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Progress in configurations of DED-based production system

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1. Development and commercialization

In the early of 1990s, laser directed energy deposition (DED-L), combining laser cladding technology with rapid prototyping method, was firstly developed [1]. Owing to this technology was proposed independently by many research institutes, it has been defined as different names, such as laser engineered net shaping (LENS) [2], laser solid forming (LSF) [3], laser metal forming (LMF) [4], etc. Until 2012, these names were unified as directed energy deposition (DED) according to American Society for Testing and Materials (ASTM) F2792-12a [5]. In recent years, DED has attracted much attention from industrial and scientific aspects due to it is capable of fabricating large-scale structure with high efficiency and repairing. Furthermore, laser, electron beam and plasma/electric arc are widely employed as the focused thermal energy in this technology, and the feedstock includes metal powder and wire.

As one of the first commercialized DED methods, LENS was licensed to Optomec®, Inc. in 1997. After nearly 30 years' development, the technical level of DED has improved a lot and thus it gained extensive investments and applications. For instance, It has been predicted that the revenue share of DED technologies would increase from 8.3% to 11.1% in the next 5 years since 2019, and the market for DED would reach $755M by 2025 [6]. The application fields cover aviation, aerospace, navigation, automobile, medical, mold, At the same time, more and more manufacturers have focused on DED technologies. Table 1 lists some leading manufacturers of DED-based production systems classified by the focused thermal energy and feedstock. Seen from Table 1, the feedstock of powder is only employed in DED-L process while the wire can be used in the DED process based on laser beam, electron beam, and plasma/electric arc. Note that the combination of wire with plasma/electric arc is also called as wire arc additive manufacturing (WAAM).

Table 1 The leading manufacturers of DED-based production systems

	Laser beam	Electron beam	Plasma/electric arc
Powder	Optomec®, Inc., Trumpf, AddUp (BeAM), FormAlloy, DMG MORI, InssTek, Inc., Mazak, and Raycham.	-	-

Wire	Evobeam GmbH	Sciaky, Inc.	WAAM, Norsk Titanium AS, Gefertec GmbH, Mazak, Lincoln Electric, and Raycham.

Note that Lincoln Electric only shows the additive solution without equipment, and "Raycham" represents "Nanjing Zhongke Raycham Laser Technology Co., Ltd", similar hereinafter.

2. Technical features

To systematically understand the technical features of the DED-based production systems, we reviewed and summarized basic features, advantages and disadvantages of the systems produced by different manufacturers. The details are listed in Table 2. There are various differences between these DED-L production systems in terms of laser type, laser power, build volume, powder feeder number, inerting device, and so on. In addition, there are some novel designs in the deposition head to adjust laser optics and powder feeding rate, as well as vibration technology in the powder dispenser for stability and reliability in the powder supply. It is worth mentioning that the closed loop control system including process monitoring and control are equipped for most of the systems. Note that the detailed information of the features of the DED-based production systems are shown in the Appendix.

Table 2 Basic features, advantages and disadvantages of the DED-L production systems from different manufacturers.

		Machine	Basic features	Advantages	Disadvantages
DED-L using powder	Optomec®, Inc.	CS250, CS 600, CS800, CS1500	1. Laser power: 0.5-3 kW; 2. 3-5 Axis with worktable of 250×250×250 mm^3- 900×1500×900 mm^3; 3. Up to 4 powder feeders; 4. Gas purification system.	1. Adjustable laser optics with LDH 3.X deposition head; 2. Thermal imaging, closed loop feedback controls and material starter recipes.	1. Small build volume; 2. Low deposition efficiency;
		HC 205, HC 254	1. Laser power: 1-3 kW; 2. 5 Axis with worktable of 356×356×356 mm^3- 762×457×508 mm^3; 3. Self-contained twin-canister powder feeder.	1. Adaptive Process Control; 2. Auto CLADTM Software for verifying repair quality.	Limited usage (only for high-value parts repair).
	Trumpf	TruLaser Cell 3000, TruLaser Cell 7040	1. Laser power: 8 kW- (2 kW-6 kW); 2. 5-axis laser processing machine: Axis travel range: 800×600×400 mm^3-4000×1500/2000×750/1000 mm^3, B=±135°, C= n×360°; 3. Flexible system with laser cutting, laser welding, and DED-L.	High efficiency for batch production: Rotary exchanger/two-station partition wall and movable table.	No controlled atmosphere.
	AddUp	Modulo 400, Magic 800	1. Laser power: 0.5 kW-2 kW; 2. Simultaneous 5-axis: 650×400×400 mm^3-1800×1000×1000 mm^3, B/C=±110°, C=±360°; 3. Powder feeder count 2; 4. Enclosure inerting device for reactive powders.	1. Vibration powder dispenser for stability and reliability in the powder supply; 2. 24Vx nozzle for massive sections of the parts and 10Vx nozzle for parts requiring precision 3. Closed loop control system.	Low deposition efficiency.
	FormAlloy	L2 Series, X5 Series	1. Laser power up to 8 kW with 2 lasers (Infrared laser and blue laser); 2. Up to 5-axes: 250×250×300 mm^3-1000×1000×650 mm^3; 3. 2 heads and 4 feeders	1. Deposition efficiency is relatively high (Up to 7kg/hr); 2. Dynamic layer selection; 3. Melt pool size monitoring & control;	Small build volume.

			4. Inert gas build chamber: <10 ppm oxygen content (L-Series). 5. Dust removal/extraction: <5 micron filtration; 6. Build plate heating.	4. Melt pool temperature and control; 5. Process monitoring.	
	DMG MORI	LASERTEC 65 DED,	1. Laser power: 2.5 kW; 2. 5 axes: 735×650×560 mm^3.	1. Laser head integrated in the headstock for high building volume; 2. Integrated thermal imaging camera for observing the whole working area, adapive process control and constant monitoring of the working distance; 3. Powder feed rate sensor and automatic powder calibration; 4. AM Evaluator for visualisation of the relevant process data (e. g. meltpool size, powder mass flow) as a digital 3D-model;	1. Small build volume; 2. Low deposition efficiency; 3. No controlled atmosphere.
		LASERTEC 65 DED hybrid, LASERTEC 125 DED hybrid, LASERTEC 3000 DED hybrid, LASERTEC 6600 DED hybrid	1. Laser power: 2.5 kW-3 kW (Optional 8 kW); 2. 5 axes: 735×650×560 mm^3-1040×610×3890 mm^3; 3. Materials: from non-reactive metals to reactive metals (LASERTEC 3000 DED hybrid). 4. Laser sensor installed on the machine cover and window (LASERTEC 6600 DED hybrid).	1. Combination of additive and 5-axis milling machining process for finished quality. 2. Integrated thermal imaging camera for observing the whole working area, adapive process control and constant monitoring of the working distance; 3. Powder feed rate sensor and automatic powder calibration; 4. AM Evaluator for visualisation of the relevant process data (e. g. meltpool size, powder mass flow) as a digital 3D-model; 5. The laser head is handled by a fully automatic shuttle-without manual intervention. 6. Comprehensive cooling measures, powerful cooling unit and multi-sensor compensation as standard; 7. Movable and high-performance dust collection duct.	1. Small build volume; 2. Low deposition efficiency.
	InssTek, Inc.	MX-Lab, MX-Fab	1. Laser power: 0.5 kW-2 kW; 2. 3-5 axes: 150×150×150 cm^3-500×600×400 cm^3 (MX-Fab1)/800×1000×700 cm^3 (MX-Fab3), A/C=±100°/360°; 3. CVM powder feeding system-6 hoppers with precision feeding rate control from 0.03-2 g/min to 0.05-20 g/min; 4. Atmosphere Control System.	1. DMT® Closed-Loop Feedback Control system (analyzing and controlling the height of the meltpool in real-time); 2. Adjusted beam diameter: 800/1200/1600/2400 μm (MX-Fab).	1. Small build volume; 2. Low deposition efficiency.
	Raycham	LDM4030, LDM8060, LDM1500, LDM2500	1. Laser power: fiber laser (1-8 kW), Semiconductor Laser (4-10 kW), blue laser (2 kW); 2. Build volume: 400×400×400 mm^3- 2500×2500×1500 mm^3; 3. Oxygen and water content: ⩽ 50ppm.	Equipped blue laser can prepare Cu-based alloys, etc.	No Closed-Loop Feedback Control system.

DED-L using wire	Evobeam GmbH	WiLaVAM Wire-feed Laser,	1. Fiber laser incl. Scanner or Wobbler; 2. Deposition rate: 200 – 500 cm^3/h. 3. Pre-vacuum avoids pores and is sufficient for steels; 4. Hard-vacuum for TiAl, refractory metals and super-alloys available; 5. Optics protected against metal vapor and thermal radiation; 6. Variable focusing system optional; 7. CNC-controlled in vacuum wire-feed system; 8. Thermal camera (1 kHz) for process control.	1. High deposition efficiency; 2. Vacuum has positive impact on material consistency; 3. Pores-free deposit.	Size limitation: Suitable for medium sized structures.
DED-BE using wire	Sciaky, Inc.	The EBAM® 53 System, The EBAM® 110 System, The EBAM®150 System, The EBAM® 200 System, The EBAM® 300 System	1. Chamber dimensions: 53” (1346 mm) ×53” (1346 mm)×72” (1880 mm)- 300” (7620 mm)×108” (2743 mm)×132” (3353 mm); 2. Build Envelope: 26” (635mm) wide×26” (635 mm) deep×26” (635 mm) high-228” (5791 mm) wide×48” (1219 mm) deep×48” (1219 mm) high; 3. High efficiency pumping (up to 1×10^{-5} Torr ultimate vacuum pressure); 4. Power level up to 42 kW–60 kV;	1. Large build volume; 2. High deposition efficiency; 3. Wirefeed with motorized wire nozzle; 4. Closed-loop control (CLC) technology.	Ultimate vacuum is required.
WAAM	WAAM	RoboWAAM	**Hardware:** 1. Motion axes: 6+2; 2. Power source: CMT/PTA; 3. Local shielding (global option); 4. Wire position system (Electronic/automatic); 5. Process camera; 6. Process monitoring (Position travel speed, arc voltage, arc current, wire position, layer height and 3D profile, lead and trail temperature, oxygen Gas flows); **Software:** 7. WAAMPlanner (Turns your part’s preform into executable RoboWAAM code); 8. WAAMKeys (Eliminates defects and keeps the layer height); 9. WAAMSim (Process simulation); 10. WAAMCtrl (an all-encompassing operating system)	1. Control centre: Supervise RoboWAAM’s operation from its front desk in the comfort of one place; 2. External wire storge: External bulk wire storge accommodating large spools (70 kg) or drums (250 kg); 3. Control electronics: PLC and monitoring hardware in the control system govern the machine from behind the scenes, connecting to the control centre at the front; 4. Fume management systemTM provides best-in-class health and safety.	
	Norsk Titanium AS	MERKE IV®	1. Part build size: 900× 600×300 mm^3; 2. Layer dimensions: H =3–4 mm; W = 8–12 mm; 3. Deposition rate: 5–10 kg/hour; 4. Titanium, nickel alloys, tool steel, stainless steel are all applicable to the RPD platform.	Rapid plasma deposition.	Small build volume.
	Gefertec GmbH	arc40X, arc60X, arc80X	1. 3-axis machining: Production of metallic components from 0.72 m^3 to 8 m^3 (with a maximum mass from 800 kg to 8000 kg); 2. 5-axis machining: Production of metallic components from 0.06 m^3 to 1.1 m^3 (with a maximum mass from 200 kg to 500 kg).	1. Temperature tracking by integrated Sensortherm pyrometer; 2. Arc cooling system for local cooling by cooling gas; 3. Automatic welding torch cleaning system; 4. Titanium module; 5. Table change (from 5 to 3 axes or vice versa)	The surface finish is hard to guarantee.
	Mazak	VARIAXIS J-600/5X AM	1. Combining 5-axis machining center with wire arc: 850×550×510 mm^3, B=210°, C=360°; 2. DED-L: Diode laser of 1, 2, 4, 6 kW with Metal powder;	1. Build volume is high; 2. Deposition efficiency is high;	1. No Closed-Loop Feedback Control system; 2. No controlled atmosphere.

			3. WAAM: Type of arc: MIG, Max. current: 300 A, with metal wire of Φ1.0 mm or Φ1.2 mm. 4. AM build volume: Φ730 mm×450 mm;		
	Raycham	WAAM1500, WAAM2500	1. Power supply type: TIG/MIG (TIG current 5-700A/MIG power supply 3-400A); 2. Build dimension: 1500×1500×1000 mm^3-2500×2500×1500 mm^3; 3. Dual-axis rotary table; 4. Oxygen content ⩽50 ppm.	1. High deposition efficiency; 2. Large build volume.	No Closed-Loop Feedback Control system.
		Additive & Subtractive Hybrid Manufacturing	1. Build dimension: Diameter2000 mm×1000 mm; 2. Arc Additive Manufacturing System (Maximum Additive Forming Efficiency: 900 cm^3/h; Welding Current Range: MIG/MAG3-400A; Welding Rod: 10-400A); 3. Laser Powder Feeding 3D Printing System (Forming Efficiency: 120-350 cm^3/h; Laser Power: 4-10kW; Powder Utilization Rate: 70%--80%); 4. Subtractive Processing System (Milling Spindle Rated Power(S1/S6): 8.5/10kW; Milling Spindle Rated Torque(S1/S6): 6.7/8 N/m; Subtractive Tool Magazine Capacity: 6 tools).	1. Integrating WAAM with DED-L; 2. Large build volume; 3. High surface finish and forming precision.	No Closed-Loop Feedback Control system.

Note that "Additive & Subtractive Hybrid Manufacturing (in Nanjing Zhongke Raycham Laser Technology Co., Ltd)" and "VARIAXIS J-600/5X AM (Mazak)" are both equipped with production systems of DED-L and WAAM, and they have been listed into WAAM due to they have the feature of high efficiency.

3. Summary and prospective

DED-based production systems have experienced a rapid development both in hardware and software. As a result, the forming capacity (including maximum build volume, forming precision), processing stability, self-adaptivity, machining flexibility, and inert atmosphere control of the DED-based production systems have reached a new high. Table 3 lists the extreme features of the hardwares in the existed DED-based production systems. It can be seen that the maximum laser power and maximum TIG welding current have reached 10 kW and 700 A (400 A for MIG), respectively, which have laid a solid foundation for the high-deposition-rate forming. Meanwhile, the maximum build volume of 2500×2500×1500 mm^3 continuously meet the increasing dimensional requirement of the components in industry. In addition, the minimum oxygen content of less than 10 ppm significantly improves the purity of the deposit, especially for reactive metals.

The advancement in DED-based production systems creates new opportunities for the industrial development. Based on the features of the existed DED-based production systems, some future development trends can be given. On the one hand, that pursuing a large forming dimension and a high deposition rate of DED-based production systems is an important

development orientation. Usually, this can be achieved by employing high power of the focused thermal energy, high material feeding rate, and large CNC machine. On the other hand, developing a small-scale DED-based production systems used to produce or repair high-value components (e.g., aircraft vanes, integrated-blisks) is another trend. The systems are always equipped with thermal imaging, closed loop feedback controls, and adaptive process controls so that the forming process can be monitored and adjusted in real time to obtain a good forming quality and excellent performance. Besides, the additive and substrative hybrid forming systems are also an important development direction. The high-precision components can be obtained in one set-up, which can significantly improve the machining efficiency, and guarantee the machining precision by one time clamping.

Table 3 Extreme features of the hardwares in the existed DED-based production systems

Extreme features	Special values	Machine (Manufacturer)
Maximum laser power	10 kW (semiconductor laser)	LDM2500 (Raycham)
Equipped maximum laser types	2 types of infrared laser and blue laser	X5 Series (FormAlloy) L2 Series (FormAlloy) LDM4030 (Raycham)
Maximum build volume (WAAM)	2500×2500×1500 mm^3	LDM2500 (Raycham)
minimum oxygen content	<10 ppm	CS 600 (Optomec®, Inc.) CS 800 (Optomec®, Inc.) L2 Series (FormAlloy)
Maximum welding current	TIG current:700 A, MIG: power supply: 400 A.	WAAM1500 (Raycham) WAAM2500 (Raycham) Additive & Subtractive Hybrid Manufacturing (Raycham)
Maximum deposition rate	10 kg/hour, 900 cm^3/h	MERKE IV® (10 kg/hour, Norsk Titanium AS) Additive & Subtractive Hybrid Manufacturing (900 cm^3/h, Raycham)

Appendix

Table A1 Features of DED-L production systems using powders in Optomec®, Inc.

	Features
CS 250	1. 500-2000 W fiber lasers with latest LDH 3.1 deposition head with adjustable laser optics; 2. 3-5 Axis CNC control system with worktable of 250×250×250 mm^3; 3. Optional Oxygen-free System for processing reactive metals; 4. Up to 4 integrated powder feeders.
CS 600	1. 500 W (to 2000 W) fiber laser with 0.67 mm (2 and 3 mm) focused spot size;

	2. Siemens 840D controller with 3 axes- X/Z overhead, Y table of 600×400×400 mm^3 (3+1, 3+2, or simultaneous 5 axis motion upgrade); 3. Optional MC tool path generation with LENS additive plug-in; 4. Controlled atmosphere (O_2 levels<10 ppm) with integrated gas purification system; 5. SteadyFlowTM powder feed system/single powder feeder (up to 4); 6. LENS laser deposition head (LDH 3.X) with 4-tip nozzle; 7. Optional thermal imaging, Closed loop feedback controls and material starter recipes.
CS 800	1. 500 W (to 3000 W) fiber laser with 0.67 mm (2 and 3 mm) focused spot size; 2. Siemens 840D controller with 3 axes- X/Z overhead, Y table of 800×600×600 mm^3 (3+1, 3+2, or simultaneous 5 axis motion upgrade); 3. Optional MC tool path generation with LENS additive plug-in; 4. Controlled atmosphere (O_2 levels<10 ppm) with integrated gas purification system; 5. SteadyFlowTM powder feed system/single powder feeder (up to 4); 6. LENS laser deposition head (LDH 3.X) with 4-tip nozzle; 7. Optional thermal imaging, Closed loop feedback controls and material starter recipes;
CS 1500	1. 1 kW IPG Fiber Laser (Laser and Chiller upgrade to 3kW); 2. Siemens 840D 5 axis control system and a process work envelope of 900×1500×900 mm^3 with XYZ gantry + tilt-rotate table; 3. Integrated Gas Purification System; 4. Integrated Dual Powder Feeders; 5. Optional Closed-Loop Control System and Deep Repair Deposition Head.
HC205 (high value repair)	1. IPG1000 watt fiber laser and chiller; 2. 356×356×356 mm^3; 3. Self-contained twin-canister powder feeder; 4. Integrated GigE machine vision with LED lighting for Adaptive Process Control, Industrial i7 PC with integrated video, 22" touchscreen monitor, Profibus I/O; 5. Adaptive Process Control with Auto CLAD™ Software.
HC254 (high value repair)	1. IPG1500 watt fiber laser and Chiller; 2. 762×457×508 mm^3; 3. Self-contained twin-canister powder feeder; 4. Integrated GigE machine vision with LED lighting for Adaptive Process Control, Industrial i7 PC with integrated video, 22" touchscreen monitor, Profibus I/O; 5. Adaptive Process Control with AutoCLAD™ Software.

Note that "()" represents the optional items.

Table A2 Features of DED-L production systems using powders in Trumpf.

	Features
TruLaser Cell 3000	1. Compact and highly precise 5-axis laser processing machine: Axis travel range: **800×600×400 mm^3**, B=±135°, C= n×360º; 2. Flexible system with laser cutting, laser welding, and DED-L (TruDisk laser up to 8000 W); 3. Some options: Rotary exchanger; Digital connectivity and integration for smart solutions.
TruLaser Cell 7040	1. 5-axis laser processing machine: Axis travel range: 4000×1500/2000×750/1000 mm^3, B=±135°, C=n×360º; 2. Flexible system with laser cutting, laser welding, and DED-L (TruDisk: 2000 W-6000 W); 3. Some options: Two-station partition wall; Rotary exchanger; Movable table; BrightLine Weld (Spatter free);

Table A3 Features of DED-L production systems using powders in AddUp.

	Features

Modulo 400	1. 10Vx nozzle to make parts that require precision with 500 W laser (optional 24Vx nozzle to make the massive sections of the parts with 2000 W laser); 2. Simultaneous 5-axis (Build volume: 650×400×400 mm^3, B=±110º, C=±360º) with table temperature sensor and Optional process monitoring package; 3. Enclosure inerting device for working with reactive powders; 4. Powder feeder count 2 (vibration technology, Optical sensor of the amplitude displacement); 5. Air extraction filtration: Prefilter, HEPA, Chemical filter; 6. Suitable for small to medium metal part production and repair without support structures.
Magic 800	1. 2000 W Ytterbium fiber (Optical fiber diameter: 600 μm); 2. 5-axis (simultaneously and continuously): (Build volume: 1800×1000×1000 mm^3, A = ±110°, C = ±360°); 3. 24Vx nozzle to make the massive sections of the parts (Optional: 10Vx nozzle to make parts that require precision); 4. Enclosure inerting device for working with reactive powders; 5. Powder feeder count 2 (vibration technology); 6. Exhaust filtration: pre-filter, HEPA, and chemical filter.

Table A4 Features of DED-L production systems using powders in FormAlloy.

	Features
L2 Series	1. Build volume: 250×250×300 mm^3; 2. Deposition rate: Up to 7kg/hr; 3. Laser power up to 8 kW with 2 lasers (Infrared laser and blue laser); 4. Up to 5-axes with 2 heads and 4 feeders; 5. Dust removal/extraction: <5 micron filtration; 6. Inert gas build chamber: <10 ppm oxygen content (L-Series); 7. Some options: Build plate heating; dynamic layer selection; melt pool size monitoring & control; melt pool temperature and control; process monitoring
X5 Series	1. Build volume: 1000×1000×650 mm^3; 2. Deposition rate: Up to 7kg/hr; 3. Laser power up to 8 kW with 2 lasers (Infrered laser and blue laser); 4. Up to 5-axes with 2 heads and 4 feeders; 5. Dust removal/extraction: <5 micron filtration; 6. Some options: Build plate heating; dynamic layer selection; melt pool size monitoring & control; melt pool temperature and control; process monitoring;

Table A5 Features of DED-L production systems using powders in DMG MORI.

	Features
LASERTEC 65 DED	1. Strokes of X,Y, and Z: 735×650×560 mm^3; 2. Laser power: 2500 W; 3. Laser head integrated in the headstock for high building volume; 4. 5-axis with homogeneous powder distribution; 5. Integrated thermal imaging camera for observation of the whole working area, adapive process control and constant monitoring of the working distance; 6. Powder feed rate sensor and automatic powder calibration; 7. AM Evaluator for visualisation of the relevant process data (e. g. meltpool size, powder mass flow) as a digital 3D-model; 8. Siemens NX: Hybride CAD/CAM-Module for additive and subtractive programming;
LASERTEC 65 DED hybrid	Based on LASERTEC 65 DED, there are some functions added: 1. Laser power increases to 3000 W; 2. Combination of additive and milling machining process for 3D-parts in finished quality; 3. The laser head is handled by a fully automatic shuttle-without manual intervention;

	4. Full 5-axis milling machine;
LASERTEC 125 DED hybrid	Based on LASERTEC 65 DED hybrid, there are some functions added: 1. Strokes of X,Y, and Z increase to: 1335×1250×900 mm^3, and A-axis: +120°/-120, C-axis 360° endless; 2. Fiber-guided diode laser with 3,000 W power and 600 µm fiber diameter; 3. Combination of additive and milling machining process for 3D-parts in finished quality: Powerful motor spindles up to a maximum of 20,000 rpm, A-axis: + 120°/-120°, C-axis 360° endless; 4. Comprehensive cooling measures, powerful cooling unit and multi-sensor compensation as standard.
LASERTEC 3000 DED hybrid	Based on LASERTEC 125 DED hybrid, there are some functions added: 1. Strokes of X,Y, and Z changes to: 675×600×1562 mm^3, Large parts up to ø 670 × 932 mm (at B-axis 180°) or up to ø 400 × 1,321 mm (at B-axis 90°); 2. Additive Manufacturing of metals and reactive materials.
LASERTEC 6600 DED hybrid	1. Hybrid of metal additive manufacturing technology and subtractive machining: linear axes (X-, Y-, and Z-axis), B-axis (turn-mill spindle), C-axis; Turn-Mill spindle equipped with the AM head and AM nozzle; 2. Strokes of X,Y, and Z changes to: 1040×610×3890 mm^3, Largest workpiece size: Φ1,010 mm × 3,702 mm; 3. Laser output: 2,000 W(standard), <4,000/6,000/8,000 W(option)>; 4. Synchronized operation of Left spindle and Right spindle that transfers workpieces between the two spindles to achieve streamlined additive manufacturing processes; 5. Movable and high-performance dust collection duct; 6. Zero Sludge Coolant Tank; 7. Laser sensor installed on the machine cover and window.

Table A6 Features of DED-L production systems using powders in InssTek.

	Features
MX-Lab	1. 500 W (Ytterbium Fiber Laser); 2. 150×150×150 cm^3; 3. CVM powder feeding system-6 hoppers with precision feeding rate control (0.03-2 g/min); 4. DMT® Closed-Loop Feedback Control system (analyzing and controlling the height of the meltpool in real-time); 5. Atmosphere Control System.
MX-Fab	1. 500×600×400 cm^3 (MX-Fab1)/800×1000×700 cm^3 (MX-Fab3); 2. (A/C): ±100°/360°; 3. Laser power: 1000 W (Max. 2000 W) for MX-Fab1, 2000 W for MX-Fab3; 4. Beam diameter: 800/1200/1600/2400 µm; 5. CVM powder feeding system-2 set (6 hoppers with precision feeding rate control: 0.05-20 g/min); 6. DMT® Closed-Loop Feedback Control system (analyzing and controlling the height of the meltpool in real-time); 7. Atmosphere Control System.

Table A7 Features of DED-L production systems using powders in Nanjing Zhongke Raycham Laser Technology Co., Ltd.

	Features
LDM4030	1. Build volume: 400×400×400 mm^3; 2. Fiber laser (1 kW)/Blue Laser(2 kW); 3. Oxygen and water content: ≤50ppm.
LDM8060	1. Build volume: 800×600×900 mm^3; 2. Fiber laser (2kW)/Semiconductor laser (4kW);

	3. Oxygen and water Content: ≤50ppm.
LDM1500	1. Build volume: 1500×1000×1000 mm^3; 2. Fiber laser (4kW)/Semiconductor laser (6kW); 3. Oxygen and water content: ≤50ppm.
LDM2500	1. Build volume: 2500×2500×1500 mm^3; 2. Fiber laser (8kW)/Semiconductor Laser (10kW); 3. Oxygen and water content: ≤50ppm.

Table A8 Features of WAAM production systems in Nanjing Zhongke Raycham Laser Technology Co., Ltd.

	Features
WAAM1500	1. Build dimension: 1500×1500×1000 mm^3; 2. Dual-axis rotary table; 3. Oxygen content ≤50 ppm; 4. Power supply type: TIG/MIG (TIG current 5-700A/MIG power supply 3-400A).
WAAM2500	1. Build dimension: 2500×2500×1500 mm^3; 2. Dual-axis rotary table; 3. Oxygen content ≤50 ppm; 4. Power supply type: TIG/MIG (TIG current 5-700A/MIG power supply 3-400A).
Additive & Subtractive Hybrid Manufacturing	1. Build dimension: Diameter2000 mm×1000 mm; 2. Arc Additive Manufacturing System (Maximum Additive Forming Efficiency: 900cm^3/h; Welding Current Range: MIG/MAG3-400A; Welding Rod: 10-400A); 3. Laser Powder Feeding 3D Printing System (Forming Efficiency: 120-350 cm^3/h; Laser Power: 4-10kW; Powder Utilization Rate: 70%--80%); 4. Subtractive Processing System (Milling Spindle Rated Power(S1/S6): 8.5/10kW; Milling Spindle Rated Torque(S1/S6): 6.7/8 N/m; Subtractive Tool Magazine Capacity: 6 tools).

Note that "Additive & Subtractive Hybrid Manufacturing" includes DED-L & WAAM integrated production system.

Table A9 Features of DED-L & WAAM integrated production systems in Mazak.

	Features
VARIAXIS J-600/5X AM	1. Combining 5-axis machining center with laser metal deposition and wire arc; 2. DED-L: Diode laser of 1.0 kW, 2.0 kW, 4.0 kW, 6.0 kW with metal powders; 3. WAAM: Type of arc: MIG, Max. current: 300 A with metal wire Φ1.0 mm (Φ0.04") or Φ1.2 mm (Φ0.05").

Table A10 Features of wire-fed production systems with laser beam in Evobeam GmbH.

	Features
WiLaVAM Wire-feed Laser	1. Compact design with vacuum chamber; 2. Pre-vacuum avoids pores and is sufficient for steels; 3. Hard-vacuum for TiAl, refractory metals and super-alloys available; 4. Fiber laser incl. Scanner or Wobbler; 5. Optics protected against metal vapor and thermal radiation; 6. Variable focusing system optional; 7. CNC-controlled in vacuum wire-feed system; 8. Thermal camera (1 kHz) for process control.

Table A11 Features of wire-fed production systems with electron beam in Sciaky, Inc.

	Features
The EBAM® 300 System	1. Chamber Dimensions 300” (7620 mm)×108” (2743 mm)×132” (3353 mm); 2. Work Envelope–228” (5791 mm) wide×48” (1219 mm) deep×48” (1219 mm) high; 2. High efficiency pumping–chamber hard vacuum (1×10^{-4} Torr); 3. Power level up to 42 kW–60 kV; 4. Internal boom mounted gun with high resolution optics & servo gun tilt axis; 5. X, Y & Z servo axes with multiple part positioner & dual wirefeed options; 6. CNC control–joint scanning and digitizing system; 7. Wirefeed with motorized wire nozzle; 8. Closed-loop control (CLC) technology; 9. The largest build envelope in the market for large metal part production.
The EBAM® 200 System	1. Chamber dimensions: 200" (5080 mm)×110" (2794 mm)×110" (2794 mm); 2. Build envelope: 160" (4064 mm) wide×47" (1194 mm) deep×60" (1524 mm) high; 3. High efficiency pumping (up to 1×10^{-5} Torr ultimate vacuum pressure); 4. Power level up to 42 kW–60 kV; 5. Internal boom mounted gun with high resolution optics & servo gun tilt axis; 6. X, Y & Z servo axes with multiple part positioner options; 7. CNC control: Joint scanning and digitizing system; 8. Wirefeed with motorized wire nozzle-dual wirefeed optional; 9. Electron beam additive manufacturing (EBAM®) package with IRISS® Closed-Loop Control (CLC); 10. one of the largest Additive Manufacturing systems on the market
The EBAM®150 System	1. Chamber dimensions 150” (3810 mm)×150” (3810 mm)×120” (3048 mm); 2. Work Envelope–110” (2794 mm) wide×62” (1575 mm) deep×62” (1575 mm) high; 3. High fffficiency pumping–chamber hard vacuum (1×10^{-4} Torr); 4. Power level up to 42 kW–60 kV; 5. Internal boom mounted gun with High resolution optics & servo gun tilt axis; 6. X, Y & Z servo axes with multiple part positioner & dual wirefeed Options; 7. CNC control–joint scanning and digitizing system; 8. Wirefeed with motorized wire nozzle; 9. Closed-loop control (CLC) technology;
The EBAM® 110 System	1. Chamber dimensions 110” (2794 mm) ×110” (2794 mm)×110” (2794 mm); 2. Work Envelope–70” (1778 mm) wide×47” (1194 mm) deep×63” (1600 mm) high; 3. High efficiency pumping–chamber hard vacuum (1×10^{-4} Torr); 4. Power level up to 42 kW–60 kV; 5. Internal boom mounted gun with high resolution optics & servo gun tilt axis; 6. X, Y & Z servo axes with multiple part positioner options; 7. CNC control–joint scanning and digitizing system; 8. Wirefeed with motorized wire nozzle; 9. Closed-loop control (CLC) technology.
The EBAM® 53 System	1. Chamber dimensions: 53” (1346 mm) ×53” (1346 mm)×72” (1880 mm); 2. Build Envelope: 26” (635mm) wide×26” (635 mm) deep×26” (635 mm) high; 3. High efficiency pumping (up to 1×10^{-5} Torr ultimate vacuum pressure); 4. Power level up to 42 kW–60 kV; 5. Internal boom mounted gun with high resolution optics & servo gun tilt axis; 6. X, Y & Z servo axes with multiple part positioner options; 7. CNC control: Joint scanning and digitizing system; 8. Wirefeed with motorized wire nozzle - dual wirefeed optional; 9. Electron beam additive manufacturing (EBAM®) package with IRISS® closed-loop control (CLC); 10. The ideal platform for materials research laboratory settings.

Table A12 Features of WAAM production systems in WAAM.

	Features
RoboWAAM	Hardware: 1. Motion axes: 6+2; 2. Power source: CMT/PTA; 3. Local shielding (global option); 4. Wire position system (Electronic/automatic); 5. Fume management system™; 6. Process camera; 7. Process monitoring (Position travel speed, arc voltage, arc current, wire position, layer height and 3D profile, lead and trail temperature, oxygen Gas flows); Software: 8. WAAMPlanner (Turns your part's preform into executable RoboWAAM code); 9. WAAMKeys (Eliminates defects and keeps the layer height); 10. WAAMSim (Process simulation); 11. WAAMCtrl (an all-encompassing operating system)

Table A13 Features of WAAM production systems using plasma in Norsk Titanium AS.

	Features
MERKE IV®	1. Rapid plasma deposition; 2. Part build size: 900mm× 600mm×300mm; 3. Layer dimensions: H = 3–4 mm; W = 8–12 mm; 4. Deposition rate: 5–10 kg/hour 5. Titanium, nickel alloys, tool steel, stainless steel are all applicable to the RPD platform.

Table A14 Features of WAAM production systems using plasma in Gefertec GmbH.

	Features
arc40X	1. 3-axis machining: Production of metallic components up to 0.72 m³ with a maximum mass of 800 kg; 2. 5-axis machining: Production of metallic components up to 0.06 m³ with a maximum mass of 200 kg.
arc60X	1. 3-axis machining: Production of metallic components up to 3.0 m³ with a maximum mass of 3000 kg; 2. 5-axis machining: Production of metallic components up to 0.8 m³ with a maximum mass of 500 kg.
arc80X	1. 3-axis machining: Production of metallic components up to 8.0 m^3 with a maximum mass of 8000 kg; 2. 5-axis machining: Production of metallic components up to 1.1 m^3 with a maximum mass of 500 kg.

References

[1] C. Tan, F. Weng, S. Sui, Y. Chew, G. Bi, Progress and perspectives in laser additive manufacturing of key aeroengine materials, *International Journal of Machine Tools and Manufacture*, 170 (2021) 103804.

[2] C. Atwood, M. Griffith, L. Harwell, E. Schlienger, M. Ensz, J. Smugeresky, T. Romero, D. Greene, D. Reckaway, Laser engineered net shaping (LENS™): A tool for direct fabrication of metal parts, *ICALEO® '98: Proceedings of the Laser Materials Processing Conference*, (1998) 1-7.
[3] Y.M. Ren, X. Lin, X. Fu, H. Tan, J. Chen, W.D. Huang, Microstructure and deformation behavior of Ti-6Al-4V alloy by high-power laser solid forming, *Acta Materialia*, 132 (2017) 82-95.
[4] S.H. M Gäumann, F Cléton, J.-D Wagnière, W Kurz, Epitaxial laser metal forming: analysis of microstructure formation, *Materials Science and Engineering: A*, 271 (1999) 232-241.
[5] ASTM F2792-12a, Standard Terminology for Additive Manufacturing Technologies (Withdrawn 2015), ASTM International, West Conshohocken, PA, 2012.
[6] D. Svetlizky, M. Das, B. Zheng, A.L. Vyatskikh, S. Bose, A. Bandyopadhyay, J.M. Schoenung, E.J. Lavernia, N. Eliaz, Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications, *Materials Today*, 49 (2021) 271-295.