Laser Powder Bed Fusion

Subjects: Ergonomics

Contributor: Eleonora Santecchia , Stefano Spigarelli , Marcello Cabibbo

Laser powder bed fusion (LPBF) is the most used metal additive manufacturing technique, and it is based on the efficient interaction between a high-energy laser and a metal powder feedstock. The reuse of the powder feedstock is crucial to make the process cost-efficient and environmentally friendly. However, since studies of the mechanical and microstructural properties of parts produced with reused powders show scattered results, a closer look to the powder, heat source and shielding gas properties and to how they interact during the LPBF process is presented.

laser radiation metal powder additive manufacturing LPBF spatter condensate

1. The LPBF Process

The powder bed is a layer of powder characterized by a packing density (which depends on the arrangement of the particles and the unfilled areas between them), which is then subjected to the action of the laser, which melts the requested areas of the bed. The remaining unmelted powder serves, layer-upon-layer, as additional support to the part under construction, and some areas of the bed close to the laser action can be heated several times during the overall process performed to obtain a 3D object.

The interaction between the metal powder and the laser radiation during the process is associated with energy deposition following the powder coupling (absorption of radiation by metal particles, which appear as gray bodies due to their morphology) and bulk coupling (absorption of radiation by a metallic surface, related to the intrinsic properties of the considered metal) mechanisms [1][2]. The optical penetration is often evaluated comparing the powder bed to a bulk, but this is not completely right. The interaction with particles can, indeed, generate multiple reflections [3][4], which enhance the penetration depth of the laser. Since the action of the laser is very short in time and characterized by a very high energy (resulting cooling rates of about ~10^5–10^6 K/s [5]), evaporation and melting of the exposed powder particles can easily occur [6][7].

In addition to studying the full LPBF process to realize parts and samples for tensile and fatigue tests, single-track experiments are extensively used to understand the powder–laser interaction [8][9][10][11]. These experiments allow highlighting the presence of stability zones, where the track is continuous, and instability zones, whose irregularities (i.e., distortions, balling) are highly dependent on the scanning speed values, on the laser power, on the thickness of the powder layer and the substrate material on which it is spread, and on the powder particle morphology and granulometry [12][2][6][8][13][14][15].

2. Powder Feedstock Features

The quality of samples and parts built with laser powder bed fusion is strongly influenced by the properties of the metal powders particles themselves [16][17][18], as also outlined by official regulation agencies such as ASTM (ASTMF2924-14 [19]). Granulometry, flowability, particle size, density, and chemical composition are among the most crucial properties which are typically checked before processing the selected powder [7][20][21][22][23][24].

The quality and properties of the feedstock materials depend a lot on the manufacturing process, which, in the case of metal powders for LPBF, can be quite varied [25][26][27][28][29][30][31], ranging from rotary, water, and gas atomization [30][31][32][33][34] to the plasma rotating electrode process (PREP) [35][36]. Furthermore, in order to make the additive manufacturing process more cost-efficient and to reduce the price of the feedstock, the reuse of scraps and chips produced by traditional manufacturing of expensive metals and alloys (i.e., Ti-6Al-4V, aluminum) was proposed via spheroidization [37][38] and milling [39][40].

The literature shows that powder recycling, when referring to the LPBF process, can be done in a variety of ways [41][42], ranging from the reintroduction of sieved powder after each build and adding the used and sieved powder together with the virgin one with or without mixing, to the mixing of used powder with powder of the same age after each cycle (defined as the number of jobs after which the amount of feedstock in not enough to perform further jobs). According to literature, the first two procedures seem to be the most used [19][43][44][45][46]. Denti et al. [16] recently suggested a parameter called “average usage time” (AUT) to account for the real duration of laser–powder interaction, instead of the number of jobs performed, which could be widely adopted as a reliable method to evaluate the level of interaction. Modifications of powder properties with reuse in LPBF are highly influenced by the starting material, the process parameters, and the environment inside the build chamber. In the case of highly reactive powders (i.e., Al- and Ti-based powders), even the storage and handling conditions might affect the quality of the powder [47].

What is most striking from the results of studies performed on many different alloys (stainless steels, Ti-6Al-4V, Alsi10Mg, IN718 and IN625, Co–Cr, Scalmalloy) [19][16][48][22][47][49][50][51][52][53][54], in terms of reused powder characterization and, most importantly, of the microstructural and mechanical properties of the final parts, is that, while the former are quite similar for the same alloy, the latter are characterized by very scattered results [42]. Mechanical properties could be improved, decreased, or unaffected by the reuse of feedstock material, as shown by the results reported in Table 1. This result suggests that more attention should be paid to what really happens inside the chamber during the laser–powder interaction and not only to the metal powder quality itself.

Table 1. Summary of studies on powder recycling (IED—input energy density, UTS—ultimate tensile strength, ND —not determined).

Material	Reuse Times (Max)	Reuse Strategy	IED (Linear)	Tensile Properties (UTS)	Charpy	Fatigue Life	Reference

			(P/v) (J/m)				
Ti-6Al-4V	12	Sieving	ND	Virgin: 1030 MPa Reused: up to 1101 MPa but plateau at 1072 from 6 to 12 reuses	ND	ND	[44]
Ti-6Al-4V	31	Powder sampled from trap capsules (double cone shape); sieving	ND	Virgin: 984.3 ± 0.6 Reused: 1002.7 ± 1.2 (all samples subjected to hot isostatic pressing)	ND	ND	[51]
Ti-6Al-4V	15	Sieving	233.3	Comparable	ND	No differences in as-built condition Longer life with the reused powder at a strain of 0.004 mm/mm with machined surface condition	[53]

Ti-6Al-4V	ND	Sieving	ND	Comparable	Decrease with reuse	ND	[43]
Ti-6Al-4V	100	Addition of virgin powder when needed	233.3	Scattered results but no decrease (stress relieved samples)	ND	ND	[16]
IN718	14	Sieving and drying	ND	ND	Variations with the number of reuses but no clear trend	ND	[19]
IN718	10	Sieving	ND	Consistent from build to build (samples were stress-relieved, hot isostatically pressed, solution-treated, and aged)	ND	Comparable low cycle fatigue	[55]
AlSi10Mg	1	Sieving	284.6	Comparable	ND	ND	[49]
AlSi10Mg	1	Sieving	284.6	Comparable	ND	ND	[54]
AlSi10Mg	8	Sieving	ND	Decrease with reuse	ND	High cycle fatigue	[46]

						decreases with reuse	
AlSi10Mg	18	Sieving	284.6	No effects	ND	ND	[45]
17-4 PH	1	Sieving	237.5	Similar trend for spatter-rich and non-spatter-rich samples. Abrupt failure for spatter-rich samples and 5% lower ductility	ND	ND	[56]
17-4 PH	10	Sieving	243.7	Similar UTS but failure strain of print 10 parts decreased by ~7%.	ND	ND	[57]

3. Heat Source

The interaction between metal power particles and laser radiation during LPBF is quite complex and includes a number of physical phenomena, such as chemical reactions and phase transformation, heat transfer, and a complex fluid flow within the melt pool due to the surface-tension gradient, as well as absorption and scattering of the laser radiation [26]. The high-energy solid-state lasers typically employed in LPBF have an axisymmetric Gaussian profile of the power density distribution, with beam diameters between 50 and 100 µm for fine resolution, and an intensity which decreases upon penetration through the powder layers deposited on top of each other [1][8][58], since the radiation also penetrates through the pores between the particles in the bed.

The connection between the shape of the laser beam profile and the melt pool was extensively studied in the literature [11][59][60]. Furthermore, the top-hat shape employed in laser welding [61] was shown to produce keyholes having a shorter depth and, for this reason, Tenbrock et al. [62] recently applied this profile in laser powder bed fusion of 316 L stainless steel, showing that an efficient LPBF processes can also be realized by applying diode lasers as long as a proper defined intensity threshold is exceeded ($I \approx 8–10 \times 10^5$ W/cm^2 [62]).

The use of ultrafast lasers (i.e., femtosecond lasers) is also under study since they could allow processing metal and alloys with high melting temperatures and thermal conductivity (i.e., rhenium) and ceramics [63][64].

4. Shielding Gas Flow

The laser powder bed fusion process is always performed under inert atmosphere, in order to avoid any possible interaction between the metal particles (very reactive with a high specific surface area) and impurities such as humidity and light elements (i.e., oxygen, carbon oxides), which might affect the local chemical composition and the resulting mechanical properties of the manufactured parts [26][42][22]. Furthermore, a continuous flow of inert gas is essential in order to limit the redeposition on the powder bed of by-products during the process; this is crucial because should the removal of by-products by the shielding gas flow not be effective, there is a high risk of laser attenuation [65][66][67]. Owing to the formation of metal vapor plume during the laser–powder interaction, the incident laser energy could be absorbed partially. These effects were particularly studied by Grünberger and Domröse [68], who generated the so-called splashy process by changing the focal position of the laser and concluded that a proper gas flow rate is mandatory in order to avoid the occurrence of this phenomenon, since, in areas of the build chamber where the local gas flow velocity is slow, there is a higher beam scattering. The gas flow in the process chamber was found to be a crucial parameter to limit the presence of defects in parts obtained by laser powder bed fusion [65][69].

The most used inert gases are argon and nitrogen, although, in the case of highly reactive materials prone to nitride formation, Ar is the only available option [70]. However, Pauzon et al. [71] recently studied combinations of Ar and He to process Ti-6Al-4V, and their results showed improved cooling rates and an impressively higher build rate (up to 40%).

References

1. P. Fischer; Valerio Romano; H.P. Weber; N.P. Karapatis; E. Boillat; R. Glardon; Sintering of commercially pure titanium powder with a Nd:YAG laser source. *Acta Materialia* **2003**, *51*, 1651-1662, 10.1016/s1359-6454(02)00567-0.
2. Abdolreza Simchi; Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features. *Materials Science and Engineering: A* **2006**, *428*, 148-158, 10.1016/j.msea.2006.04.117.
3. Von Allmen, M.F.; Blatter, A. Laser-Beam Interactions with Materials; Springer: Berlin, Germany, 1994.

4. Slavin, A.J.; Arcas, V.; Greenhalgh, C.A.; Irvine, E.R.; Marshall, D.B. Theoretical model for the thermal conductivity of apacked bed of solid spheroids in the presence of a static gas with no adjustable parameters except pressure and temperature. Int. J. Heat Mass Transf. 2002, 45, 4151–4161.
5. Starke, E.J.; Fine, M.E. Rapidly Solidified Powder Aluminum Alloys; ASTM: West Conshohocken, PA, USA, 1986.
6. J.P. Kruth; L. Froyen; J. Van Vaerenbergh; P. Mercelis; M. Rombouts; B. Lauwers; Selective laser melting of iron-based powder. *Journal of Materials Processing Technology* **2004**, *149*, 616-622, 10.1016/j.jmatprotec.2003.11.051.
7. Rainer J. Hebert; Viewpoint: metallurgical aspects of powder bed metal additive manufacturing. *Journal of Materials Science* **2015**, *51*, 1165-1175, 10.1007/s10853-015-9479-x.
8. Igor Yadroitsev; I. Smurov; Selective laser melting technology: From the single laser melted track stability to 3D parts of complex shape. *Physics Procedia* **2010**, *5*, 551-560, 10.1016/j.phpro.2010.08.083.
9. Alberta Aversa; Mandanà Moshiri; Erica Librera; Mehdi Hadi; Giulio Marchese; Diego Manfredi; Massimo Lorusso; Flaviana Calignano; Sara Biamino; Mariangela Lombardi; Matteo Pavese; Single scan track analyses on aluminium based powders. *Journal of Materials Processing Technology* **2018**, *255*, 17-25, 10.1016/j.jmatprotec.2017.11.055.
10. Subin Shrestha; Kevin Chou; Single track scanning experiment in laser powder bed fusion process. *Procedia Manufacturing* **2018**, *26*, 857-864, 10.1016/j.promfg.2018.07.110.
11. Nkutwane Washington Makoana; Ina Yadroitsava; Hein Moller; Igor Yadroitsev; Characterization of 17-4PH Single Tracks Produced at Different Parametric Conditions towards Increased Productivity of LPBF Systems—The Effect of Laser Power and Spot Size Upscaling. *Metals* **2018**, *8*, 475, 10.3390/met8070475.
12. Valérie Gunenthiram; Patrice Peyre; Matthieu Schneider; Morgan Dal; Frédéric Coste; Rémy Fabbro; Analysis of laser–melt pool–powder bed interaction during the selective laser melting of a stainless steel. *Journal of Laser Applications* **2017**, *29*, 22303, 10.2351/1.4983259.
13. Abdolreza Simchi; The role of particle size on the laser sintering of iron powder. *Metallurgical and Materials Transactions B* **2004**, *35*, 937-948, 10.1007/s11663-004-0088-3.
14. Igor Yadroitsev; Philippe Bertrand; I. Yu. Smurov; Parametric analysis of selective laser melting technology. *International Congress on Applications of Lasers & Electro-Optics* **2006**, *2006*, 1805, 10.2351/1.5060792.
15. Kamran Aamir Mumtaz; Poonjolai Erasenthiran; Neil Hopkinson; High density selective laser melting of Waspaloy®. *Journal of Materials Processing Technology* **2008**, *195*, 77-87, 10.1016/j.jmatprotec.2007.04.117.

16. Lucia Denti; Antonella Sola; Silvio Defanti; C. Sciancalepore; Federica Bondioli; Effect of Powder Recycling in Laser-based Powder Bed Fusion of Ti-6Al-4V. *Manufacturing Technology* **2019**, *19*, 190-196, 10.21062/ujep/268.2019/a/1213-2489/mt/19/2/190.
17. David Bricin; Antonin Kriz; Assessment of Usability of WC-Co Powder Mixtures for SLM. *Manufacturing Technology* **2018**, *18*, 719-726, 10.21062/ujep/166.2018/a/1213-2489/mt/18/5/719.
18. XiaoMing Zhao; Jing Chen; Xin Lin; Weidong Huang; Study on microstructure and mechanical properties of laser rapid forming Inconel 718. *Materials Science and Engineering: A* **2008**, *478*, 119-124, 10.1016/j.msea.2007.05.079.
19. L.C. Ardila; F. Garciandía; J.B. González-Díaz; P. Alvarez; A. Echeverria; M.M. Petite; R. Deffley; J. Ochoa; Effect of IN718 Recycled Powder Reuse on Properties of Parts Manufactured by Means of Selective Laser Melting. *Physics Procedia* **2014**, *56*, 99-107, 10.1016/j.phpro.2014.08.152.
20. ASTM F2924-14, Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion; ASTM International: West Conshohocken, PA, USA, 2014.
21. William Sames; F. A. List; S. Pannala; Ryan Dehoff; S. Suresh Babu; The metallurgy and processing science of metal additive manufacturing. *International Materials Reviews* **2016**, *61*, 315-360, 10.1080/09506608.2015.1116649.
22. Sreekar Karnati; Frank F. Liou; Joseph W. Newkirk; Characterization of copper–nickel alloys fabricated using laser metal deposition and blended powder feedstocks. *The International Journal of Advanced Manufacturing Technology* **2019**, *103*, 239-250, 10.1007/s00170-019-03553-0.
23. Andrea Claudio Santomaso; P Lazzaro; Paolo Canu; Powder flowability and density ratios: the impact of granules packing. *Chemical Engineering Science* **2003**, *58*, 2857-2874, 10.1016/s0009-2509(03)00137-4.
24. Andrea Gatto; Elena Bassoli; Lucia Denti; Repercussions of powder contamination on the fatigue life of additive manufactured maraging steel. *Additive Manufacturing* **2018**, *24*, 13-19, 10.1016/j.addma.2018.09.004.
25. Mohsen Seifi; Ayman Salem; Jack Beuth; Ola Harrysson; John Lewandowski; Overview of Materials Qualification Needs for Metal Additive Manufacturing. *JOM* **2016**, *68*, 747-764, 10.1007/s11837-015-1810-0.
26. Xi Zhang; Enquan Liang; Metal additive manufacturing in aircraft: current application, opportunities and challenges. *IOP Conference Series: Materials Science and Engineering* **2019**, *493*, 012032, 10.1088/1757-899x/493/1/012032.
27. Jason Dawes; Robert Bowerman; Ross Trepleton; Introduction to the Additive Manufacturing Powder Metallurgy Supply Chain. *Johnson Matthey Technology Review* **2015**, *59*, 243-256, 10.1595/205651315x688686.

28. Gang Chen; S.Y. Zhao; P. Tan; Jian Wang; C.S. Xiang; H.P. Tang; A comparative study of Ti-6Al-4V powders for additive manufacturing by gas atomization, plasma rotating electrode process and plasma atomization. *Powder Technology* **2018**, *333*, 38-46, 10.1016/j.powtec.2018.04.013.
29. Amir Mostafaei; Colleen Hilla; Erica Stevens; Peeyush Nandwana; Amy M. Elliott; Markus Chmielus; Comparison of characterization methods for differently atomized nickel-based alloy 625 powders. *Powder Technology* **2018**, *333*, 180-192, 10.1016/j.powtec.2018.04.014.
30. Ivan Goncharov; Nikolay Razumov; A.O. Silin; Nikolai Ozerskoi; A.I. Shamshurin; Artem Kim; Q.S. Wang; A.A. Popovich; Synthesis of Nb-based powder alloy by mechanical alloying and plasma spheroidization processes for additive manufacturing. *Materials Letters* **2019**, *245*, 188-191, 10.1016/j.matlet.2019.03.014.
31. Chaorun Si; Xingling Tang; Xianjie Zhang; Junbiao Wang; Weichao Wu; Characteristics of 7055Al alloy powders manufactured by gas-solid two-phase atomization: A comparison with gas atomization process. *Materials & Design* **2017**, *118*, 66-74, 10.1016/j.matdes.2017.01.028.
32. E.J. Garboczi; N. Hrabe; Particle shape and size analysis for metal powders used for additive manufacturing: Technique description and application to two gas-atomized and plasma-atomized Ti64 powders. *Additive Manufacturing* **2020**, *31*, 100965, 10.1016/j.addma.2019.100965.
33. Iver E Anderson; Robert L Terpstra; Progress toward gas atomization processing with increased uniformity and control. *Materials Science and Engineering: A* **2002**, *326*, 101-109, 10.1016/s0921-5093(01)01427-7.
34. Vishnu Teja Mantripragada; Sabita Sarkar; Prediction of drop size from liquid film thickness during rotary disc atomization process. *Chemical Engineering Science* **2017**, *158*, 227-233, 10.1016/j.ces.2016.10.027.
35. Y Seki; S Okamoto; H Takigawa; N Kawai; Effect of atomization variables on powder characteristics in the high-pressured water atomization process. *Metal Powder Report* **1990**, *45*, 38-40, 10.1016/s0026-0657(10)80014-1.
36. Chongliang Zhong; Jing Chen; Stefanie Linnenbrink; Andres Gasser; Shang Sui; Reinhart Poprawe; A comparative study of Inconel 718 formed by High Deposition Rate Laser Metal Deposition with GA powder and PREP powder. *Materials & Design* **2016**, *107*, 386-392, 10.1016/j.matdes.2016.06.037.
37. A Ozols; H.R Sirkin; E.E Vicente; Segregation in Stellite powders produced by the plasma rotating electrode process. *Materials Science and Engineering: A* **1999**, *262*, 64-69, 10.1016/s0921-5093(98)01021-1.
38. Wen-Hou Wei; Linzhi Wang; Tian Chen; Xuan-Ming Duan; Wei Li; Study on the flow properties of Ti-6Al-4V powders prepared by radio-frequency plasma spheroidization. *Advanced Powder Technology* **2017**, *28*, 2431-2437, 10.1016/j.apt.2017.06.025.

39. Mustafa Ustundag; Remzi Varol; Comparison of a commercial powder and a powder produced from Ti-6Al-4V chips and their effects on compacts sintered by the sinter-HIP method. *International Journal of Minerals, Metallurgy and Materials* **2019**, *26*, 878-888, 10.1007/s12613-019-1787-8.
40. Amir Mahboubi Soufiani; Fathallah Karimzadeh; Mohammad Hossein Enayati; Arman Mahboubi Soufiani; The effect of type of atmospheric gas on milling behavior of nanostructured Ti6Al4V alloy. *Advanced Powder Technology* **2012**, *23*, 264-267, 10.1016/j.apt.2012.01.003.
41. A. Canakci; T. Varol; A novel method for the production of metal powders without conventional atomization process. *Journal of Cleaner Production* **2015**, *99*, 312-319, 10.1016/j.jclepro.2015.02.090.
42. Silvia Vock; Burghardt Klöden; Alexander Kirchner; Thomas Weißgärber; Bernd Kieback; Powders for powder bed fusion: a review. *Progress in Additive Manufacturing* **2019**, *4*, 383-397, 10.1007/s40964-019-00078-6.
43. Annika Strondl; Ola Lyckfeldt; H. Brodin; U. Ackelid; Characterization and Control of Powder Properties for Additive Manufacturing. *JOM* **2015**, *67*, 549-554, 10.1007/s11837-015-1304-0.
44. V. Seyda; N. Kaufmann; C. Emmelmann; Investigation of Aging Processes of Ti-6Al-4 V Powder Material in Laser Melting. *Physics Procedia* **2012**, *39*, 425-431, 10.1016/j.phpro.2012.10.057.
45. Ahmed Maamoun; Mohamed Elbestawi; Goulnara K. Dosbaeva; Stephen C. Veldhuis; Thermal post-processing of AlSi10Mg parts produced by Selective Laser Melting using recycled powder. *Additive Manufacturing* **2018**, *21*, 234-247, 10.1016/j.addma.2018.03.014.
46. Francesco Del Re; V. Contaldi; A. Astarita; Biagio Palumbo; A. Squillace; P. Corrado; P. Di Petta; Statistical approach for assessing the effect of powder reuse on the final quality of AlSi10Mg parts produced by laser powder bed fusion additive manufacturing. *The International Journal of Advanced Manufacturing Technology* **2018**, *97*, 2231-2240, 10.1007/s00170-018-2090-y.
47. Laura Cordova; Mónica Campos; Tiedo Tinga; Revealing the Effects of Powder Reuse for Selective Laser Melting by Powder Characterization. *JOM* **2019**, *71*, 1062-1072, 10.1007/s11837-018-3305-2.
48. Michael J. Heiden; Lisa A. Deibler; Jeff M. Rodelas; Josh R. Koepke; Dan J. Tung; David J. Saiz; Bradley Jared; Evolution of 316L stainless steel feedstock due to laser powder bed fusion process. *Additive Manufacturing* **2019**, *25*, 84-103, 10.1016/j.addma.2018.10.019.
49. Hamed Asgari; Carter Baxter; Keyvan Hosseinkhani; Mohsen Mohammadi; On microstructure and mechanical properties of additively manufactured AlSi10Mg_200C using recycled powder. *Materials Science and Engineering: A* **2017**, *707*, 148-158, 10.1016/j.msea.2017.09.041.
50. Daniel Galicki; F. List; S. Suresh Babu; A. Plotkowski; H. M. Meyer; R. Seals; C. Hayes; Localized Changes of Stainless Steel Powder Characteristics During Selective Laser Melting Additive

Manufacturing. *Metallurgical and Materials Transactions B* **2019**, *50*, 1582-1605, 10.1007/s11661-018-5072-7.

51. Oscar A. Quintana; Jorge Alvarez; Roderick McMillan; Weidong Tong; Charles Tomonto; Effects of Reusing Ti-6Al-4V Powder in a Selective Laser Melting Additive System Operated in an Industrial Setting. *JOM* **2018**, *70*, 1863-1869, 10.1007/s11837-018-3011-0.
52. Marco Simonelli; Chris Tuck; Nesma T Aboulkhair; Ian Maskery; Ian Ashcroft; Ricky D. Wildman; Richard Hague; Christopher Tuck; A Study on the Laser Spatter and the Oxidation Reactions During Selective Laser Melting of 316L Stainless Steel, Al-Si10-Mg, and Ti-6Al-4V. *Metallurgical and Materials Transactions B* **2015**, *46*, 3842-3851, 10.1007/s11661-015-2882-8.
53. Patricio E. Carrion; Arash Soltani-Tehrani; Nam Phan; Nima Shamsaei; Powder Recycling Effects on the Tensile and Fatigue Behavior of Additively Manufactured Ti-6Al-4V Parts. *JOM* **2018**, *71*, 963-973, 10.1007/s11837-018-3248-7.
54. Amir Hadadzadeh; Carter Baxter; Babak Shalchi-Amirkhiz; Mohsen Mohammadi; Strengthening mechanisms in direct metal laser sintered AlSi10Mg: Comparison between virgin and recycled powders. *Additive Manufacturing* **2018**, *23*, 108-120, 10.1016/j.addma.2018.07.014.
55. Brian A. Hann; Powder Reuse and Its Effects on Laser Based Powder Fusion Additive Manufactured Alloy 718. *SAE International Journal of Aerospace* **2016**, *9*, 209-213, 10.4271/2016-01-2071.
56. Usman Ali; Reza Esmaeilizadeh; Farid Ahmed; Dyuti Sarker; Waqas Muhammad; Ali Keshavarzkermani; Yahya Mahmoodkhani; Ehsan Marzbanrad; Ehsan Toyserkani; Identification and characterization of spatter particles and their effect on surface roughness, density and mechanical response of 17-4 PH stainless steel laser powder-bed fusion parts. *Materials Science and Engineering: A* **2019**, *756*, 98-107, 10.1016/j.msea.2019.04.026.
57. Ahmed, F.; Ali, U.; Sarker, D.; Marzbanrad, E.; Choi, K.; Mahmoodkhani, Y.; Toyserkani, E. Study of powder recycling and its effect on printed parts during laser powder-bed fusion of 17-4 PH stainless steel. J. Mater. Process. Technol. 2020, 278, 116522.
58. P. Fischer; N. Karapatis; Valerio Romano; R. Glardon; H.P. Weber; A model for the interaction of near-infrared laser pulses with metal powders in selective laser sintering. *Applied Physics A* **2002**, *74*, 467-474, 10.1007/s003390101139.
59. Gustavo Tapia; Saad Khairallah; Manyalibo Matthews; Wayne E. King; Alaa Elwany; Gaussian process-based surrogate modeling framework for process planning in laser powder-bed fusion additive manufacturing of 316L stainless steel. *The International Journal of Advanced Manufacturing Technology* **2017**, *94*, 3591-3603, 10.1007/s00170-017-1045-z.
60. Jitka Metelkova; Yannis Kinds; Karolien Kempen; Charlotte De Formanoir; Ann Witvrouw; Brecht Van Hooreweder; On the influence of laser defocusing in Selective Laser Melting of 316L.

Additive Manufacturing **2018**, *23*, 161-169, 10.1016/j.addma.2018.08.006.

61. Alexander F.H. Kaplan; Modelling the Primary Impact of an Yb:Fibre Laser Beam Profile on the Keyhole Front. *Physics Procedia* **2011**, *12*, 627-637, 10.1016/j.phpro.2011.03.079.
62. Tenbrock, C.; Fischer, F.G.; Wissenbach, K.; Schleifenbaum, J.H.; Wagenblast, P.; Meiners, W.; Wagner, J. Influence of keyhole and conduction mode melting for top-hat shaped beam profiles in laser powder bed fusion. J. Mater. Process. Technol. 2020, 278, 116514.
63. Bai Nie; Lihmei Yang; Huan Huang; Shuang Bai; Peng Wan; Jian Liu; Femtosecond laser additive manufacturing of iron and tungsten parts. *Applied Physics A* **2015**, *119*, 1075-1080, 10.1007/s00339-015-9070-y.
64. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Compos. Part B 2018, 143, 172–196.
65. Alexander Ladewig; Georg Schlick; Maximilian Fisser; Volker Schulze; Uwe Glatzel; Influence of the shielding gas flow on the removal of process by-products in the selective laser melting process. *Additive Manufacturing* **2016**, *10*, 1-9, 10.1016/j.addma.2016.01.004.
66. P Yu Shcheglov; Andrey Gumenyuk; I B Gornushkin; Michael Rethmeier; V N Petrovskiy; Vapor–plasma plume investigation during high-power fiber laser welding. *Laser Physics* **2012**, *23*, 16001, 10.1088/1054-660x/23/1/016001.
67. Greses, J.; Hilton, P.A.; Barlow, C.Y.; Steen, W.M. Plume attenuation under high power Nd:yttrium-aluminium-garnet laser welding. J. Laser Appl. 2004, 16, 9.
68. Hanqin Tian; Identification and classification of forest landscape pattern: fuzzy modeling and processing of remote sensing image. *Optical Engineering and Photonics in Aerospace Sensing* **1993**, *1941*, 61-67, 10.1117/12.154704.
69. Austin T. Sutton; Caitlin S. Kriewall; Ming C. Leu; Joseph W. Newkirk; Ben Brown; Characterization of laser spatter and condensate generated during the selective laser melting of 304L stainless steel powder. *Additive Manufacturing* **2020**, *31*, 100904, 10.1016/j.addma.2019.100904.
70. Pauzon, C.; Forêt, P.; Hryha, E.; Arunprasad, T. Effect of helium – argon mixtures as laser – powder bed fusion processing atmospheres on the properties of the built Ti-6Al-4V parts. In Proceedings of the WorldPM2018 Congress, Beijing, China, 16–20 September 2018; pp. 1633–1639.
71. Pauzon, C.; Forêt, P.; Hryha, E.; Arunprasad, T.; Nyborg, L. Argon-helium mixtures as Laser-Powder Bed Fusion atmospheres: Towards increased build rate of Ti-6Al-4V. J. Mater. Process. Technol. 2020, 279, 116555.

72. Pauzon, C.; Forêt, P.; Hryha, E.; Arunprasad, T.; Nyborg, L. Argon-helium mixtures as Laser-Powder Bed Fusion atmospheres: Towards increased build rate of Ti-6Al-4V. J. Mater. Process. Technol. 2020, 279, 116555.

Retrieved from https://encyclopedia.pub/entry/history/show/8130