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Rapid manufacturing of metal components by laser forming

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Abstract

This overview will focus on the direct fabrication of metal components by using laser-forming techniques in a layer-by-layer fashion. The main driving force of rapid prototyping (RP) or layer manufacturing techniques changed from fabrication of prototypes to rapid tooling (RT) and rapid manufacturing (RM). Nowadays, the direct fabrication of functional or structural end-use products made by layer manufacturing methods, i.e. RM, is the main trend. The present paper reports on the various research efforts deployed in the past decade or so towards the manufacture of metal components by different laser processing methods (e.g. selective laser sintering, selective laser melting and 3-D laser cladding) and different commercial machines (e.g. Sinterstation, EOSINT, TrumaForm, MCP, LUMEX 25, Lasform). The materials and applications suitable to RM of metal parts by these techniques are also discussed.

Keywords: Rapid manufacturing; Laser forming; Metal components

1. Introduction

Layer manufacturing, also called rapid prototyping (RP), techniques have about 20 years of history. These techniques directly fabricate, layer-by-layer, physical models from 3-D solid models produced in CAD [1–3]. They are also called additive manufacturing, solid-free form fabrication, digital manufacturing or e-manufacturing [4,5]. There are several machines in the market that utilize different building methods, such as 3-D printing, fused deposition modelling, laminated object manufacturing, selective laser sintering (SLS), selective laser melting (SLM) and 3-D laser cladding [5–8].

In the beginning, RP was mostly used for the fabrication of prototypes made from polymers as communication and inspection tools (e.g. assembly). The capability of producing several physical models in short time directly from computer solid models helped to shorten the production development steps. The fabrication of conceptual and functional prototypes made from polymers is already well established in the market [5,9–11].

Components made by layer manufacturing techniques are no longer used only as visualization tools or for assembly testing. The next natural step for these techniques is to produce functional parts directly from metals and ceramics [12–20]. Nowadays, rapid tooling (RT), i.e. fabrication of moulds and dies by additive manufacturing, and rapid manufacturing (RM), i.e. fabrication of end-use parts directly from RP machines, have been the subject of a lot of research [12]. The current future trend is shifting towards RM, thus eliminating the need for most prototype tooling and production tooling.

In this paper, the diverse systems utilized for the fabrication of metal parts by laser-equipped RP machines will be discussed. A historical perspective is given in Section 2. Section 3 will define RM and classify the systems. In Section 4, the main lasers used for these processes will be listed. The main RP technologies for direct metal laser fabrication (DMLF) and the associated machines that are currently available in the market will be addressed in Section 5.

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2. History and development of direct metal laser fabrication

The layer manufacturing techniques for metals have their roots in the 1971 patent of Ciraud [21], who can be considered the precursor of the 3-D laser cladding processes and in the 1977 patent of Housholder [22], who described the concept of the SLS and SLM systems. These earlier ideas were not ready for commercialization due to the lack of powerful computers and the high price of laser systems at the time.

The work of Deckard (1986) at the University of Texas in Austin resulted in the first DTM machines in late 1992 [23]. DTM was acquired by 3-D systems in 2001. The process is called SLS and is used by different machines in the market (e.g. Sinterstation, EOSINT). The first EOS machine was released in 1994 by EOS GmbH optical system with cooperation of Electrolux. In 1995, Fockele and Schwarze from MCP Tooling Technologies developed a system called MCP Realizer that works under the principle of SLM. In 2004, EOS GmbH acquired the right to all the relevant patents of DTM, University of Texas and 3-D systems related to laser sintering [24].

Other important developments were made by the Westinghouse Electric Corp., in a patent application filed in 1988 and by Sandia National Laboratories in the middle of 1990s [25]. The Westinghouse project was further developed by Arcella at Johns Hopkins University. In 1997 Aeromet was founded. Today, Aeromet specializes in making complex parts from titanium for aeronautical applications by using the laser engineering net shaping (LENS) process, in which the method of depositing the powder changes from 'powder-in-bed' to 'powder injection'. Optomec also started to commercialize its LENS system around 1997 for the fabrication of parts made from titanium alloys and tool steel in partnership with Sandia National Laboratories.

In 2003, TRUMPF introduced two new machines in the market based on the SLM and 3-D laser cladding systems: TrumaForm LF 250 and TrumaForm DMD 505, respectively. TRUMPF holds the rights of direct metal laser fabrication (powder-in-bed) with complete melting of single component metals [24].

3. Definition of RM

RM is the application of layer manufacturing techniques for the fabrication of functional long-term models or end-use products. A representation of RM of metals by laser forming is presented in Fig. 1. The physical inputs into the RP systems are the materials, CAD model and laser. By using different RP technologies, final net shape metallic parts can be fabricated. It is a one-step process in which tooling is eliminated thereby reducing production time and cost. The process is suitable for low volume production of materials difficult to process and for fabrication of complex parts of high aggregate value for the automotive and aerospace industries [26]. RM also offers great potential for mass-customization, for example the fabrication of prostheses and implants for the biomedical industry.

Fig. 2 shows a classification of RM for direct laser fabrication of metal parts based on Levy et al. [13] and Greulich [27]. The main methods for RM of metals can be divided into non-melting and melting processes. Some of the processes are: SLS (partial-melting; powder-in-bed), laser microsintering (partial-melting; powder-in-bed), SLM (full-melting; powder-in-bed) and 3-D cladding (full-melting; powder injection through nozzles). Single component powders, pre-alloyed powders or mixtures of low melting point and high melting point powders are currently used. The density of the fabricated parts by the partial-melting systems varies from 45% to 85% of the theoretical density. Furnace sintering and infiltration by a lower melting point material (e.g. copper, bronze) are usually applied to increase the final density of the components [28–32]. The SLM and 3-D laser cladding systems build parts of high density, close to the theoretical one. Heat treatment of annealing may be used to decrease the thermal residual stresses or optimize the microstructure of the fabricated parts. In order to achieve the high accuracy required for

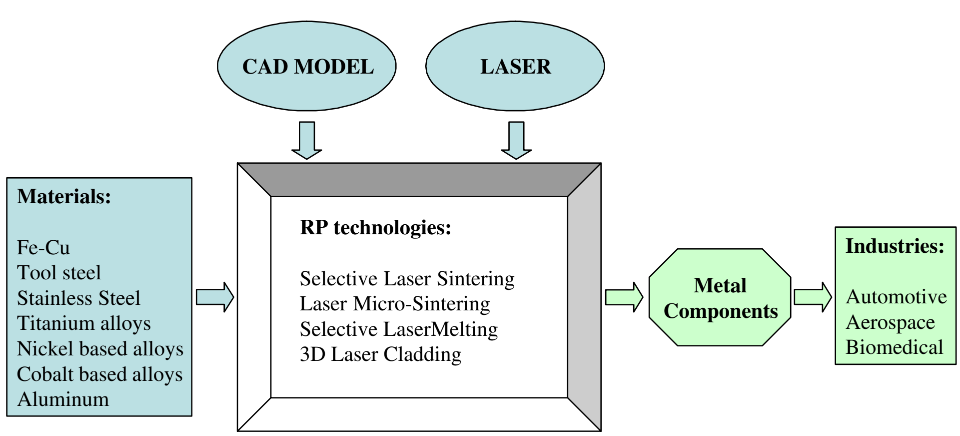

Fig. 1. Schematic representation of rapid manufacturing of metal components by layer manufacturing techniques.

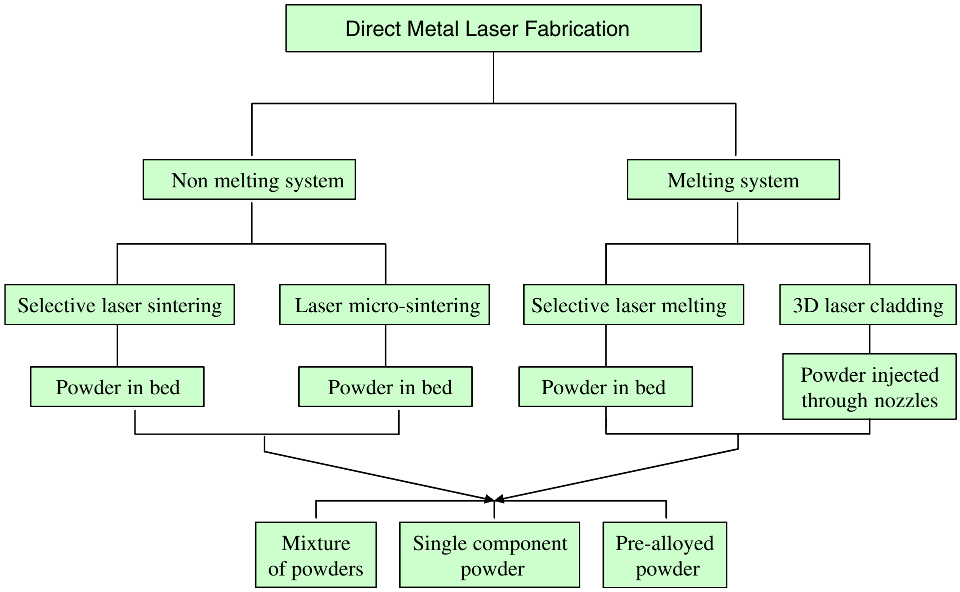

Fig. 2. Classification of rapid manufacturing methods for direct laser fabrication of metal parts.

Table 1
Commercial machines and lasers for DMLF

Machines	Company	Process	Laser	Power
Sinterstation 2000/2500	DTM	DMLS	CO_2	50 W
EOSINT 250	EOS	DMLS	CO_2	200 W
EOSINT 270	EOS	DMLS	Ytterbium fibre laser	200 W
LUMEX 25C	MATSUURA	SLM	Pulsed CO_2	500 W
TrumaForm LF 250	TRUMPF	SLM	Disk laser	250 W
Realizer	MCP	SLM	Nd:YAG	100 W
Lasform	Aeromet	3D laser cladding	CO_2	10–18 kW
LENS 850	Optomec	3D laser cladding	Nd:YAG	1 kW
Trumaform DMD 505	TRUMPF	3D laser cladding	CO_2	2–6 kW

some parts or a high quality surface finish, a post-processing (usually machining) may be necessary.

4. Type of lasers

Some of the commercial machines in the market for laser forming of metals by layer manufacturing technologies are cited in Table 1 with their respective laser systems. Most of the RP machines for direct metal laser fabrication (DMLF) use CO_2 or Nd:YAG lasers in continuous mode. The laser power is in the range of 50–500 W, but very high power CO_2 lasers up to 18 kW are also used [33].

The main difference between CO_2 and Nd:YAG lasers lies in their wavelength. Nd:YAG lasers have a wavelength of 1.06 μm and CO_2 lasers has a wavelength of 10.6 μm. The absorptivity of most metals increases by decreasing the wavelength. Table 2 shows the absorptivity of some common metals used in DMLF. Several research studies have reported that, it is possible to have a larger melting depth for the same power density by using an Nd:YAG laser because of the higher absorptivity and better coupling [34]. Another advantage of the Nd:YAG lasers is the possibility to use optical fibres to guide the beam.

Table 2
Absorptivity of powder to Nd:YAG and CO_2 laser radiation

Material	Nd:YAG laser ($\lambda = 1.06\,\mu m$)	CO_2 laser ($\lambda = 10.6\,\mu m$)
Cu	0.59	0.26
Fe	0.64	0.45
Sn	0.66	0.23
Ti	0.77	0.59
Pb	0.79	
Co-alloy (1% C; 28% Cr; 4% W)	0.58	0.25
Cu-alloy (10% Al)	0.63	0.32
Ni-alloy I (13% Cr; 3% B; 4% Si; 0.6% C)	0.64	0.42
Ni-alloy II (15% Cr; 3.1% Si; 4%; 0.8% C)	0.72	0.51

Source: Tolochko et al. [34].

The RP/RM research team at the University of Leuven [35] performed several comparisons processing Fe–Cu and

WC–Co powders by CO_2 and Nd:YAG lasers. They concluded that at the same laser energy, the Nd:YAG laser resulted in a higher density, a deeper sintering depth and a larger processing window. The Fraunhofer Institutes ILT and IPT (Aachen, Germany) applied a 300 W Nd:YAG laser for SLM of bronze and steel powders [36]. At Osaka University (Osakada laboratory), a pulsed Nd:YAG laser with a maximum peak power of 3 kW and maximum average power of 50 W was applied for fabrication of 3-D metal parts made of nickel, aluminium, steel, bronze and titanium with full success [37–42]. When comparing continuous and pulsed Nd:YAG lasers, the latter seems more suitable for DMLF in 'powder in bed' methods. By using pulsed lasers, very good metallurgical bonding between the tracks and layers is obtained with less heat-affected zone by the high pulse energy in a short pulse length [42]. In order to achieve effective bonding between the tracks, the depth of penetration should be in the order of the layer thickness. This is achieved by using pulse lengths in the order of a few milliseconds for layer thickness between 20 and 100 μm [43–44]. The LUMEX 25C from MATSUURA is the only commercial machine in the market using millisecond-pulsed lasers for SLM [45].

Q-sw Nd:YAG lasers with high pulse repetition (60 kHz) and nanosecond pulse length were applied by Morgan et al. [46] for fabricating stainless steel models of density close to 90%. Regenfuss et al. at the Laserinstitut Mittelsachsen e.V. (Mittweida, Germany) also used Q-sw Nd:YAG lasers for the fabrication of microsized components of tungsten, copper, silver, titanium and other metals by laser micro-sintering [47].

Most of the commercial machines are equipped with CO_2 lasers, although Nd:YAG lasers offer better absorption characteristics for metallic powders [34,35]. CO_2 lasers have higher efficiency, lower price and easier maintenance compared with Nd:YAG lasers and these may be the main reasons; this is especially true in the very high power range with average power >5 kW [43,44,48]. The newest generation of machines employs lasers with much better beam quality and M^2 close to unit. The EOSINT M 270 uses an ytterbium fibre laser while the TrumaForm LF 250 uses a disc laser [24,49].

Diode lasers are considered to be more cost effective than CO_2 or Nd:YAG lasers. The University of Manchester and the University of Connecticut apply a 60 W diode laser of 810 nm [50,51] but until this moment no commercial machine has been introduced in the market. The main disadvantage of laser diodes is the low beam quality, mainly caused by the high beam divergence [13,52,53].

5. Laser-equipped layer manufacturing techniques for fabrication of metal components

5.1. Selective laser sintering

Fig. 3 shows a schematic illustration of SLS. In this process a thin layer of powder is first deposited from the raised part-build cylinder onto the part-build area. The laser beam guided by the galvano mirrors is scanned onto the powder bed to form solidified/sintered layers. The powder in other areas remains loose and acts as a support. After the building-area drops one-layer thickness (typically 0.02–0.1 mm) another powder layer is deposited. The cycle is repeated until the 3-D part is complete. The fabrication

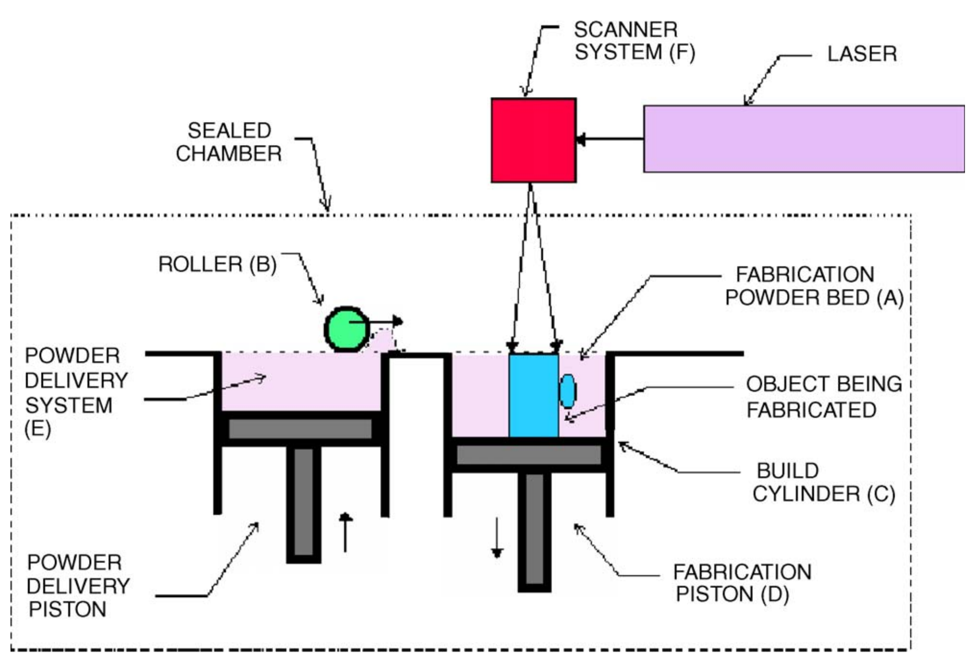

Fig. 3. Illustration of the selective laser sintering process. *Source*: EdGrenda, Worldwide Guide to Rapid Prototyping website. Copyright Castle Island Co. [71].

chamber is closed and the process is performed in an inert atmosphere (nitrogen or argon) to avoid oxidation.

A mixture of powders or specially developed powders developed to allow fabrication of parts with densities typically higher than 60% are used. The densification mechanism during build up of the parts is liquid phase sintering, characterized by melting and wetting or liquid flow [54]. In the case of single component powders, liquid phase sintering happens due to the surface melting of the particles and liquid flow. When mixed powders are used, the powder of low melting point is melted and acts as a binder [55–57]. The process is also called direct metal laser sintering (DMLS) [24]. Post-processing of infiltration or sintering is usually necessary to increase the final density and mechanical properties of the laser sintered parts.

Table 3 shows the materials currently used for this process and their mechanical properties [3,13]. The Rapid Steel 2.0 from DTM is a polymer coated 316 stainless steel powder. The fabricated parts undergo sintering and bronze infiltration. The DirectMetal and DirectSteel powders from EOS are bronze- and steel-based powders. The DirectSteel powders do not require secondary infiltration. The surface roughness of the parts is mainly influenced by the powder particle size. In general, the smaller the particle size, the thinner the layer thickness, and the higher the surface quality exhibited by the as-sintered part.

At the University of Texas in Austin a combination of SLS and hot-isostatic pressing was applied to Inconel 625, stainless steel (17–4 H), Ti–6Al–4V and molybdenum [3,29]. The principle was to consolidate the interior of a component to 80% or higher density and the outline (surface) of the component to a density exceeding 92%. After laser sintering, the part underwent hot-isostatic pressing. This method can produce fully dense parts of mechanical properties close to the wrought material. Table 3 displays the mechanical properties of Inconel 625 and Ti–6Al–4V processed by SLS and HIP.

At the Laser Institut Mittelsachen e.V (LIM) in Mittweida, Germany, Q-sw lasers are used for the fabrication of micrometre-sized or micrometre-structured components. Fig. 4 shows the process and the fabricated part of tungsten. The main features of this system are the equipment for handling and processing of the sub-micrometre-sized metal powders and application of Q-sw Nd:YAG lasers. The laser microsintering process is realized by using a Q-switched Nd:YAG laser with maximum average power of 10 W and maximum frequency of 100 kHz. Structures with a resolution of less than 30 μm and minimal roughness of R_a of 1.5 μm are fabricated [52].

5.2. Selective laser melting

SLM is very similar to SLS in terms of equipment but uses a much higher energy density, which enables full melting of the powders. Therefore the fabricated parts exhibit a density very close to the theoretical one.

Fig. 5 shows the SLM system developed at Osaka University. A Nd:YAG laser of maximum peak power of 3 kW and maximum average power of 50 W is used. The laser light is guided through the optical fibre and the laser beam diameter is 0.8 mm focused onto the powder bed. The laser head is attached to the $x-y$ table controlled by a computer. A steel substrate is attached to the piston, which moves down one layer thickness of 0.05 or 0.1 mm (z direction). The process is carried out in a closed chamber and argon is flushed continuously in order to minimize oxygen and nitrogen pick-up. The system was used for processing aluminum, bronze, steel and pure titanium powders [37–42].

The main machines in the market that use SLM are Trumaform LM 250, MCP Realizer and LUMEX 25C (see Table 1). These machines fabricate full density metal parts from titanium, steel, bronze and other materials.

Table 3
Mechanical properties of materials processed by SLS

Material	Particle size (μm)	Tensile strength (MPa)	Yield strength (MPa)	Young modulus (GPa)
Reference steel: P20	—	950	751	210
Reference: Ti–6Al–4V	—	1030	925	110
DTM RapidTool 1	50	475	255	210
DTM RapidSteel 2.0	34	580	413	263
DTM LaserForm ST 100	23	510	305	137
DTM LaserForm ST 200	20	435	n.a.	142
EOS Ni–Bronze Sn60Pb infiltrated	100	162	124	60
EOS (Electrolux) DMLS DirectMetal™ 50-V3	100	199	n.a.	n.a.
EOS (Electrolux) DMLS DirectMetal™ 50-V2	50	199	n.a.	n.a.
EOS (Electrolux) DMLS DirectMetal™ 50-V1	50	499	n.a.	n.a.
EOS (Electrolux) DMLS DirectMetal™ 20-V2	20	450	n.a.	n.a.
EOS (Electrolux) DMLS DirectMetal™ 50-V1	20	600	n.a.	n.a.
Inconel 625 superalloy (SLS + HIP)	16–44	855	490	208
Ti–6Al–4V (SLS + HIP)	37–74	962	884.6	110

Source: Lu et al. [3] and Levy et al. [13].

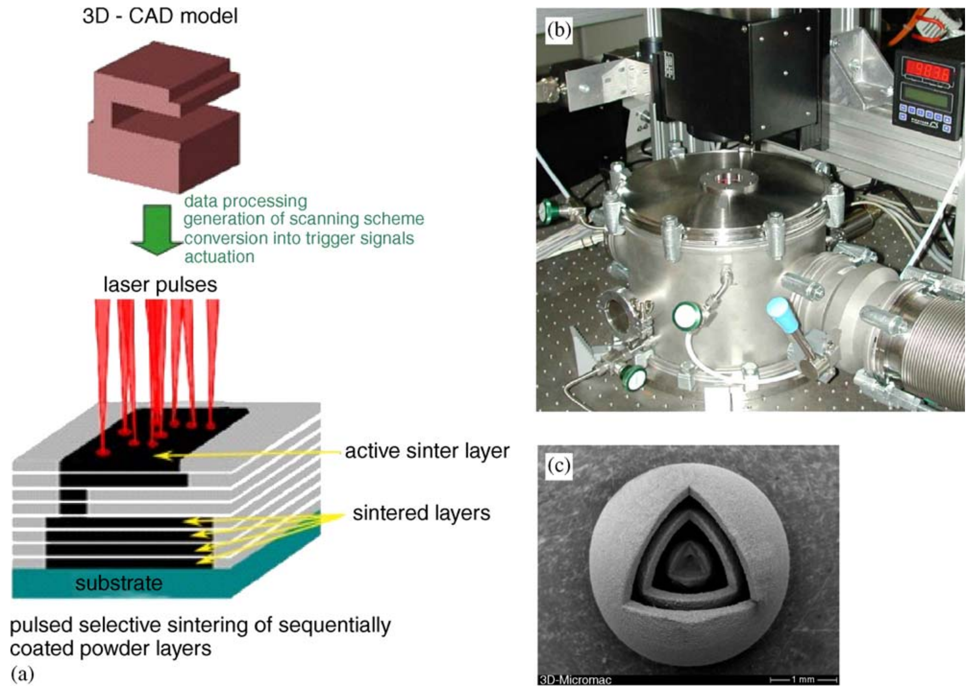

Fig. 4. Laser microsintering with separately set pulses: (a) Fundamental of laser microsintering; (b) sinter chamber; (c) three nested spherical shells fabricated by laser microsintering. *Source*: LIM, Mittweida [51].

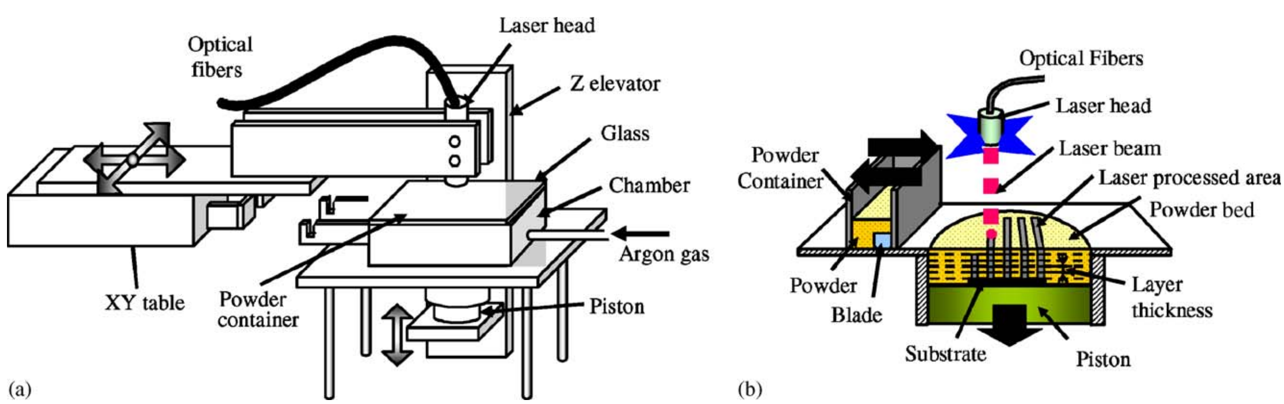

Fig. 5. Selective laser melting: (a) Illustration of the machine; and (b) working principle of the system.

The Trumaform LM 250 uses a disc laser with an excellent beam quality of 4 mm mrad and the focal diameter can be varied between 0.2 and 0.4 mm. The final parts can be finished by conventional processes-like machining, eroding or grinding. The machine can build complex end-use parts in small batches as well as customized implants [49].

In Fig. 6, the illustration of the MCP Realizer and some parts fabricated by this machine are shown. This equipment was recently acquired by the University of Liverpool. The equipment is used for the fabrication of ultra light mesh structures in pure steel for permanent bone replacement purposes in a project (EPSRC) in conjunction with MCP and Stryker Howmedica Osteonics. The MCP Realizer is also used for the production of dental caps, crowns and bridges in stainless steel and cobalt–chrome [58,59].

One of the newest developments in SLM came from Japan with the introduction of the LUMEX 25C in 2004 by MATSUURA. The system uses a pulsed CO_2 laser of average power of 500 W, maximum peak power of 1.5 kW, maximum frequency of 100 kHz and laser spot diameter of 0.6 mm for fabricating parts from steel powders. The machine is equipped with a CNC milling system for processing the parts after 5–10 layers. The machine was designed initially for fabrication of steel moulds and dies with internal cooling channels for injection moulding, but the process can also be used for the fabrication of end-use parts in different metals [45].

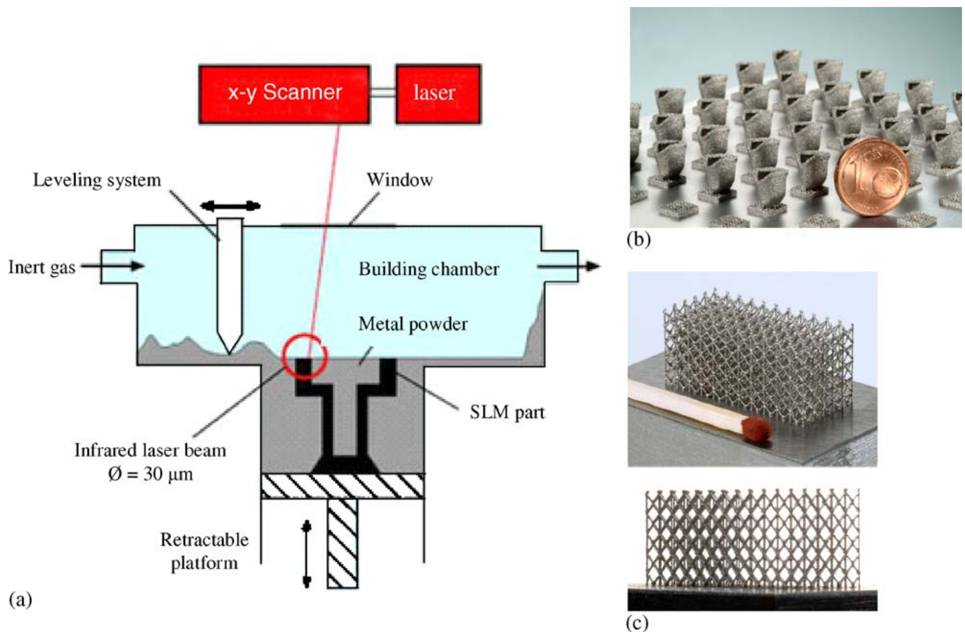

Fig. 6. MCP Realizer: (a) SLM building principle; (b) dental caps and crown made of titanium; and (c) airbone structure made of stainless steel. *Source*: MCP technologies [66].

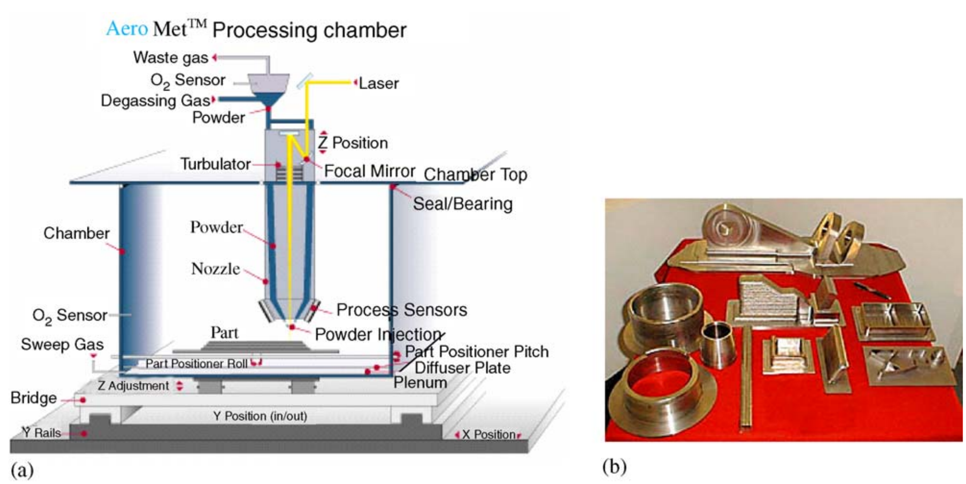

Fig. 7. Laser engineering net shaping: (a) working principle; and (b) parts fabricated on titanium alloy. *Source*: Aeromet [33].

5.3. 3-D laser cladding

The 3-D laser cladding process is also known as laser generating [60]. Instead of fusing material in a powder bed, the powder is delivered in a gas jet through nozzles. The powder is usually delivered coaxially with the laser beam (perpendicular to the substrate). The powder feeder and the laser beam axis may also form an angle between them (usually from 0° to 45°). Some researches showed that the maximum powder efficiency of the process is achieved when the powder arrives almost perpendicular to the substrate [61]. The metal powder is fused in the focal zone of a high-energy laser beam and parts with complex geometries can be formed. The process occurs in closed chambers with controlled inert atmospheres. Fully dense parts with mechanical properties close (or even superior) to the conventionally processed material are usually achieved [62–65]. Fig. 7 shows the illustration of the process and some fabricated parts of the system used by Aeromet. The process is also called laser engineered net shaping (LENS). Three-axis LENS machines cannot produce complex parts with overhangs because there is no powder support during build-up. This restriction was overcome by applying five-axis machines or by depositing separate support material around the part [13,66]. The Aeromet machine uses a very high CO_2 power ($>10\,kW$) laser for the fabrication of parts for the aeronautical industry [33].

Titanium alloys, nickel alloys, steels, cobalt alloys and aluminium alloys are the main materials used for this process. Hedges [64] used a LENS machine equipped with a 300 W Nd:YAG laser for the fabrication of hip implants made of Ti–6Al–4V with tensile and fatigue properties equivalent to the wrought materials. The parts fabricated have full density and require final surface finishing (machining). The IRC at the University of Birmingham [67] together with Rolls-Royce have developed a new low cost burn-resistant beta Ti alloy for the fabrication of turbine blades made by 3-D laser cladding. The parts were produced by using an in-house built system with a closed chamber kept at Ar atmosphere (O_2 <5 ppm) and a 1.75 kW CO_2 laser. Kathuria [68,69] utilized laser micro-cladding process with a Nd:YAG laser of average power of 20 W and minimum spot diameter of 20 μm for the fabrication of microparts made of Co-alloys, nickel and stainless steel. Xue et al. at the National Research Council of Canada reported the manufacturing of functional net-shape Ti–6Al–4V and Inconel 625 alloys components for a space robot manipulator by a laser cladding process they called Laser Consolidation [70]. This process was performed with a Nd:YAG laser with an average power ranging from 50 to 300 W and a powder feeder rate ranging from 1 to 20 g/min. The Ti–6Al–4V parts exhibited yield strength, tensile strength and Young modulus of about 1062, 1157 MPa and 116 GPa, respectively, these values being higher than those of as-cast or annealed wrought alloys. Furthermore, the authors reported that the laser processed structural components were free of cracks and pores.

6. Conclusions

Layer manufacturing techniques are moving from rapid prototyping and rapid tooling to rapid manufacturing. The production of end-use parts made of metal is one of the most promising applications for these techniques. Rapid manufacturing of metal parts are especially suitable for the fabrication of small number of pieces and mass customization. Direct fabrication of metal products of high density and excellent mechanical properties is possible by using laser-based layer manufacturing techniques. The aeronautic, automotive and medical industries are the main markets. The advent of the new machines equipped with fibre and disc lasers is supposed to increase the accuracy and mechanical properties of the processed parts.

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References

[1] C.K. Chua, K.F. Leong, Rapid Prototyping: Principles and Applications in Manufacturing, Wiley, New York, 1997.
[2] J. Beaman, J.W. Barlow, D.L. Bourell, R.H. Crawford, H.L. Marcus, K.P. McAlea, Solid Freeform Fabrication: A New Direction in Manufacturing, Kluwer Academic Publishers, Dordrecht, 1997.
[3] L. Lu, J. Fuh, Y.S. Wong, Laser Induced Materials and Processes for Rapid Prototyping, Kluwer Academic Publishers, Dordrecht, 2001.
[4] M. Shellabear, J. Lenz, V. Junior, E-manufacturing with laser sintering—to series production and beyond, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September, Erlangen, Germany, pp. 435–444.
[5] T. Wohlers, Wholers Report, Rapid Prototyping and Tooling, State of the Industry, Wohlers Associates, 2002.
[6] P.F. Jacobs, Rapid Prototyping and Manufacturing: Fundamentals of ÿTereolithography, McGraw-Hill, New York, 1993.
[7] L. Wood, Rapid Automated Prototyping: An Introduction, Industrial Press, 1993.
[8] G. Bennett, Developments in Rapid Prototyping and Tooling, Institution of Mechanical Engineers, 1997.
[9] S. Jayanthi, The transition to functional prototyping, in: User's Conference on Rapid Prototyping and Manufacturing, June 1999, London, UK, pp. 2.0–2.21.
[10] G. Wolfgang, Progressive product development processes with rapid technologies, in: Proceedings of the Rapid Prototyping and Manufacturing: 3D Scanning Applications, Malmoe, Sweden, 2000.
[11] J.P. Kruth, M.C. Leu, T. Nakagawa, Progress in additive manufacturing and rapid prototyping, Annals of the CIRP 47 (2) (1998) 525–540.
[12] J.P. Kruth, X. Wang, T. Laoui, L. Froyen, Lasers and materials in selective laser sintering, Keynote paper, in: Proceedings of the Third Laser Assisted Net Shape Engineering, LANE 2001, August, Erlangen, Germany, pp. 3–24.
[13] G.N. Levy, R. Schindel, J.P. Kruth, Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives, Annals of the CIRP 52 (2) (2003) 589–609.
[14] G.K. Lewis, Direct laser metal deposition process fabricates near-net-shape components rapidly, Materials Technology 10 (3/4) (1995) 51–54.
[15] Y.P. Kathuria, Laser assisted rapid prototyping in Japan, in: Proceedings of the Seventh International Conference on Laser and Laser-information technologies, ILLA 2001, June 2001, Suzdal, Russia, pp. 400–406.
[16] Y. Zhang, L. Shi, Research on laser direct metal deposition, in: Proceedings of the First International Symposium on High-Power Laser Macroprocessing, May 2002, Osaka, Japan, pp. 487–492.
[17] W.T. Carter, M.G. Jones, Direct Laser sintering of metals, in: Proceedings of the Fourth Solid Freeform Fabrication Symposium, August 1993, Austin, TX, pp. 51–59.
[18] M. Fukai, T. Horikawa, K. Nishiyama, K. Okumura, Application of direct metal laser sintering for fabrication of production injection moulds, in: Proceedings of the Eighth International Conference on Rapid Prototyping, June 2000, Tokyo, Japan, pp. 407–412.
[19] G.K. Lewis, E. Schlienger, Practical consideration and capabilities for laser assisted direct metal deposition, Materials and Design 21 (2000) 417–423.
[20] A. Safari, S.C. Danforth, M. Jafari, M. Allahverdi, B. Jadidian, F. Mohammadi, N. Ve, Fabrication of advanced functional ceramics by fused deposition technique, in: Proceedings of the Ninth European Conference on Rapid Prototyping and Manufacturing, Athens, Greece, July 2000.
[21] P. Ciraud, Verfahren und vorrichtung zur herstellung beliebiger gegenstande aus beliebigem schmelzbarem material, German Patent Publication DE 2263777, priority filed December 28, 1971, published July 5, 1973.

[22] R. Housholder, Molding process, US Patent 4247508, filed December 3, 1979, published January 27, 1981.

[23] C. Deckard, Methods and apparatus for producing parts by selective laser sintering, US Patent 4863538, filed October 17, 1986, published September 5, 1989.

[24] O.N. Shellabear, DMLS—development history and state of the art, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, pp. 393–404.

[25] F. Arcella, Casting shapes, US Patent 4818562, filed March 24, 1988, published April 4, 1989.

[26] D.T. Pham, C. Ji, C.C. Dimov, Layered manufacturing technologies, in: Proceedings of the First International Conference on New Forming Technology, ICNFT, September 2004, Harbin, China, pp. 317–324.

[27] M. Greulich, Rapid prototyping and fabrication of tools and metal parts by laser sintering of metal powders, Materials Technology 12 (5/6) (1997) 155–157.

[28] D.L. Bourell, R.S. Evans, S.W. Chen, S.L. Barrow, Rapid manufacturing of functional parts using infiltration post-processing, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, pp. 93–104.

[29] S. Das, M. Wohlert, J.J. Beaman, D.L. Bourell, Producing metal parts with selective laser sintering/hot isostatic pressing, JOM 50 (12) (1998) 17–20.

[30] N. Volpato, T.H.C. Childs, T.D. Stewart, P. Watson, Indirect selective laser sintering of metal parts with overhung features, Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture 215 (6) (2001) 873–876.

[31] T.D. Stewart, K.W. Dalgarno, T.H.C. Childs, Strength of the DTM rapid steel 1.0 material, Materials and Design 20 (2/3) (1999) 133–138.

[32] Y. Yokoyama, K. Maekawa, I. Ohshima, Fabrication of miniature mechanical and electrical parts from powders using greentape laser sintering method, in: Proceedings of the Eighth International Conference on Rapid Prototyping, June 2000, Tokyo, Japan, pp. 213–218.

[33] Lasform, Aeromet, http://www.aerometcorp.com/.

[34] N.K. Tolochko, Y.V. Khlopkov, S.E. Mozzharov, M.B. Ignatiev, T. Laoui, V.I. Titov, Absorptance of powder materials suitable for laser sintering, Rapid Prototyping Journal 6 (3) (2000) 155–160.

[35] B. Lauwers, J.P. Kruth, L. Froyen, T. Laoui, Comparison between Nd:YAG and CO_2 laser for use with selective laser sintering of metal powders, in: Proceedings of the PHOTOMEC'99–ETE'99, European Workshop, November 1999, Liege, Belgium, pp. 165–173.

[36] F. Klocke, H. Wirtz, W. Meiners, Direct manufacturing of metal prototypes and prototype tools, in: Proceedings of the Seventh Solid Freeform Fabrication Symposium, August 1996, Texas, USA, pp. 141–148.

[37] E.C. Santos, M. Shiomi, K. Osakada, F. Abe, Microstructure and mechanical properties of pure titanium models fabricated by selective laser melting, Journal of Mechanical Engineering Science, Part C, Proceedings of the Institution of Mechanical Engineers, ImechE 218 (2004) 711–719.

[38] E.C. Santos, M. Shiomi, M. Morita, K. Osakada, F. Abe, fabrication of titanium dental implants by selective laser melting, in: Proceedings of the Fifth International Symposium on Laser Precision Microfabrication, May 2004, Nara, Japan, pp. 268–273.

[39] F. Abe, E.C. Santos, K. Osakada, M. Shiomi, Influence of forming conditions on the titanium model in the rapid prototyping with the selective laser melting process, Journal of Mechanical Engineering Science, Part C, Proceedings of the Institution of Mechanical Engineers, ImechE 217 (2003) 1–8.

[40] F. Abe, A. Yoshidome, K. Osakada, M. Shiomi, Direct manufacturing of metallic model by laser rapid prototyping, International Journal of the Japan Society for Precision Engineering 32 (3) (1998) 221–222.

[41] F. Abe, K. Osakada, M. Shiomi, K. Uematsu, M. Matsumoto, The manufacturing of hard tools from metallic powders by selective laser melting, Journal of Materials Processing Technology 111 (1/3) (2001) 210–213.

[42] E.C. Santos, Processing of pure titanium by selective laser melting, Master Degree Dissertation, Graduate School of Engineering Science, Osaka University, 2003.

[43] J.F. Ready, Industrial Applications of Lasers, second ed, Academic press, New York, 1997.

[44] W.M. Steen, Laser Materials Processing, third ed, Springer, Berlin, 1996.

[45] LUMEX25C, Matsuura Machinery Corporation, http://www.matsuura.co.jp/index.shtm (in Japanese).

[46] R. Morgan, A. Papworth, C. Sutcliffe, P. Fox, B. O'Neill, Direct metal laser re-melting of 316L stainless steel powder Part 2: analysis of cubic primitives, in: Proceedings of the 12th Solid Freeform Fabrication Symposium, August 2001, Austin, TX, pp. 283–295.

[47] P. Regenfuss, R. Ebert, S. Klotzer, L. Hartwig, H. Exner, Th. Brabant, T. Petsh, Industrial laser microsintering, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, pp. 413–424.

[48] A.G. Grigoryants, Basic of Laser Material Processing, Mir Publishers, 1994.

[49] J. Hutfless, Approaching new markets with near net shape technologies, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, pp. 79–92.

[50] T. Manzur, C. Roychoudhuri, H. Marcus, SFF using diode lasers, in: Proceedings of the Seventh Solid Freeform Fabrication Symposium, August 1996, Texas, USA, pp. 363–368.

[51] L. Li, K.L. Ng, A. Slocombe, Diode laser sintering of compacted metallic powders for desktop rapid prototyping, in: Proceedings of the Seventh European Conference on Rapid Prototyping and Manufacturing, 1998, pp. 281–296.

[52] G. Esser, A. Otto, M. Geiger, Requirements towards future laser systems for flexible manufacturing, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, pp. 37–45.

[53] R. Propawe, Development of new beam sources–fiber, slab, disc and rod, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, pp. 47–54.

[54] R.M. German, Powder Metallurgy Science, second ed, MPIF, 1994.

[55] N. Tolochko, S. Mozzharov, T. Laoui, L. Froyen, Selective laser sintering of single- and two-component metal powders, Rapid Prototyping Journal 9 (2) (2003) 68–78.

[56] J.P. Kruth, X. Wang, T. Laoui, L. Froyen, Lasers and materials in selective laser sintering, Assembly Automation 23 (4) (2003) 357–371.

[57] J.P. Kruth, T. Laoui, Selective laser sintering: state-of-the-art, International Journal of Electrical Machining (6) (2001) 7–17.

[58] R.C. Bennett, Ch. Sutcliffe, Selective laser melting—applications and developments using MCP Realizer^{SLM}, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, p. 545.

[59] S. Ritt, MCP Realizer II SLM—industrial applications, brochures, MCP-HEK TOOLING, private communication.

[60] Y.P. Kathuria, Metal rapid prototyping via a laser generating/selective laser sintering process, Proceedings of the Institution of Mechanical Engineers, Part B, IMECH 214 (999) (2000) 1–9.

[61] R. Vilar, Laser cladding, Journal of Laser Applications 11 (2) (1999) 64–79.

[62] M.L. Griffith, T. Ensz, J.D. Puskar, C.V. Robnio, Understanding the microstructure and properties of components fabricated by laser engineered net shaping (LENS®), Materials Research Society, Symposium Y Proceedings 625 (2000) 9–20.

[63] J.A. Brooks, C.V. Robino, T. Headley, S. Goods, M. Griffith, Microstructure and property optimization of LENS® deposited H13

tool steel, in: Proceedings of the 10th Solid Freeform Fabrication Symposium, August 1999, Austin, TX, pp. 375–382.

[64] M. Hedges, Laser based additive manufacturing using LENS^{TM} and M^{3}D^{TM}, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 1, September 2004, Erlangen, Germany, pp. 523–534.

[65] L. Sexton, S. Lavin, G. Byrne, A. Kennedy, Laser cladding of aerospace materials, Journal of Materials Processing Technology 122 (2002) 63–68.

[66] M. Kerschbaumer, G. Ernst, P. O'Leary, Toolpath generation for 5-Axis laser cladding, in: Proceedings of the Fourth Laser Assisted Net Shape Engineering, LANE 2004, vol. 2, September 2004, Erlangen, Germany, pp. 831–842.

[67] X. Wu, R. Sharman, J. Mei, W. Voice, Direct laser fabrication and microstructure of a burn-resistant Ti alloy, Materials and Design 23 (2002) 239–247.

[68] Y.P. Kathuria, An overview of 3D structuring in microdomain, The Journal of the Indian Institute of Science 81 (2001) 659–664.

[69] Y.P. Kathuria, Laser assisted metal rapid prototyping in micro-domain, in: Proceedings of the Eighth International Conference on Rapid Prototyping, 2000, Tokyo, Japan, pp. 160–165.

[70] L. Xue, A. Theriault, B. Rubinger, D. Parry, F. Ranjbaran, M. Doyon, Manufacturing structural components by laser consolidation, The Industrial Laser User 36 (2004) 31–33.

[71] EdGrenda, Worldwide Guide to Rapid Prototyping, http://home.att.net/~castleisland/.