Laser-Based Powder Bed Fusion

Subjects: Engineering, Manufacturing

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Laser-based powder Bed Fusion (L-PBF), formerly SLM, is one of the seven Additive Manufacturing basic process categories in the new standards.

rapid tooling | additive manufacturing (AM) | laser-based powder bed fusion (L-PBF) | production tools | cold working | hot working | injection molding

1. Introduction

During the past 15 years, layered manufacturing has been subject to further research studies, standardization and industrialization. According to the developed standards, the technology is named Additive Manufacturing (AM). Laser-based powder Bed Fusion (L-PBF), formerly SLM, is one of the seven AM basic process categories in the new standards [1][2][3][4]. For a detailed description of L-PBF, see [5][6][7][8][9].

Table 1 displays the features of the current (2020) machines for AM by L-PBF. This table, which is based on the machine makers specifications, shows that the maximum object size that can be 3D-printed today is 600 × 600 × 600 mm^3 (although the largest height is 850 mm in one of the other machines). This size has more than doubled compared to that in the 1995 machine for selective laser sintering. In addition to higher laser power, some of the current machines have more than one laser and therefore a much higher productivity.

Due to the complexity of L-PBF, the manufacturers of metal AM systems have developed sets of optimized processing conditions for some existing powder metals. The machine manufacturer sets the process parameters for one or some specific powder metals as the default values for additive manufacturing based on the customer preferences before machine delivery and installation, Table 2. The number of these powder metals is much larger than those in 1995. However, this number is still very small, compared to the number of existing materials made and used conventionally.

Table 1. The features of the current L-PBF machines [10][11][12][13][14][15][16].

Manufacturer	Model	Number and Type of Lasers	Laser Power (per Laser) (W)	Build Volume (l × w × h) (mm^3)	Build Rate (cm^3/hr)	Layer Thickness (μm)	Scan Speed (m/s)
3D Systems	DMP Factory 500 Printer Module	3 fiber	500	500 × 500 × 500 [1]	-	2–200, Typical: 30, 60 & 90	-
	DMP Factory/Flex 350	1 fiber	500	275 × 275 × 420	-	5–200, Typical: 30, 60 & 90	-
	DMP Flex 100	1 fiber	100	100 × 100 × 90	-	10–100	-
	ProX DMP 300	1 fiber	500	250 × 250 × 330	-	10–100, preset: 40	-
	ProX DMP 200	1 fiber	300	140 × 140 × 115	-	10–100, preset: 30	-
Additive Industries	MetalFAB1	1 to 4 Yb fiber	500	420 × 420 × 400	-	20–100	-
Concept Laser	X Line 2000R	2 (cw) fibre	1000	800 × 400 × 500	-	-	-
	M Line Factory	4 fiber	1000	500 × 500 × 400	-	-	-
	M2 Multilaser	2 (cw) fiber	400	250 × 250 × 350	-	-	-
EOS	EOS M 400-4	4 Yb-fiber	400	400 × 400 × 400 [1]	100	80	7
	EOS M 400	1 Yb-fiber	400	400 × 400 × 400 [1]	50	-	7
	EOS M 300-4	4 Yb-fiber	400	300 × 300 ×	10	-	7

Manufacturer	Model	Number and Type of Lasers	Laser Power (per Laser) (W)	Build Volume (l × w × h) (mm^3)	Build Rate (cm^3/hr)	Layer Thickness (µm)	Scan Speed (m/s)
				400			
	EOS M 290	1 Yb-fiber	400	250 × 250 × 325 [1]	-	-	7
	EOS M 100	1 Yb-fiber	200	f100 × 95 [1 & 2]	-	-	7
SLM Solutions	SLM®NXG XII 600	12	1000	600 × 600 × 600	1000	-	-
	SLM®800	4	400 or 700	500 × 280 × 850 [1]	Up to 171	20–90	10
	SLM®500	4 IPG fiber	700	500 × 280 × 365 [1]	Up to 171	20–75	10
	SLM®280	1, 2, 3 or dual	400, 700, or 700 & 1000	280 × 280 × 365 [1]	Up to 113	20–90	10
	SLM®125	1 IPF fiber	400	125 × 125 × 125 [1]	Up to 25	20–75	10
Renishaw	RenAM 500Q/S	1 or 4 Yb-fiber	500	250 × 250 × 350 [1]	Up to 150	20–100	10
	RenAM 500E	1 Yb-fiber	500	250 × 250 × 350 [1]	Up to 150	20–100	10
	RenAM 500M	1 Yb-fiber	500	250 × 250 × 350 [1]	Up to 150	20–100	10
	AM 400	1	400	250 × 250 × 300 [1]	-	-	-

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Manufacturer	Model	Number and Type of Lasers	Laser Power (per Laser) (W)	Build Volume (l × w × h) (mm^3)	Build Rate (cm^3/hr)	Layer Thickness (µm)	Scan Speed (m/s)
Trumpf	AM 250	is now replaced by AM 400		250 × 250 × 300 [1]	-	-	-
	TruPrint 1000	1 fiber	200	f100 × 100 [1 & 2]	2–18	10–50	-
	TruPrint 2000	1 fiber	300	f200 × 200 [2]	-	20–100	-
	TruPrint 3000	1 fiber	500	f300 × 400 [2]	5–60	20–150	-
	TruPrint 5000	3 fiber	500	f300 × 400 [2]	5–180	30–150	-

[1] Height includes the thickness of the substrate/building plate. [2] Diameter × height.

Table 2. Materials the current machines L-PBF machines can be set in for upon installation [10][11][12][13][14][15][16].

Manu-facturer	Model	Powder Metals Based on… Al	Co	Cu	Fe	Ni	Ti	W
3D Systems	DMP Factory 500 Printer Module	By request				Nickel alloys	By request	
	DMP Factory/Flex 350	AlSi7Mg0.6, AlSi10Mg	CoCrF75	-	Maraging Steel, 17-4PH, 316L	Ni625, Ni718	Ti Gr1, Ti Gr5, Ti Gr23	-
	DMP Flex 100	-	CoCr	-	17-4PH, 316L	-	-	-
	ProX DMP 300	AlSi12	CoCr	-	Maraging steel, 17-4PH	-	-	-
	ProX DMP 200	AlSi12	CoCr	-	Maraging steel, 17-	-	-	-

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Manu-facturer	Model	Powder Metals Based on…						
		Al	Co	Cu	Fe	Ni	Ti	W
					4PH, 316 L			
Additive Industries	MetalFAB1	AlSi10Mg, ScalmAlloy©	-	-	Tool steel 1.2709, 316L	IN718	Ti6Al4V	-
	X Line 2000R	AlSi10Mg—Balanced & Productivity	-	-	-	Nickel 718	Ti6AL4V Grade 23	-
Concept Laser	M Line Factory	A205	CoCrMo	-	-	Nickel 718 CL	-	-
	M2 Multilaser	AlSi10Mg, AlSi7Mg	CoCrMo	-	Maraging M300, 316L, 17-4PH	Nickel 625, Nickel 718	Ti6AL4V Grade 23	-
	EOS M 400-4	AlSi10Mg	-	-	MS1, 316L	HX, IN718	Ti64, TiCP Grade 2	-
	EOS M 400	AlSi10Mg	-	-	MS1	IN718	Ti64, Ti64ELI	-
EOS	EOS M 300-4	AlSi10Mg	-	-	MS1	IN718	Ti64	-
	EOS M 290	AlSi10Mg	MP1	-	MS1, CX, PH1, 17-4PH, 316L	HX, IN625, IN718	Ti64, Ti64ELI, TiCP Grade 2	-
	EOS M 100	-	SP2	-	316L	-	Ti64	W1
SLM Solutions	SLM®NXG XII 600	ALSi10Mg (No limitations)	No limitations			IN718 (No limit.)	No limitations	
	SLM®800	AlSi10Mg, AlSi7Mg0.6, AlSi9Cu3	CoCr28Mo6, SLM® MediDent	CuSn10, CuNi2SiCr	Maraging 1.2709, 316L (1.4404), 15-5PH (1.4545), 17-4PH (1.4542),	HX, IN625, IN718, IN939	Ti6Al4V ELI (Grade 23), TA15, and Ti (Grade 2)	-
	SLM®500							
	SLM®280							

Manu-facturer	Model	Powder Metals Based on…						
		Al	Co	Cu	Fe	Ni	Ti	W
	SLM®125				H13 (1.2344), Invar 36®			
	RenAM 500Q/S							
Renishaw	RenAM 500E	AlSi10Mg	CoCr	-	Maraging M300, 316L	IN625, IN718	Ti6Al4ELI	-
	RenAM 500M							
	AM 400							
	AM 250							
	TruPrint 1000	Yes to all except W + precious metal alloys + amorphous metals						
Trumpf	TruPrint 2000	Yes to all except Cu and W + amorphous metals						
	TruPrint 3000	Yes to all except Co, Cu and W						
	TruPrint 5000	Yes to all except Co, Cu and W						

2. Tool Design for Metal Additive Manufacturing by L-PBF

Additive manufacturing provides significantly larger design freedom (compared to conventional manufacturing), the benefits of which can be maximized by the emerging computer-aided design (CAD) technologies like generative design (GD). It is now possible to:

(1) Generate a wide range of design alternatives by artificial intelligence-based algorithms (GD software) after setting the part/object design space, constraints, criteria and objectives. The designer reviews the different design options and chooses the best-suited for the application [17][18].

(2) Topology optimize the selected design alternative, the purpose of which is to remove unnecessary material while meeting (or exceeding) the performance criteria. The goal is to optimize a part properly (weight, stiffness, frequency …) while respecting a certain set of constraints. The topology optimization process uses various mathematical algorithms and methods (each having several versions) [19][20][21][22].

(3) Optimize the internal lattice and surface structure of the topology optimized object by creating an internal mesh while meeting (or exceeding) the performance criteria [23][24][25][26].

(4) Produce this complex object by L-PBF (and post-processing).

During the past two decades, different new design methodologies have emerged, among them the Design for X (DfX). X represents a particular perspective to improve during the product design as well as the design process [27][28]. DfX applied to the Additive Manufacturing process is named DfAM. It aims at using the full potential of the AM technologies for design, for which there are two methods [18][29][30].

A new detailed DfAM process has been proposed including the available design support (methods, design rules, guidelines and software tools), the tools and methods that are best suited at different stages of the design process are specified, and the possibility to achieve a more automated DfAM is indicated [31].

As far as the L-PBF process design (i.e., the preparation of the L-PBF process) is concerned, the part orientation, support structures, overhangs and part supporting angles, channels and holes, wall thickness, tolerances and offsets are addressed in [32][33][34]. VDI 3405 Part 2, [32], addresses the qualification, quality assurance and post processing. The procedure described in this standard is applied to DIN 1.2709 in a VDI inter-laboratory test. The obtained properties in this inter-laboratory test are accounted for in [32].

The angle between the building platform and the building direction is also of great significance for the properties of the as-built object. In other words, the properties of the as-built object are anisotropic due to the layered manufacturing, the loading direction etc. Table 3 and Figure 1 display 7 different configurations, in which tensile specimens in 316L (1.4404) were built with an oversize of 0.4 mm in width and thickness. After milling to final shape, the specimens were tested. Table 4 displays the tensile properties of these specimens. The maximum strength is obtained at a 45° layer versus loading offset [35].

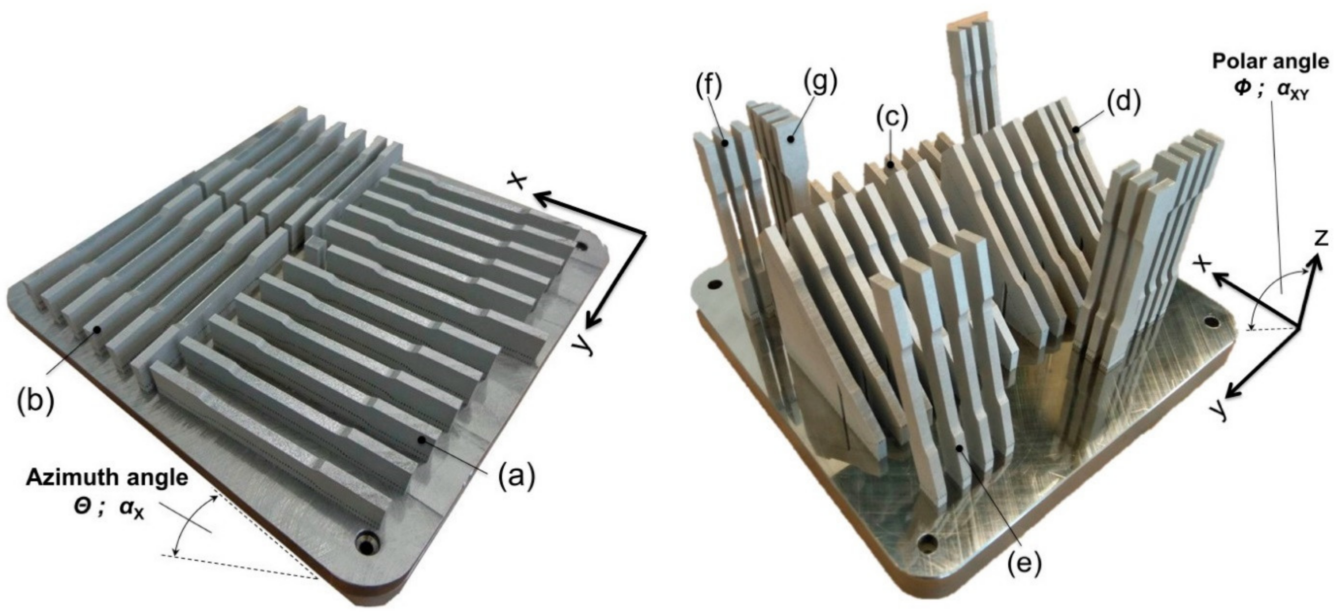

Figure 1. The tensile samples in 1.4404 (316L) on the building platform: overview of the positioning, building angles and arrangement (configurations). See also Table 3 and Table 4. The figure is from [35].

Table 3. The tested configurations. See also Figure 1 and Table 4. The table is from [35].

Config.	Polar Angle Φ; α_{XY} (°)	Azimuth Angle Θ; α_X (°)	Total Runtime (h)
(a)	0	0	-
(b)	0	90	39.5
(c)	15	0	-
(d)	45	0	-
(e)	75	0	86.5
(f)	90	0	-
(g)	90	90	-

Table 4. The tensile properties of 1.4404 (316L) in different building configurations. See also Table 3 and Figure 1. The specimens were built with an oversize of 0.4 mm in width and thickness and milled to final shape before tensile testing. The table is from [35].

Config.	Young's Modulus *E* (GPa)		Yield Strength $R_{p0.2}$ (MPa)		Ultimate Tensile Strength R_m (MPa)		Elongation at Failure At (%)		Poisson's Ratio ν (-)	
	Average	STDEV	Average	STDEV	Average	STDEV	Average	STDEV	Average	STDEV
(a)	151.01	25.56	516.51	7.16	634.43	7.39	33.24	0.57	0.444	0.031
(b)	207.57	24.22	539.47	3.29	643.67	3.25	42.74	0.82	0.155	0.014
(c)	147.87	23.59	501.32	7.70	624.65	4.36	34.09	1.12	0.479	0.058
(d)	227.35	25.12	589.89	11.86	698.98	23.65	32.56	10.17	0.203	0.024
(e)	151.43	18.80	485.65	11.93	571.23	18.63	22.84	7.27	0.558	0.020
(f)	137.78	14.25	438.60	9.69	511.99	17.95	11.76	5.38	0.453	0.005
(g)	137.83	16.25	457.21	17.29	530.22	8.09	17.46	4.42	0.170	0.085

Design demands knowledge of the precise material properties. These properties are anisotropic and the component orientation on the build platform needs therefore to be considered [35]. (Post L-PBF heat treatment affects also these properties. See the properties of 316L (1.4404) before and after heat treatment)

It is possible to achieve ±0.2% in tolerance, with the minimal value being 0.2 mm. It is also possible to achieve a wall thickness of 0.5 mm. However, the wall shape is dependent upon the orientation, its height (in relation to the thickness), and the possibility to have support if needed. As far as gaps (between walls or solid portions) are concerned, the minimum gap width should be larger than at least the melt pool width. It is also important to add an allowance of 0.3–0.5 mm to the locations and surfaces that require post-processing by machining to reach the required tolerance and surface roughness [24][32].