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Trend of Metal 3D Printing by Welding

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Abstract

Metal AM(Additive Manufacturing) has been steadily developed and that is classified into two method. PBF(Powder Bed Fusion) deposited in the bed by the laser or electron beam as a heat source of the powder material and DED(Directed Energy Deposition) deposited by varied heat source of powder and solid filler material. In the developed countries has been applying high productivity process of solid filler metal based DED method to the aerospace and defense sectors. The price of the powder material is quite expensive compared to the solid filler metal. A study on DED method that is based on a solid filler metal is increasing significantly although was low accuracy and degree of freedom.

Key Words : Metal 3D printing, Additive manufacturing, Welding

1. 서 론

3D printing은 CAD로 설계된 부품의 정보를 일정한 두께의 층으로 슬라이싱한 STL파일로 변환 하여 소재를 적층제조하는 공정을 의미하며 AM(Additive manufacturing)이 ASTM의 공식 명칭이다^{1,2)}. 플라스틱 소재를 사용하는 기존의 AM은 소재의 용융점이 약 100~400℃로 낮아 쉽게 만들 수 있었으나, 금속을 사용하는 AM은 용융점이 약 1000~2000℃로 용융 및 적층시키기 위하여 플라스틱 AM과는 달리 상당한 기술이 필요하다. 지난 30년간 RP(Rapid Prototyping)라는 명칭으로 metal AM은 꾸준히 발전해왔으며 분말베드에 고에너지열원인 레이저와 전자빔으로 적층하는 PBF(Powder Bed Fusion)방식으로 가장먼저 개발 적용되었으며, 현재는 소재를 직접 공급하면서 열원으로 용융·적층하는 DED(Directed Energy Deposition)방식의 metal AM

이 연구·적용되고 있다. DED 방식은 분말기반, 고체용가재 기반으로 나뉘며, 선진국에서는 생산성이 높은 고체용가재 기반의 DED방식으로 이미 항공우주, 국방 분야에 먼저 적용하고 있다.

따라서 이 논문은 전반적인 metal AM과 용접에 의한 AM의 연구개발 동향을 알아보고자 한다.

2. Metal AM의 분류

Metal AM의 분류는 Fig. 1과 같이 PBF방식과 DED

Fig. 1 Classification of AM

방식으로 나뉘게 된다. PBF는 분말을 소재로 베드에 분말을 평평하게 분포시킨 후 고에너지의 레이저나 전자빔을 선택적으로 조사하여 소결시키거나 용융시켜 적층하는 방법으로서 형상의 정밀도가 우수하나 생산성이 낮고 적층제품의 소결 및 용융 균일도가 좋지 못하여 제품의 강도와 충격치의 확보가 어려운 단점이 있다. DED는 소재를 직접 공급하면서 고밀도 에너지 열원으로 용융시켜 적층하는 방법으로 용접과 유사하다. DED는 정밀도가 낮아 후가공이 필요한 단점이 있지만, 생산성이 높고 재현반복성이 뛰어나며 강도와 충격치가 높은 장점을 가진다. Fig. 2와 같이 제품의 생산성, 크기, 형상의 정밀도와 해상도에 따라 다양한 metal AM방식이 사용된다³⁾.

이러한 DED방식은 고에너지의 레이저나 전자빔을 이용하여 동축으로 분말을 송급 및 적층하는 분말기반 DED, 용접과 유사하게 고체용가재를 송급하여 다양한 열원으로 용융 및 적층하는 고체용가재 기반 DED로 분류된다.

3. PBF process

Table 1은 metal AM 공정의 적층방식과 소재에 따른 분류이다. PBF는 분말과 레이저열원을 기반으로 하는 독일EOS사에서 SLS(Selective Laser Sintering) 공정을 시작으로 발전하고 있으며, 유럽의 레이저업체에서 대부분의 공정노하우를 가지고 있다. 현재는 용융방식의 SLM(Selective Laser Melting)공정이 주로 레이저 업체에 의해 개발되어지고 있다.

현재 PBF공정은 장치와 소재의 개발에 이어 모니터링 기술이 활발히 연구개발 중이다.

4. DED process

4.1 분말 기반 DED

분말을 기반으로 한 DED방식은 미국의 Optomec에

Fig. 2 Comparison of surface finish and deposition rate between powder-feed/-bed and wire-feed technologies. (a) Titanium 3D-micro framework-structure based on a diamond lattice fabricated using powder bed electron beam melting. (b) A powder-feed-directed light fabrication of 316 stainless steel hemispherical shapes. (c) Three as consolidated powder-feed laser consolidation IN-625 samples with surface roughness $1 - 2 \mu\text{m}$. (d) A large samples fabricated by WAAM from Cranfield University. (e) 2219 Al airfoil produced by wire-feed EBF3. (f) As-deposited sample made by wire-feed LAM (AeroMet) with “stair stepping” surface, and g shows the sample after surface machining³⁾

Table 1 Classification of metal AM process

	Material	Power source	Process	Company	Deposition rate
PBF	Powder based	Laser	SLS(Selective Laser Sintering)	EOS, 3D systems, TPM, Farsoon, etc.	0.1~0.2kg/h
			DMLS(Direct Metal Laser Sintering)	EOS	0.1~0.2kg/h
			SLM(Selective Laser Melting)	SLM Solutions, 3D systems, Realizer, Concept laser, etc.	0.1~0.3kg/h
		Electron beam	EBM(Electron Beam Melting)	ARCAM	0.1~0.2kg/h
DED	Laser	Laser	LENS(Laser Engineered Net Shaping)	Optomec	0.1~2kg/h
			DMD(Direct Metal Deposition)	DM3D	0.1~2kg/h
			DMT(Direct Metal Tooling)	InssTek	0.1~2kg/h
			CLAD(Construction Laser Additive Direct)	BeAM	0.1~2kg/h
	Solid filler based	Electron beam	EBAM(Electron Beam Additive Manufacturing)	Sciaky	~9kg/h
		GTAW, GMAW arc	WAAM(Wire Arc Additive Manufacturing)	Cranfield Univ.	~4kg/h
		GMAW arc	DML(Direct Metal Lamination)	MUTOH	~4kg/h
			ADED(Arc Directed Energy Deposition)	EWI	~4kg/h
		Plasma arc	IFF(Ion Fusion Formation)	Honeywell	~3kg/h
			RPD(Rapid Plasma Deposition)	Norsk titanium	~6kg/h
		GTAW arc	STAM(Super-TIG Additive Manufacturing)	Super-TIG welding	~7kg/h

Fig. 3 (a) Visual inspection system principle and (b) example image of deposited powder bed generated by craeghs et al.⁴⁾

Fig. 4 (a) Schematic showing arrangement of photodiode and camera and (b) an example output from the camera system showing varying intensity values (right) achieved⁵⁾

Fig. 5 DMD experiments - (a) Experimental set-up and associated diagnostics; (b) detail of the laser-powder-melt-pool interaction zone (H = apparent external height of the melt-pool, Δh = additive layer height)⁶⁾

서 동축으로 분말을 공급하면서 레이저를 열원으로 하는 LENS(Laser Engineered Net Shaping)공정을 개발하여 DED의 토대를 마련하였다. 분말 기반의 DED는 레이저업체에 따라 DMD(Direct Metal Deposition), DMT(Direct Metal Tooling)⁷⁾, CLAD(Construction Laser Additive Direct) 등 다양한 이름으로 연구 개발 중이다.

4.2 고체용가재 기반 DED

미국의 NASA Langley lab.에서 개발하여 미국 Sciaky 사로 기술이전된 EBAM(Electron Beam Additive Manufacturing)공정은 진공상태에서 고체용가재를 공급 하여 전자빔으로 용융·적층하는 방식으로 용착속도가 9kg/h로 전 세계에서 가장 높은 생산속도를 가지며 북미지역에서 연구가 활발히 이루어지고 있다⁸⁻¹⁵⁾.

미국의 Nottingham Univ.^{16,17)}, Kentucky Univ.^{18,19)} 등은 GMAW 아크열원을 사용하여 적층경로와 적층 제품의 방향에 따른 기계적 물성을 측정하였다. 영국 Cranfield Univ.에서는 GMAW, GTAW, PAW등의 아크 열원으

로 고체용가재를 공급하는 방식인 WAAM (Wire Arc Additive Manufacturing)을 연구개발 중이다²⁰⁻²⁵⁾. 인도의 IIT(Indian Institute of Technology) Bombay에서는 CMT(Cold Metal Transfer)를 사용하여 CNC와 결합한 metal AM장치를 연구개발 중이다²⁶⁻²⁸⁾. 중국의 Harbin Institute of Technology에서는 GMAW 아크를 열원으로 비전센서를 통한 적층 폭과 높이를 제

Fig. 6 Schematic diagram of the EBAM process¹¹⁾

Fig. 7 Machine experimental set up for (a) SAM edgetek machine (b) ABB robot (c) friction stir welding machine²⁴⁾

Fig. 8 The 3-axis hybrid layered manufacturing machine at IIT Bombay²⁸⁾

Fig. 9 Schematic diagram of the experimental set-up³²⁾

어하는 알고리즘을 만들었으며, 적층 제품의 열응력과 잔류응력을 해석하였고²⁹⁻³³⁾, Jiaotong Univ.³⁴⁾, Shanghai Univ.³⁵⁾ 등에서는 PAW 아크를 열원으로 공정최적화 변수를 연구개발 중이다.

일본의 Osaka Univ.에서는 GTAW의 아크 열원으로 TiAl, TiNi, NiAl 등의 이중재 적층방법에 대하여 연구하였으며³⁶⁻³⁸⁾ Tokyo Univ.에서는 GMAW 아크 열원을 사용한 metal AM 장치를 MUTOH사와 함께 연구 개발하였다³⁹⁾. 독일 EADS에서는 레이저열원에 고체용가재를 공급하는 공정을 주로 연구개발 중이며^{40,41)}, 레이저 열원과 GTAW 열원으로 제작된 제품의 기계적 물성에 대하여 평가하였다⁴²⁾. 벨기에의 Leuven Univ.에서는 고체용가재 기반의 레이저열원 적층방식에서 GTAW 아크로 열원을 변경하여 Ti-6Al-4V 제품의 기계적 물성을 평가하고 있다⁴³⁻⁴⁵⁾.

호주의 Wollongong Univ.에서는 GTAW와 GMAW의 아크를 열원으로 하여 Ti-6Al-4V 제품의 적층경로 최적화 및 적층 후 가공경로 최적화에 관한 연구를 진행 중이다⁴⁶⁻⁵¹⁾.

국내에서는 KIST에서 GMAW의 아크를 열원으로 적층 경로 최적화 및 기계적 물성 평가를 하였고⁵²⁻⁵³⁾, Super-TIG Welding에서 GTAW의 아크를 열원으로 C-fill-

Fig. 10 Schematic drawing of thin-wall deposited by PPAM process³⁵⁾

Fig. 11 Direct metal rapid fabrication machine³⁷⁾

Fig. 12 Automated process planning for robotic WAAM system⁵¹⁾

Fig. 13 STAM at super-TIG welding Co., Ltd.

er⁵⁴⁻⁵⁶⁾를 사용하여 용융·적층하는 공정을 개발하였고⁵⁷⁾, 적층 방향에 따른 기계적 물성을 평가하였고, 공정 최적화를 연구 개발 중이다⁵⁸⁻⁶¹⁾.

5. 결 론

본 리뷰 논문에서는 용접에 의한 metal AM과 관련한 연구동향을 알아보았다. 전 세계적으로 생산성 향상

을 위하여 PBF에서 고체용가재 기반의 DED로 옮겨가는 추세이다. 이는 Ti, Inconel과 같은 특수 분말소재의 가격에 비해 고체용가재가 저렴하고 생산성 또한 고체용가재 기반의 DED가 우수하기 때문이다.

이에 따라 낮은 정밀도와 자유도를 가짐에도 불구하고 고체용가재를 기반으로 하는 DED방식의 공정에 관한 연구가 눈에 띄게 증가하고 있었다.

References

1. ASTM, F2792-12a, Standard Terminology for Additive Manufacturing Technologies
2. Terner, Mathieu. "The Current State, Outcome and Vision of Additive Manufacturing." *Journal of Welding and Joining* (Vol. 33, No. 6) (2015), 12
3. Ding, Donghong, et al., Wire-feed additive manufacturing of metal components, technologies, developments and future interests. *The International Journal of Advanced Manufacturing Technology* 81.1-4 (2015), 465- 481
4. Craeghs, Tom, et al., Online quality control of selective laser melting. *Proceedings of the Solid Freeform Fabrication Symposium, Austin, TX* (2011)
5. Berumen, Sebastian, et al., Quality control of laser-and powder bed-based Additive Manufacturing (AM) technologies. *Physics procedia*, 5(2010), 617-622
6. Gharbi, Myriam, et al., Influence of various process conditions on surface finishes induced by the direct metal deposition laser technique on a Ti-6Al-4V alloy. *Journal of Materials Processing Technology* 213(5) (2013), 791-800
7. Kim, Woosung, et al. "Effects and Application Cases of Injection Molds by using DED type Additive Manufacturing Process." *Journal of Welding and Joining* 32.4 (2014), 348-352
8. Watson, J. K., et al., Development of a prototype low-voltage electron beam freeform fabrication system. (2002)

9. Taminger, Karen, and Robert A. Hafley, Electron beam freeform fabrication, a rapid metal deposition process, (2003)
10. Taminger, Karen M., and Robert A. Hafley, Electron beam freeform fabrication for cost effective near-net shape manufacturing, (2006)
11. Stecker, S., et al., Advanced Electron Beam Free Form Fabrication Methods & Technology, *Session 2* (2006), 12
12. Seufzer, W. J., and K. M. Taminger, Control methods for the electron beam free form fabrication process, *NATIONAL AERONAUTICS AND SPACE ADMIN LANGLEY RESEARCH CENTER HAMPTON VA*, (2007)
13. Mitzner, Scott, et al., Grain refinement of freeform fabricated Ti-6Al-4V alloy using beam/arc modulation, (2012)
14. Fox, Jason, and Jack Beuth, Process mapping of transient melt pool response in wire feed E-beam additive manufacturing of Ti-6Al-4V, *Solid Freeform Fabrication Symposium, Austin, TX*, (2013)
15. Gockel, Joy, Jack Beuth, and Karen Taminger, Integrated control of solidification microstructure and melt pool dimensions in electron beam wire feed additive manufacturing of Ti-6Al-4V, *Additive Manufacturing*, 1 (2014), 119-126
16. Dickens, P. M., et al., Rapid prototyping using 3-D welding, *Proc. Solid Freeform Fabrication Symp.*, (1992)
17. Everton, Sarah K., et al., Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing, *Materials & Design*, (2016)
18. Zhang, Yu Ming, et al., Automated system for welding-based rapid prototyping, *Mechatronics* 12(1) (2002), 37-53
19. Zhang, YuMing, et al., Weld deposition-based rapid prototyping, a preliminary study, *Journal of Materials Processing Technology* 135(2) (2003), 347-357
20. Almeida, P. S., and S. Williams, Innovative process model of Ti-6Al-4V additive layer manufacturing using cold metal transfer (CMT), *Proceedings of the Twenty-first Annual International Solid Freeform Fabrication Symposium, University of Texas at Austin, Austin, TX, USA*. (2010)
21. Ding, J., et al., Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts, *Computational Materials Science* 50(12) (2011), 3315-3322
22. Martina, F., et al., Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V, *Journal of Materials Processing Technology* 212(6) (2012), 1377-1386
23. Zhai, Yun, Early cost estimation for additive manufacture, (2012)
24. Adebayo, Adeyinka, Characterisation of integrated WAAM and machining processes, (2013)
25. Bandari, Yashwanth K., et al., ADDITIVE MANUFACTURE OF LARGE STRUCTURES, ROBOTIC OR CNC SYSTEMS?
26. Karunakaran, K. P., A. Sreenathbabu, and Vishal Pushpa, Hybrid layered manufacturing, direct rapid metal tool-making process, *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture* 218(12) (2004), 1657-1665
27. Akula, Sreenathbabu, and K. P. Karunakaran, Hybrid adaptive layer manufacturing, An Intelligent art of direct metal rapid tooling process, *Robotics and Computer-Integrated Manufacturing*, 22(2) (2006), 113-123
28. Suryakumar, S., et al., Weld bead modeling and process optimization in hybrid layered manufacturing, *Computer-Aided Design*, 43(4) (2011), 331-344
29. Zhao, Huihui, et al., Three-dimensional finite element analysis of thermal stress in single-pass multi-layer weld-based rapid prototyping, *Journal of Materials Processing Technology*, 212(1) (2012), 276-285
30. Xiong, Jun, et al., Vision-sensing and bead width control of a single-bead multi-layer part, material and energy savings in GMAW-based rapid manufacturing, *Journal of Cleaner Production*, 41 (2013), 82-88
31. Xiong, Jun, et al., Modeling of bead section profile and overlapping beads with experimental validation for robotic GMAW-based rapid manufacturing, *Robotics and Computer-Integrated Manufacturing*, 29(2) (2013), 417-423
32. Xiong, Jun, et al., Modeling of bead section profile and overlapping beads with experimental validation for robotic GMAW-based rapid manufacturing, *Robotics and Computer-Integrated Manufacturing*, 29(2) (2013), 417-423
33. Xiong, Jun, et al., Bead geometry prediction for robotic GMAW-based rapid manufacturing through a neural network and a second-order regression analysis, *Journal of Intelligent Manufacturing*, 25(1) (2014), 157-163
34. Aiyiti, Wurikaixi, et al., Investigation of the overlapping parameters of MPAAW-based rapid prototyping, *Rapid Prototyping Journal*, 12(3) (2006), 165-172
35. Lin, J. J., et al., Microstructural evolution and mechanical properties of Ti-6Al-4V wall deposited by pulsed plasma arc additive manufacturing, *Materials & Design*, 102 (2016), 30-40
36. Katou, M., et al., Freeform fabrication of titanium metal and intermetallic alloys by three-dimensional micro welding, *Materials & design*, 28(7) (2007), 2093-2098
37. Horii, Toshihide, Soshu Kiriara, and Yoshinari Miyamoto, Freeform fabrication of Ti-Al alloys by 3D micro-welding, *Intermetallics*, 16(11) (2008), 1245-1249
38. Horii, Toshihide, Soshu Kiriara, and Yoshinari Miyamoto, Freeform fabrication of superalloy objects by 3D micro welding, *Materials & Design*, 30(4) (2009), 1093-1097
39. Keizo, TANAKA, et al., Strength of manufacturing object made by direct metal lamination using arc discharge, *The japan society of mechanical engineers*, 79(800) (2013), 1168-1178

40. Brandl, Erhard, et al., Mechanical properties of additive manufactured titanium (Ti-6Al-4V) blocks deposited by a solid-state laser and wire, *Materials & Design*, 32(10) (2011), 4665-4675
41. Brandl, Erhard, et al., Deposition of Ti-6Al-4V using laser and wire, part I, Microstructural properties of single beads, *Surface and Coatings Technology*, 206(6) (2011), 1120-1129
42. Brandl, E., et al., Additive manufactured Ti-6Al-4V using welding wire, comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications, *Physics Procedia*, 5 (2010), 595-606
43. Levy, Gideon N., Ralf Schindel, and Jean-Pierre Kruth, Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives, *CIRP Annals-Manufacturing Technology*, 52(2) (2003), 589-609
44. Baufeld, Bernd, Erhard Brandl, and Omer Van der Biest, Wire based additive layer manufacturing, comparison of microstructure and mechanical properties of Ti-6Al-4V components fabricated by laser-beam deposition and shaped metal deposition, *Journal of Materials Processing Technology*, 211(6) (2011), 1146-1158
45. Baufeld, Bernd, and Omer Van der Biest, Mechanical properties of Ti-6Al-4V specimens produced by shaped metal deposition, *Science and technology of advanced materials*, (2016)
46. Ding, Donghong, et al., A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM), *Robotics and Computer-Integrated Manufacturing*, 31 (2015), 101-110
47. Ma, Yan, et al., The effect of location on the microstructure and mechanical properties of titanium aluminides produced by additive layer manufacturing using in-situ alloying and gas tungsten arc welding, *Materials Science and Engineering*, A 631 (2015), 230-240
48. Ma, Yan, et al., Effect of interpass temperature on in-situ alloying and additive manufacturing of titanium aluminides using gas tungsten arc welding, *Additive Manufacturing*, 8 (2015), 71-77
49. Ding, Donghong, et al, Wire-feed additive manufacturing of metal components, technologies, developments and future interests, *The International Journal of Advanced Manufacturing Technology*, 81(1-4) (2015), 465-481
50. Ding, Donghong, et al., Towards an automated robotic arc-welding-based additive manufacturing system from CAD to finished part, *Computer-Aided Design*, (2016)
51. Ding, Donghong, et al., Bead modelling and implementation of adaptive MAT path in wire and arc additive manufacturing, *Robotics and Computer-Integrated Manufacturing*, 39 (2016), 32-42
52. Song, Yong-Ak, et al., 3D welding and milling, Part I-a direct approach for freeform fabrication of metallic prototypes, *International Journal of Machine Tools and Manufacture*, 45(9) (2005), 1057-1062
53. Song, Yong-Ak, Sehyung Park, and Soo-Won Chae, 3D welding and milling, part II-optimization of the 3D welding process using an experimental design approach, *International Journal of Machine Tools and Manufacture*, 45(9) (2005), 1063-1069.
54. Sang-Myung Cho, et al., Filler metal shpae for welding, *Korea patent*, 1016440190000 (2015)
55. Sang-Myung Cho, et al., Filler metal shpae for welding, *Korea patent*, 1016273680000 (2016)
56. Sang-Myung Cho, et al., Filler metal shpae for TIG welding, *Korea patent*, 1016216960000 (2016)
57. Jun, Jae-Ho, Sung-Ryul Kim, and Sang-Myung Cho, A Study on Productivity Improvement in Narrow Gap TIG Welding, *J. of Welding and Joining*, 34(1) (2016), 68-74 (in Korean)
58. Jae-Gyu Byun, Jae-Ho Jun, Song-Yi Park, Sang-Jun Lee, Dong-Soo Oh, Sang-Myun Cho, Study of Mechanical Property of Metal 3D Printing by Super-TIG Welding, *Abstracts of KWJS*, 62(2015), 86 (in Korean)
59. Jae-Gyu Byun, Jae-Ho Jun, Sang-Jun Lee, Dong-Soo Oh, Sang-Myung Cho, Development of The Process to Improve Degree of Freedom in STS316L Metal 3D Printing by Super-TIG Welding, *Abstracts KWJS*, 63 (2015), 62 (in Korean)
60. Sang-Jun Lee, Jae-Gyu Byun, Sang-Myung Cho, Development of Additive Process on Cylindrical Parts by Super-TIG Metal 3D Printing, *Abstracts o the KWJS*, 64 (2016), 141 (in Korean)
61. Jae-Gyu Byun, Sang-Jun Lee, Yung-Gyu Lee, Soo-Yoong Park, Young-Tae Cho, Sang-Myung Cho, Development of The Metal 3D Printing Equipment by Super-TIG Welding, *Abstracts of KWJS*, 64(2016), 148