METAL 3D PRINTING VIA SELECTIVE LASER MELTING AND DIRECT METAL DEPOSITION: MATERIALS, PROPERTIES AND APPLICATIONS

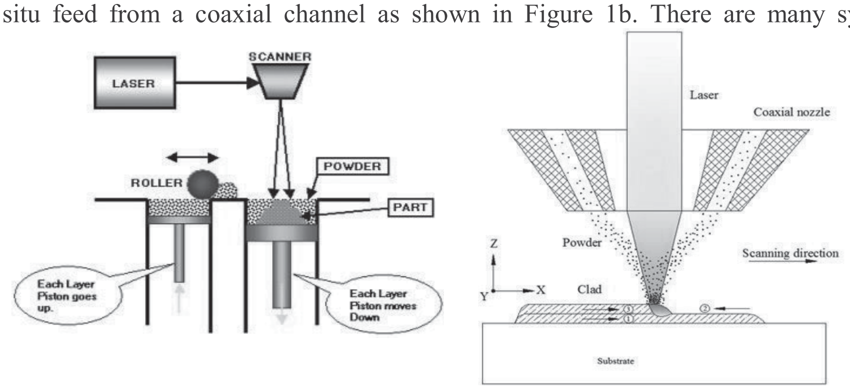
JINGJING WANG, ERJIA LIU*, SHU BENG TOR, CHEE KAI CHUA
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

ABSTRACT: Recently, metal 3D printing has gained a lot of interest. In particular, selective laser melting (SLM) and direct metal deposition (DMD) are the most important methods explored due to the superior properties being achieved. This article overviews the two methods in terms of basics of the technologies (powder bed fusion and powder blow), material selection, properties as well as some of the applications and future directions. SLM is superior in producing parts with higher precision and complexity. However, DMD is more processing efficient and allows for large components to be manufactured. A recent design of hybrid system of DMD with milling technology can achieve high precision and surface finishing. Moreover, DMD can also produce functionally graded materials (FDMs) as well as composite materials.

KEYWORDS: Metal 3D printing, Selective laser melting, Direct metal deposition, Additive manufacturing

INTRODUCTION

Selective laser melting (SLM) and direct metal deposition (DMD) play significant roles in metal 3D printing (Chua & Leong (2014), Loh et al. (2014)). Many research works have been devoted to process optimization, material development, equipment and technology upgrading. Both starting with a CAD model, SLM creates a 3D object cross-sectional by placing thin layers of powder followed by laser hatch melting as illustrated in Figure 1a. On the other hand, DMD adopts a synchronized system to create a melt pool by laser power on the substrate and melt the powder in-situ feed from a coaxial channel as shown in Figure 1b. There are many synonyms of DMD



(a) (b)

Figure 1 Schematic diagrams of (a) SLM (http://mehran005.blogspot.sg/2012/04/hollow-lightweight-structures-via.html)) and (b) DMD (http://ilam.sjtu.edu.cn/research/Numerical%20modeling%20of%20direct%20metal%20deposition%20.html)

Proc. of the 2nd Intl. Conf. on Progress in Additive Manufacturing
Edited by Chee Kai Chua, Wai Yee Yeong, Ming Jen Tan, Erjia Liu and Shu Beng Tor

Published by Research Publishing, Singapore
ISSN: 2424-8967

including laser engineered net shaping (LENS), solid forming (SF), laser metal deposition (LMD), directed light fabrication (DLF), direct laser deposition (DLD), direct laser fabrication (DLF), laser rapid forming (LRF), and laser melting deposition (LMD), which are all based on powder blow technology with minor differences in technologies.

Some important process parameters are listed in Table 1. DMD uses higher laser power and larger spot size and can build a larger object almost 10 times faster than SLM. However, SLM is superior in precision tolerance, surface finishing and structural complexity.

Table 1. Comparison of SLM and DMD Processes

	SLM	DMD
Powder deposition method	Powder bed	Powder blow (Coaxial feeding)
Bonding mechanism	Complete melting	Complete melting
Laser type	Nd:YAG laser (100-400 W) Fiber laser	Nd:YAG laser (up to 5 kW) CO_2 laser (up to 8 kW) Fiber laser
Spot size	Small (<100 μm)	Large (up to a few mm)
Scanning/traversing speed	19,200 mm/min	500 mm/min
Layer thickness/powder feed rate	30-100 μm	Up to 15 g/min
Forming shape	Complex	Less complex

MATERIAL

Metals, MMCs, FGMs

Many kinds of metals have been developed via SLM and DMD processes, but only limited metals are commercially available. Table 2 shows some selected metal materials that have been developed including stainless steels, other steels, metal alloys such as titanium alloys, aluminum alloys and copper alloys, metal matrix composites (MMCs), functionally graded materials (FGMs), etc. (Abe et al. (2001), Kruth et al. (2004), Badrossamay & Childs (2007), Yadroitsev et al. (2010), Yadroitsev & Smurov (2010), Yadroitsev & Smurov (2011), Guan et al. (2013), Kamath et al. (2014)). Among them stainless steel is the most well developed metal and near full density can be achieved by SLM process. (Kamath et al. (2014)) achieved >99% of relative density for SS316L and claimed that the density could be further increased to near full density by using higher laser power.

DMD process also successfully developed a wide range of materials with superior mechanical properties ((Zhao et al. (2009), Amano & Rohatgi (2011)). To fabricate FGM (Liu & DuPont (2003), Balla et al. (2009), Articek et al. (2013)) and MMC materials (Liu & DuPont (2003), Xiong et al. (2008)) is a unique characteristic of DMD process due to its multiple powder feeding system.

Raw powder

There are several aspects that need to be considered for selecting raw powders used in additive manufacturing processes, including particle size, particle morphology, particle size distribution as well as impurity level (Gu et al. (2012)). Ideal particles should possess near spherical shape and homogeneous size because those particles can give high initial packing density and good flowability that can help achieve denser parts, which is especially important for powder bed based SLM processes. Due to laser melting mechanism, particle size has to fall within a reasonable range, normally submicron to 200 μm with a narrow distribution to enhance laser fuse bonding and prevent balling effect. Balling phenomena are observed for both small and large sized powders due to over-melting, under-melting or wettability. Since the process is less sensitive to powder morphology and powder size distribution, DMD is more tolerant in raw powder selection. Oxidation at ppm level or lower is tolerable as it may not substantially affect the densification and final properties of printed parts. To avoid oxidation, one remedy is to use gas atomized powder with lower oxidation level instead of water atomized powder.

Table 2. Selected metals developed via SLM and DMD

Metal powder	SLM	DMD
Stainless steels	316L, 304L,420,347,Inox 904L,17-4PH,15-5PH	316L,410
Other steels	H13	H13,SAE4140,AISI4340
CoCrMo alloy	CoCrMo	CoCrMo
Ti alloy	Ti-6Al-4V, CP Ti, TiAl	Ti-6Al-4V, CPTi
Super alloys	Inconel625,718, waspaloy, stellite	Inconel 625,718, Rene88DT, Rene41
Al alloys	Al-Si-Mn,Al-10Si-Mg,6061	
Cu alloys	Cu	Cu-30Ni
Intermetallic alloys	Fe-Ni-Cu-Fe3P	Ni-Al-Cr-Hf, γ -TiAl
FGM		Ti-TiC,Ti-TiO2,H13-Cu
MMC	Fe-C, Fe-B	WC-Co, TiC-Ti

PROPERTIES

SLM and DMD can achieve superior properties of printed parts over conventional manufacturing processes such as casting and powder metallurgy, which are attributed to the very fine microstructures of the printed parts due to the rapid cooling process (Yin & Felicelli (2010), Amano & Rohatgi (2011), Bian et al. (2015)). It is known that refining grain size can increase the tensile strength and hardness of a material. For example, when grain size is reduced from 50 μm to sub-micron level, the mechanical properties of the material will be much more improved. Some typical properties are listed in Table 3 based on which near full densification can be achieved via SLM and DMD processes (Kruth et al. (2005)). As DMD is usually superior than SLM in densification and refining grain size, the mechanical properties of DMD printed parts are expected to be better (Gu et al. (2012)), Frazier (2014).

However, laser assisted processes have some drawbacks. A common problem is residual stress (Shiomi et al. (2004), Song et al. (2012), Vrancken et al. (2014)). As metal powders are completely melted and solidified at a very fast cooling rate typically in the range of 10^3-10^4K/s, a residual stress inevitably develops within the solidified body, which is a key factor for distortion and may develop into cracks or even delamination. Proper process parameters have to be decided for each material. The relationships between process parameters – such as laser power, scan speed, layer thickness, powder feed rate, cooling rate, and microstructure determined properties have been systematically explored by researchers (Glardon et al. (2001), Li et al. (2010), Tsopanos et al. (2010), Song et al. (2012), Guan et al. (2013), Zhang et al. (2013), Loh et al. (2014), Song et al.

(2014), Zhang et al. (2014)). Other than experimental works, simulation works have also been carried out to understand the residual stress issue as well as the process optimization by monitoring molten pool dynamics, temperature field, etc. (Wang et al. (2008a), Wang et al. (2008b), Shifeng et al. (2014), Loh et al. (2015)). Amano and co-workers have conducted experimental and numerical studies on laser engineered net shaping process for SAE 4140 low alloy steel and found the optimum processing parameters based on the simulation results (Amano & Rohatgi (2011)). Another way to reduce residual stress is by preheating substrate to slow down cooling rate and reduce internal stress accumulation.

Balling effect is another common problem seen in laser assisted melting process, which is normally caused by insufficient wetting, over wetting, or sparking. The balling effect could be prevented by proper process setting and material selection (e.g., lower oxidation level, particle size, etc.) (Li et al. (2010), ANTONY et al. (2014)).

Table 3. Typical properties achieved via SLM and DMD

	SLM	DMD
Tensile property	Better than cast materials	Equivalent to wrought materials or higher
Elongation	Lower than wrought 10.5% (Ti-6Al-4V)	Lower than wrought 13% (Ti-6Al-4V)
Densification	Up to 99.9%	Near full density
Surface roughness	Low (<10 μm)	High (up to 100 μm)
Hardness	Higher than cast and PM materials	Higher than cast and PM materials

APPLICATIONS and FUTURE TREND

Both SLM and DMD can be used as rapid prototyping technologies and are good for producing components with a complex structure of low quantum and high value under stringent processing conditions. SLM is more suitable for producing complex geometries (e.g., hidden voids or channels, lattice structures, etc,), thin walls, and high precision parts to be used in aerospace and automobile industries. DMD provides an alternative option for repair and remanufacturing, cladding and hardfacing, potential large-scale components in marine and offshore, automobile parts as well as designed materials (basically functionally graded materials and metal matrix composite materials).

Further research works on 3D printing equipment and new techniques, powder deposition methods and printing strategy should be advocated in near future. Material development needs to be enhanced to expedite 3D printing technologies and widen their applications.

ACKNOWLEDGMENT

The authors thank Singapore Centre for 3D Printing (SC3DP) and National Research Foundation (NRF) of Singapore for their financial support of this research.

REFERENCES

Abe, F., Osakada, K., Shiomi, M., Uematsu, K. & Matsumoto, M. (2001). "The manufacturing of hard tools from metallic powders by selective laser melting." *Journal of Materials Processing Technology* 111(1–3): 210-213.

Amano, R. S. & Rohatgi, P. K. (2011). "Laser engineered net shaping process for SAE 4140 low alloy steel." *Materials Science and Engineering: A* 528(22-23): 6680-6693.

ANTONY, K., ARIVAZHAGAN, N. & SENTHILKUMARAN, K. (2014). "Studies on wettability of stainless steel 316L powder in laser melting process." *Journal of Engineering Science and Technology* 9(5): 533-540.

Articek, U., Milfelner, M. & Anzel, I. (2013). "Synthesis of functionally graded material H13/Cu by LENS technology." *Advances in Production Engineering & Management* 8(3): 169-176.

Badrossamay, M. & Childs, T. H. C. (2007). "Further studies in selective laser melting of stainless and tool steel powders." *International Journal of Machine Tools and Manufacture* 47(5): 779-784.

Balla, V. K., DeVasConCellos, P. D., Xue, W., Bose, S. & Bandyopadhyay, A. (2009). "Fabrication of compositionally and structurally graded Ti-TiO2 structures using laser engineered net shaping (LENS)." *Acta Biomater* 5(5): 1831-1837.

Bian, L., Thompson, S. M. & Shamsaei, N. (2015). "Mechanical Properties and Microstructural Features of Direct Laser-Deposited Ti-6Al-4V." *Jom* 67(3): 629-638.

Chua, C. K. & Leong, K. F. (2014). *3D printing and additive manufacturing : principles and applications*, World Scientific.

Frazier, W. E. (2014). "Metal Additive Manufacturing: A Review." *Journal of Materials Engineering and Performance* 23(6): 1917-1928.

Glardon, R., Karapatis, N., Romano, V. & Levy, G. N. (2001). "Influence of Nd:YAG Parameters on the Selective Laser Sintering of Metallic Powders." *CIRP Annals - Manufacturing Technology* 50(1): 133-136.

Gu, D. D., Meiners, W., Wissenbach, K. & Poprawe, R. (2012). "Laser additive manufacturing of metallic components: materials, processes and mechanisms." *International Materials Reviews* 57(3): 133-164.

Guan, K., Wang, Z., Gao, M., Li, X. & Zeng, X. (2013). "Effects of processing parameters on tensile properties of selective laser melted 304 stainless steel." *Materials & Design* 50: 581-586.

Kamath, C., El-dasher, B., Gallegos, G. F., King, W. E. & Sisto, A. (2014). "Density of additively-manufactured, 316L SS parts using laser powder-bed fusion at powers up to 400 W." *The International Journal of Advanced Manufacturing Technology* 74(1-4): 65-78.

Kruth, J. P., Froyen, L., Van Vaerenbergh, J., Mercelis, P., Rombouts, M. & Lauwers, B. (2004). "Selective laser melting of iron-based powder." *Journal of Materials Processing Technology* 149(1-3): 616-622.

Kruth, J. P., Mercelis, P., Vaerenbergh, J. V., Froyen, L. & Rombouts, M. (2005). "Binding mechanisms in selective laser sintering and selective laser melting." *Rapid Prototyping Journal* 11(1): 26-36.

Li, R., Shi, Y., Wang, Z., Wang, L., Liu, J. & Jiang, W. (2010). "Densification behavior of gas and water atomized 316L stainless steel powder during selective laser melting." *Applied Surface Science* 256(13): 4350-4356.

Liu, W. & DuPont, J. N. (2003). "Fabrication of functionally graded TiC/Ti composites by Laser Engineered Net Shaping." *Scripta Materialia* 48(9): 1337-1342.

Loh, L.-E., Chua, C.-K., Yeong, W.-Y., Song, J., Mapar, M., Sing, S.-L., Liu, Z.-H. & Zhang, D.-Q. (2015). "Numerical investigation and an effective modelling on the Selective Laser Melting (SLM) process with aluminium alloy 6061." *International Journal of Heat and Mass Transfer* 80: 288-300.

Loh, L. E., Liu, Z. H., Zhang, D. Q., Mapar, M., Sing, S. L., Chua, C. K. & Yeong, W. Y. (2014). "Selective Laser Melting of aluminium alloy using a uniform beam profile: The paper analyzes the results of laser scanning in Selective Laser Melting using a uniform laser beam." *Virtual and Physical Prototyping* 9(1): 11-16.

Shifeng, W., Shuai, L., Qingsong, W., Yan, C., Sheng, Z. & Yusheng, S. (2014). "Effect of molten pool boundaries on the mechanical properties of selective laser melting parts." *Journal of Materials Processing Technology* 214(11): 2660-2667.

Shiomi, M., Osakada, K., Nakamura, K., Yamashita, T. & Abe, F. (2004). "Residual Stress within Metallic Model Made by Selective Laser Melting Process." *CIRP Annals - Manufacturing Technology* 53(1): 195-198.

Song, B., Dong, S., Deng, S., Liao, H. & Coddet, C. (2014). "Microstructure and tensile properties of iron parts fabricated by selective laser melting." *Optics & Laser Technology* 56: 451-460.

Song, B., Dong, S., Zhang, B., Liao, H. & Coddet, C. (2012). "Effects of processing parameters on microstructure and mechanical property of selective laser melted Ti6Al4V." *Materials & Design* 35: 120-125.

Tsopanos, S., Mines, R. A. W., McKown, S., Shen, Y., Cantwell, W. J., Brooks, W. & Sutcliffe, C. J. (2010). "The Influence of Processing Parameters on the Mechanical Properties of Selectively Laser Melted Stainless Steel Microlattice Structures." *Journal of Manufacturing Science and Engineering* 132(4): 041011.

Vrancken, B., Cain, V., Knutsen, R. & Van Humbeeck, J. (2014). "Residual stress via the contour method in compact tension specimens produced via selective laser melting." *Scripta Materialia* 87: 29-32.

Wang, L., Felicelli, S., Gooroochurn, Y., Wang, P. T. & Horstemeyer, M. F. (2008a). "Optimization of the LENS® process for steady molten pool size." *Materials Science and Engineering: A* 474(1-2): 148-156.

Wang, L., Felicelli, S. D. & Pratt, P. (2008b). "Residual stresses in LENS-deposited AISI 410 stainless steel plates." *Materials Science and Engineering: A* 496(1-2): 234-241.

Xiong, Y., Smugeresky, J. E., Ajdelsztajn, L. & Schoenung, J. M. (2008). "Fabrication of WC–Co cermets by laser engineered net shaping." *Materials Science and Engineering: A* 493(1-2): 261-266.

Yadroitsev, I., Gusarov, A., Yadroitsava, I. & Smurov, I. (2010). "Single track formation in selective laser melting of metal powders." *Journal of Materials Processing Technology* 210(12): 1624-1631.

Yadroitsev, I. & Smurov, I. (2010). "Selective laser melting technology: From the single laser melted track stability to 3D parts of complex shape." *Physics Procedia* 5: 551-560.

Yadroitsev, I. & Smurov, I. (2011). "Surface Morphology in Selective Laser Melting of Metal Powders." *Physics Procedia* 12: 264-270.

Yin, H. & Felicelli, S. D. (2010). "Dendrite growth simulation during solidification in the LENS process." *Acta Materialia* 58(4): 1455-1465.

Zhang, B., Dembinski, L. & Coddet, C. (2013). "The study of the laser parameters and environment variables effect on mechanical properties of high compact parts elaborated by selective laser melting 316L powder." *Materials Science and Engineering: A* 584: 21-31.

Zhang, S., Wei, Q., Cheng, L., Li, S. & Shi, Y. (2014). "Effects of scan line spacing on pore characteristics and mechanical properties of porous Ti6Al4V implants fabricated by selective laser melting." *Materials & Design* 63: 185-193.

Zhao, J., Cao, W., Ge, C., Tan, Y., Zhang, Y. & Fei, Q. (2009). "Research on laser engineered net shaping of thick-wall nickel-based alloy parts." *Rapid Prototyping Journal* 15(1): 24-28.