Supplementary Information

Multi-objective low-carbon optimization of process parameters for high-power laser directed energy deposition of titanium alloys

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Table S1 Regional grid electricity carbon emission factor

Power grid	North	**Northeast**	East	Central	Northwest	South
C_e ($kgCO_2/kWh$)	0.7120	**0.6012**	0.5992	0.5354	0.5951	0.4326

Table S2 Chemical composition of substrate and powders

Elements	Al (wt%)	V (wt%)	Fe (wt%)	C (wt%)	O (wt%)	N (wt%)	H (wt%)	Ti (wt%)
Powder	6.2	4.2	0.12	0.01	0.13	0.01	0.002	Bal
Substrate	5.7	3.8	0.30	0.10	0.20	0.04	0.015	Bal

Table S3 Process parameters of each experiment

Parameters	Value	Parameters	Value
P_{lin} (W)	3500–4300	T_{rt} (min)	6
V_f (mm/min)	300–2700	T_p (s)	5
V_p (r/min)	1–9	T_{ls} (s)	60
D (mm)	4	ΔT (K)	2
α (%)	30–40	V_c (L/min)	100
β (%)	10–30	ρ (kg/m^3)	1×10^3
L (mm)	80	c ($J \cdot kg^{-1} \cdot ℃^{-1}$)	4.2×10^3

Table S4 Subsystem operational state

Operating state	Laser	Chiller	Robot	Powder	Auxiliary
Opening equipment	Standby	Running	Standby	Standby	Running
Robot upping	Standby	Running	Running	Standby	Running
Deposition process	Running	Running	Running	Running	Running
Robot downing	Standby	Running	Running	Standby	Running
Closing equipment	Closing	Closing	Closing	Closing	Closing

Table S5 Rotation speed of powder pan corresponds to real-time powder feeding amount

V_p (r/min)	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5
M (g/min)	9.27	10.56	11.68	13.00	13.73	15.04	16.61	17.47	18.52	20.58	21.73

Table S6 Analysis of actual and projected carbon emissions

No	P_{lin}	V_f	V_p	η		φ		γ	
				Actual value	Predicted value	Actual value	Predicted value	Actual value	Predicted value
1	3700	35	7	32.97	32.77	157.94	156.01	3.81	3.88
2	4100	35	3	38.12	37.42	89.41	89.07	7.57	7.64
3	3900	25	5	39.09	37.97	135.65	133.51	4.23	4.29
4	4100	15	7	37.98	38.21	183.66	182.95	2.54	2.62
5	3700	15	3	44.91	45.39	83.78	82.07	4.85	4.93
6	3900	25	5	37.68	37.97	134.15	133.51	4.20	4.29
7	4226	25	5	36.04	35.58	137.16	136.84	4.16	4.23
8	3900	25	8.26	42.00	41.71	192.9	188.49	2.81	2.89
9	3900	25	5	37.95	37.97	134.98	133.51	4.20	4.29
10	3900	8.7	5	55.00	53.39	148.31	146.78	2.49	2.56
11	3900	41.3	5	29.91	31.24	129.23	127.71	5.56	5.64
12	3574	25	5	27.92	27.99	128.42	125.99	4.03	4.11
13	3900	25	1.74	65.83	66.03	50.64	49.12	11.75	11.83
14	3900	25	5	38.9	37.97	135.3	133.51	4.23	4.29
15	3700	35	3	34.99	34.48	84.47	81.88	7.45	7.53
16	3700	15	7	40.00	40.08	175.51	175.77	2.30	2.36
17	4100	35	7	27.99	27.37	164.19	163.2	3.93	4.00
18	3900	25	5	37.95	37.97	135.04	133.51	4.19	4.29
19	3900	25	5	38.9	37.97	135.1	133.51	4.21	4.29
20	4100	15	3	62.93	62.73	90.49	89.26	5.13	5.19

Table S7 Experimental results of signal-to-noise ratio for I-NSGA-III algorithm

maxFE	N	Runtime	GD	HV	IGD	Spacing	Spread
5000	100	0.2813	0.0818	0.2133	1.2898	0.7629	1.0600
5000	200	0.2445	0.0577	0.2133	0.6272	0.3744	0.9309
5000	300	0.2308	0.0484	0.2149	0.4241	0.2806	0.9382
5000	400	0.2552	0.0438	0.2137	0.3155	0.2455	0.9416
10000	100	0.5727	0.0857	0.2088	1.4434	0.6846	0.9949
10000	200	0.4433	0.0593	0.2070	0.5208	0.3647	0.8984
10000	300	0.3972	0.0484	0.2092	0.3143	0.2509	0.9601
10000	400	0.4694	0.0419	0.2084	0.2406	0.2229	0.9773
15000	100	0.9285	0.0909	0.2093	1.1868	0.6415	0.9620
15000	200	0.6133	0.0614	0.2021	0.4378	0.3311	0.9138
15000	300	0.5765	0.0496	0.2044	0.2889	0.2802	0.9334
15000	400	0.7322	0.0430	0.2058	0.2161	0.2034	0.9265
20000	100	1.1825	0.0822	0.2092	1.1406	0.6721	0.9785
20000	200	0.8275	0.0587	0.2012	0.5128	0.3610	0.9628
20000	300	0.7468	0.0466	0.2044	0.2554	0.2373	0.9284
20000	400	0.9251	0.0416	0.2056	0.2050	0.2174	0.9595

Table S8 Evolution result

Level-1	Level-2	1	2	3	4	5	6	7	8	9	10	11
Carbon emissions	Intensity	86	75	90	78	82	77	80	85	89	82	88
	Footprint	92	85	85	86	76	84	82	78	80	78	78
	Environment	83	80	90	85	80	88	87	90	88	89	86
Powder utilization	Equipment	75	80	80	82	72	82	79	88	83	84	80
	Recycle	89	70	75	78	84	86	85	82	85	86	84
Deposition efficiency	Production	82	75	85	84	76	83	80	76	80	77	75
	Time	80	60	68	74	85	87	81	79	82	76	84
	Cost	91	85	55	87	89	83	90	88	87	88	91