remain with their respective owners and the respective images cannot be used for commercial purposes.

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