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Additive manufacturing for steels: a review

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Abstract. Additive manufacturing (AM) of steels involves the layer by layer consolidation of powder or wire feedstock using a heating beam to form near net shape products. For the past decades, the AM technique reaches the maturation of both research grade and commercial production due to significant research work from academic, government and industrial research organization worldwide. AM process has been implemented to replace the conventional process of steel fabrication due to its potentially lower cost and flexibility manufacturing. This paper provides a review of previous research related to the AM methods followed by current challenges issues. The relationship between microstructure, mechanical properties, and process parameters will be discussed. Future trends and recommendation for further works are also provided.

1. Introduction

Steel has been widely used in various applications, starting from the defense, petroleum, automotive, nuclear and chemical industries, due to its excellent mechanical properties and cost efficient [1]. Among them, stainless steels are getting more attention due to its excellent corrosion and oxidation resistance. Chromium additions impart passive protection layer when the amount of more than 11% [2]. However, there is a difficulty using conventional manufacturing to fabricate complex shape parts with cooling channels, mesh structure or inner cavities.

Additive manufacturing (AM) is a revolutionize technology which can manufacture solid parts from 3D image data through layer by layer processing. This technique melts the powder particle using electron or laser beam, while heat source is moving relative to base materials and then parts will solidify. AM process can be classified into two categories: powder bed (PB) and flow-based technique [3–5]. The PB process covers the electron beam melting (EBM) and selective laser melting (SLM), while flow-based method includes the laser-engineered net shaping (LENS), direct metal deposition (DMD) and direct metal laser sintering (DMLS).

PB technique starts from the bed of powder and the beam scanning the powder that melts the powder and solidified as final parts. The illustration of the process is shown in figure 1. These methods give parts with high density, excellent mechanical properties, and smooth surface, but it is limited for small scale product due to small beam size. While flow-based method begins with the injection of powder feedstock through the deposition head and heat from beam melts layer by layer until the desired part. This technique can build large scale products due to high deposition rate and volume, but it creates a rough surface and imprecision dimension. The methods are illustrated in figure 2.

Several types of steels have been processed through AM technique. Starting from pure iron, stainless steel (304, 316, 321, 347, 420, 17-4PH), tool steel (H13, M2 HSS), maraging steel (18Ni300), until low-alloyed steel (4140, 4340). The lists of previous work on the AM of steel are shown in table 1.

The focus of this paper is the development of the AM technique for steels materials, along with the current scientific, technical challenges and economic consideration that still need to be solved.

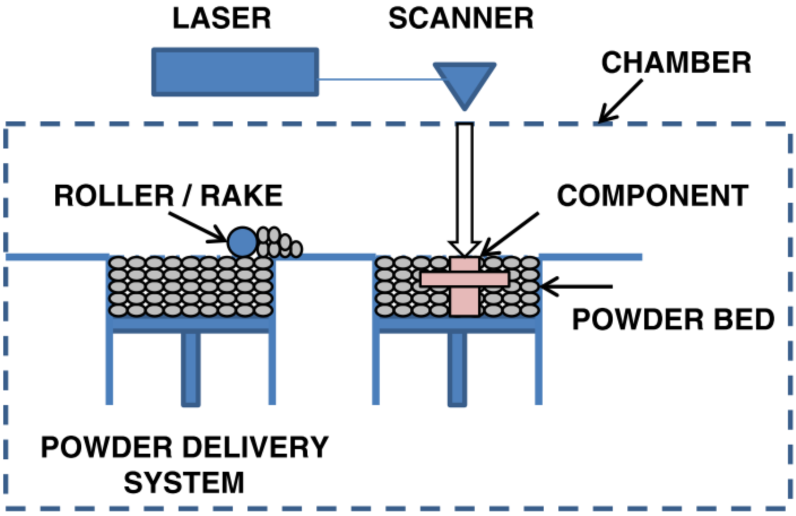

Figure 1. Powder bed fusion illustration scheme (adapted from [4])

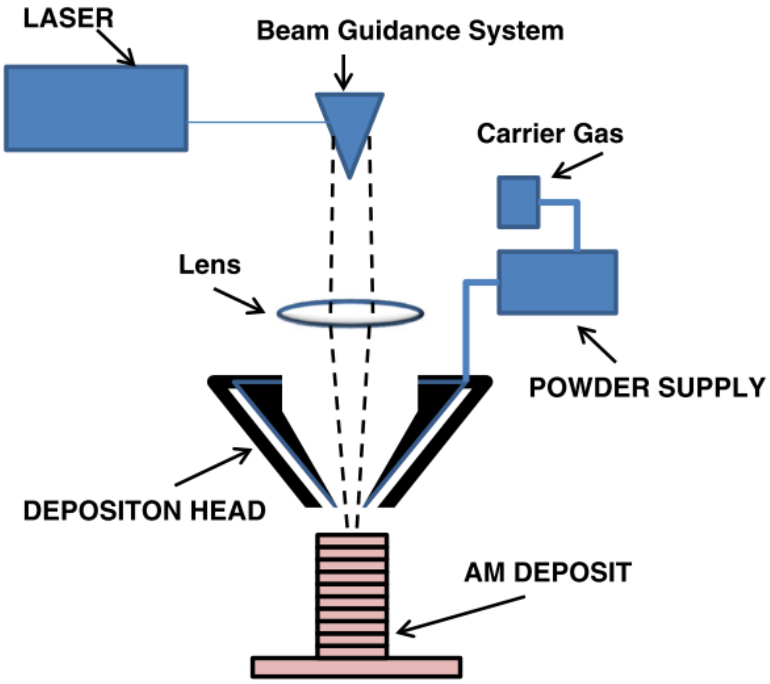

Figure 2. Flow-based illustration scheme (adapted from [4])

Table 1. List of publication

AM Technique	Machine Type	Alloy	Heat Source Power	Input Feedstock Characteristics	References
EBM	Arcam (Sweden)	H13 steel	Electron beam	Powder particle	[6]
EBM	Arcam S12	Pure iron	Electron beam	Gas atomized powder	[7]
EBM	Arcam AB	316	Electron beam	Powder particle	[8]
EBM	EBSM (China)	316L	Electron beam	Gas atomized powder	[9]
EBM	Sciaky (USA)	Stainless steel 321, 347	Electron beam	Wire filler	[10]
SLM	EOS (Germany)	Stainless steel (17-4, 15-5 PH)	Yb-fiber laser beam	Powder particle	[11,12]
SLM	Realizer (Germany)	316L	Laser beam	Powder particle	[13]
SLM	SLM-Solution (Germany)	316-L	Yttrium fiber laser	Powder particle	[14–16]
SLM	Concept Laser (Germany)	Maraging steel (18Ni300)	Continuous fiber laser	Powder particle	[17]
SLM	Concept Laser (Germany)	M2 HSS	Nd: YAG laser beam	Gas atomized powder	[18]
SLM	Concept Laser (Germany)	316L	Laser beam	Powder particle	[12,19–21]
SLM	Concept Laser (Germany)	17-4 PH stainless steel	Fiber laser beam	Water atomized powder	[22]
SLM	Concept Laser (Germany)	Low alloyed steel	Nd: YAG laser beam	Water and gas atomized powder	[23]
SLM	HRPM (China)	316L	Fiber laser	Gas atomized powder	[24]
SLM	HRPM (China)	AISI 420	Continuous fiber laser	Gas atomized powder	[25]
SLM	LSNF (China)	304 SS	Continuous fiber laser	Gas atomized	[1]
DMLS	EOS (Germany)	4340 steel	Ytterbium fiber laser	Powder particle	[26]
DMLS	Laser-based	316L	Continuous CO_2 laser	Powder particle	[27,28]
LENS	LENS (SNL-USA)	304L and 17-4PH	Laser beam	Atomized powder	[29]
LENS	LENS (SNL-USA)	316 and 316L SS	Nd: YAG laser beam	Powder particle	[30–33]
LENS	LENS	H-13 steel	Laser beam	Powder particle	[34–36]
LENS	LENS	AISI 4140	Laser beam	Pre-alloyed powder	[37]
DMD	Laser-based	AISI 4340 steel	Laser beam	Pre-alloyed powder	[38]
DMD	Laser-based	H13 steel	Laser beam	Powder particle	[39,40]

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2. Microstructure and Mechanical Properties of AM Parts

The final properties of an AM product are depending on the process parameter such as laser power, scanning speed, beam diameter, layer thickness, beam scan pattern, build direction, and powder mass flow rate. The microstructures are also controlled by thermal history cause by repeating heating and cooling process during AM or also called thermal cycle. The thermal cycle induced the grain to growth on preferred crystallographic orientation, for example <100> direction for fcc alloys, which cause strong crystallographic texture, anisotropic tensile properties and evolve the microstructure [41]. However, Dehoff et al. show that the microstructure can vary from columnar grains with very strong texture to almost equiaxed grains with weaker texture using a modification of build parameters [42]. It makes the randomly crystallographic texture is possible in the AM process. On the other hand, Peter demonstrated that hot-isostatic processing (HIP) could also result in the equiaxed grain formation [43].

Table 2. Tensile properties of steel fabricated by AM technique

Machine Type	Alloy	Condition	Specimen Orientation	σ_y (MPa)	σ_{UTS} (MPa)	ε (%)	Hardness (HB)	Ref.
SLM 250	316L	As-built	Z	500	600.2	55	NA	[16]
		Heat-treated		475	617.9	54.1	NA	
		HIP		380	586.6	64.4	NA	
SLM M1	316L	As-built	NA	640	760	30	NA	[12]
LENS	316L	As-built	Z	405-415	620-660	34-40	NA	[33]
		Heat treated		325-355	600-620	42-43		
Wrought Alloy	316L	Anneal treated		235	560	55	146	a
EOS M270	15-5 PH	As-built	NA	1100	1470	15	NA	[12]
Wrought Alloy	15-5 PH	H900 condition		1275	1380	14	420	b
EOS M250	AISI 4340	Stress relieved	XY	1303	1372	16-17	430-468	[26]
DMD	4340	Stress relieved	XY	NA	1398	1.66	NA	[38]
Wrought Alloy	4340	Heat treated		1475	1595	12	NA	c

a Nominal wrought 316L data from Online Metals Corp. (www.onlinemetals.com)
b Nominal wrought 15-5 PH data from Online Metals Corp. (www.onlinemetals.com)
c Nominal wrought AISI 4340 data from Material Property Data (www.matweb.com)

The thermal cycles can also trigger a variety of metallurgical phenomena such as solid-state phase transformation and segregation behavior. El Kadiri et al. investigate the phase transformation of low-alloyed steel fabricated by LENS [37]. They found that delta ferrite is the primary phase of the solidification process. Due to very high cooling rates, they observed fine allotriomorphs ferrite in the microstructure which can lead very brittle behavior. In addition, Jagle et al. studied the microstructure evolution in the maraging steel fabricated by SLM [17]. They found that martensite is the main phase in the as-built condition also due to high cooling rates. Several post-heat treatments have been used to formed precipitate phase and reported that it could increase the hardness of the maraging steels. Therefore, these unconventional thermal history processes unleash possibility to control the microstructure of any kinds of steels materials.

Defects density can induce by the process parameters, including microvoids, inclusion, pores de-bonding and weak grain boundary. Xue et al. investigate the effect of microporosity on the tensile strength of 316L fabricated by LENS methods [32]. It is reported that an increasing porosity volume can significantly decrease the tensile properties. Therefore, the HIP treatment has been used to reduce the amount of porosity and proven to increase the fatigue limit on the 316L stainless steel [15].

There are only a few research works using wire filler. Qi et al. reported that high amount of MC carbides formed in the stainless steel fabrication [9]. This secondary phase can lead brittle properties and lower the ductility. Therefore, most of the previous works used powder as an input feedstock.
Table 2 summarizes the tensile properties of steel from the previous research works. The table shows that most of the AM fabricated steel has an excellent mechanical properties compare to the conventional process product.

3. Technology Challenges

From the heat source, AM methods can be divided as two, using laser or electron beam. Due to its different nature energy carried out by photons and electron, it gives significant differences. The electron beam can provide higher scan rate up to 10^4 mm/s compared to the laser beam that only 1200 mm/s [44]. The electron beam can leap instantly from point to point and move inertia-free, but it has significant disadvantages which need a vacuum atmosphere to operate. Therefore, there are only a few studies using electron beam for steel fabrication, but it is popular for Ti alloy and Ni-base alloys manufacturing.

One of the major drawbacks on the AM technologies is the residual stresses that decrease the mechanical properties of the final product. The melting process creates thermal gradients between different layers which lead to significant residual stress. These residual stresses can be accurately measured using x-ray or neutron diffraction [20]. According to Rangaswamy et al. the magnitude of local residual stress reach up to 75% of the yield strength of the material, and it goes higher for superalloys parts [45]. As a result, these residual stresses also cause considerable inaccuracies on the dimension in the final product. Additional treatment has been proposed by Klingbeil et al and Shiomi et al which showed that substrate preheating and post-annealing treatment can be used to limit warping displacement induced by residual stresses [46,47].

4. Economic Consideration

According to the conclusion from Baumers, there are two AM advantages over conventional manufacturing techniques [48]. First, AM methods can efficiently fabricate complex geometry components and second, this technology can manufacture very small production quantities at relatively low average cost. This indicates that AM have future in economic perspective. The implementation of AM method can reduce cost budgeting, increase the efficiency of raw material used and reduce the waste of production in various industries.

The AM process can be replacing the production of tool dies in the injection moulding machine, which made of tool steel. The die requires a complex shape with a cooling channel and inner cavities. Kinsella investigated the flow-based AM method for Nickel superalloy (IN718) in forged engine case [49]. It is reported that more than 30% cost saving can be achieved using AM process compared to conventional process. However, only a few researches have been done investigating the prospective studies in steel materials.

The cost in manufacturing can be divided into (i) fixed cost such as tools, dies, buildings, etc, and (ii) recurring costs include raw materials, labour, etc. Figure 3 shows the illustration of total cost of manufacturing component via AM and conventional process. The total cost was calculated as a linear function of amount of parts being produced. The slope line represent the ratio of the recurring cost of AM divided by the recurring cost of conventional method. This cost model calculated that the budget of AM has a cheaper manufacturing cost than the conventional one for small-scale production, proven by interception in 175 parts for 2 recurring cost while 90 parts for 1.5 recurring cost. In summary, the

AM is currently favoured in small-production due to significant recurring cost driven by the high cost of raw material.

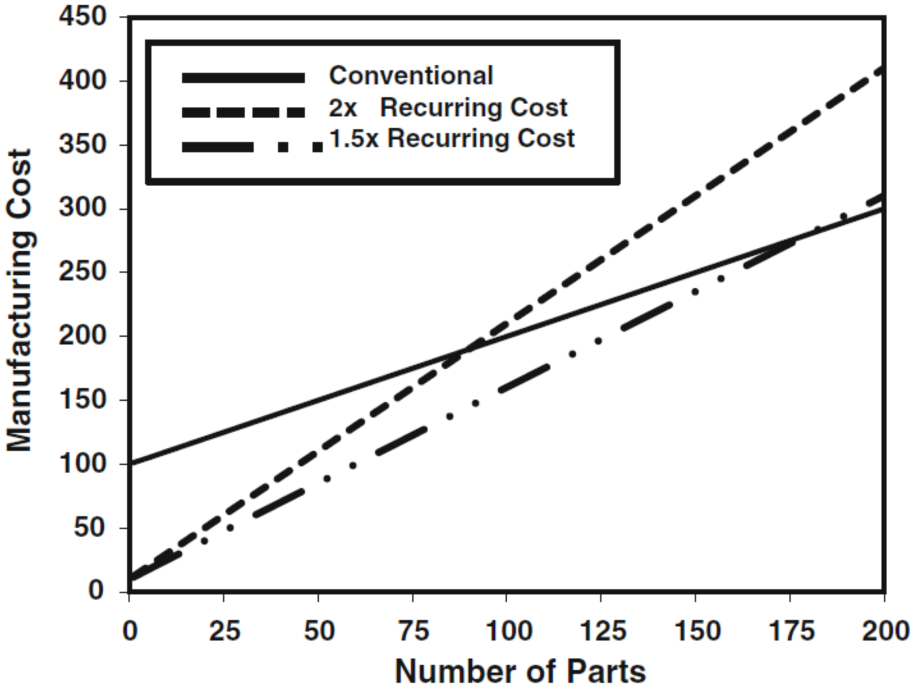

Figure 3. Cost comparison between AM and conventional process (adapted from [4]).

5. Conclusion and Further Works

Additive manufacturing revolutionize future industrial production by offering several advantages compare to conventional one, such as production of small quantities with complex geometry, design freedom, and reduction of development times. Along with optimum processing parameters and post-treatment, the resulting AM mechanical properties are comparable or even better than the conventional production methods. However, the AM processes with various type of machine, are presently far from being completely developed to manufacture the controlled-microstructure materials. Therefore, the future works should focus on the better understanding of process control, enhance the machine power and design new alloys. The computational approach also could be used to minimize the trial and error experiment. In addition, the cost reduction of raw materials should be continued.

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References

[1] Guan K, Wang Z, Gao M, Li X and Zeng X 2013 *Mater. Des.* **50** 581–6
[2] ASM 1993 *ASM Handbook Volume 1 Properties and Selection: Irons Steels and High Performance Alloys*
[3] Elahinia M, Shayesteh Moghaddam N, Taheri Andani M, Amerinatanzi A, Bimber B A and Hamilton R F 2016 *Prog. Mater. Sci.* **83** 630–63
[4] Frazier W E 2014 *J. Mater. Eng. Perform.* **23** 1917–28
[5] Froes F H and Dutta B 2014 *Adv. Mater. Res.* **1019** 19–25
[6] Cormier D, Harrysson O and West H 2004 *Rapid Prototyp. J.* **10** 35–41
[7] Murr L E, Martinez E, Pan X, Meng C, Yang J, Li S, Yang F, Xu Q, Hernandez J, Zhu W, Gaytan S M, Medina F and Wicker R B 2013 *J. Mater. Res. Technol.* **2** 376–85

[8] Hinojos A, Mireles J, Reichardt A, Frigola P, Hosemann P, Murr L E and Wicker R B 2016 *Mater. Des.* **94** 17–27
[9] Qi N B, Yan Y N, Lin F, He W and Zhang R J 2006 *Proc. Inst. Mech. Eng. Part B (Journal Eng. Manuf.* **220** 1845–53
[10] Wanjara P, Brochu M and Jahazi M 2007 *Mater. Des.* **28** 2278–86
[11] Abele E, Stoffregen H A, Kniepkamp M, Lang S and Hampe M 2015 *J. Mater. Process. Technol.* **215** 114–22
[12] Spierings A B, Starr T L and Wegener K 2013 *Rapid Prototyp. J.* **19** 88–94
[13] Tolosa I, Garciandía F, Zubiri F, Zapirain F and Esnaola A 2010 *Int. J. Adv. Manuf. Technol.* **51** 639–47
[14] Buican G R, Oancea G, Lancea C and Pop M A 2015 *Appl. Mech. Mater.* **760** 515–20
[15] Riemer A, Leuders S, Thöne M, Richard H A, Tröster T and Niendorf T 2014 *Eng. Fract. Mech.* **120** 15–25
[16] Leuders S, Lieneke T, Lammers S, Tröster T and Niendorf T 2014 *J. Mater. Res.* **29** 1911–9
[17] Jägle E A, Choi P, Humbeeck J Van and Raabe D 2014 *J. Mater. Res.* **29** 2072
[18] Kempen K, Vrancken B, Buls S, Thijs L, Van Humbeeck J and Kruth J-P 2014 *J. Manuf. Sci. Eng.* **136** 61026
[19] King W E, Barth H D, Castillo V M, Gallegos G F, Gibbs J W, Hahn D E, Kamath C and Rubenchik A M 2014 *J. Mater. Process. Technol.* **214** 2915–25
[20] Wu A S, Brown D W, Kumar M, Gallegos G F and King W E 2014 *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.* **45** 6260–70
[21] Yusuf S, Chen Y, Boardman R, Yang S and Gao N 2017 *Metals (Basel).* **7** 64
[22] Lebrun T, Tanigaki K, Horikawa K and Kobayashi H 2014 *Mech. Eng. J.* **1** 1–13
[23] Rombouts M, Kruth J P, Froyen L and Mercelis P 2006 *CIRP Ann. - Manuf. Technol.* **55** 187–92
[24] Li R, Liu J, Shi Y, Wang L and Jiang W 2012 *Int. J. Adv. Manuf. Technol.* **59** 1025–35
[25] Zhao X, Wei Q, Song B, Liu Y, Luo X, Wen S and Shi Y 2015 *Mater. Manuf. Process.* **6914** 37–41
[26] Jelis E, Clemente M, Kerwien S, Ravindra N M and Hespos M R 2015 *JOM* **67** 582–9
[27] Gu D and Shen Y 2009 *Mater. Des.* **30** 2903–10
[28] Gu D and Shen Y 2008 *Appl. Surf. Sci.* **255** 1880–7
[29] Susan D F, Puskar J D, Brooks J A and Robino C V 2000 *Proceedings of the 11th Solid Freeform Fabrication Symposium*
[30] Griffith M L, Harwell L D, Romero J T, Schlienger E, Atwood C L and Smugeresky J E 1997 *Proc. 8th Solid Free. Fabr. Symp.* 387–94
[31] Lewis G K and Schlienger E 2000 *Mater. Des.* **21** 417–23
[32] Xue Y, Pascu A, Horstemeyer M F, Wang L and Wang P T 2010 *Acta Mater.* **58** 4029–38
[33] Yadollahi A, Shamsaei N, Thompson S M and Seely D W 2015 *Mater. Sci. Eng. A* **644** 171–83
[34] Maziasz P ., Payzant E ., Schlienger M . and McHugh K . 1998 *Scr. Mater.* **39** 1471–6
[35] Griffith M ., Schlienger M ., Harwell L ., Oliver M ., Baldwin M ., Ensz M ., Essien M, Brooks J, Robino C ., Smugeresky J ., Hofmeister W ., Wert M . and Nelson D . 1999 *Mater. Des.* **20** 107–13
[36] Brooks J, Robino C, Headley T, Goods S and Griffith M 1999 *Proc. Solid Free. Fabr. Symp.* 375–82
[37] El Kadiri H, Wang L, Horstemeyer M F, Yassar R S, Berry J T, Felicelli S and Wang P T 2008 *Mater. Sci. Eng. A* **494** 10–20
[38] Sun G, Zhou R, Lu J and Mazumder J 2015 *Acta Mater.* **84** 172–89
[39] Mazumder J, Choi J, Nagarathnam K, Koch J and Hetzner D 1997 *JOM* **49** 55–60
[40] Choi J and Chang Y 2005 *Int. J. Mach. Tools Manuf.* **45** 597–607
[41] Cakmak E, Kirka M M, Watkins T R, Cooper R C, An K, Choo H, Wu W, Dehoff R R and Babu S S 2016 *Acta Mater.* **108** 161–75

[42] Dehoff R R, Kirka M M, List F A, Unocic K A and Sames W J 2015 *Mater. Sci. Technol.* **31** 939–44
[43] Peter W H, Nandwana P, Kirka M M, Dehoff R R, Sames W, Erdman D, Eklund A and Howard R 2015 *Undestanding the Role of Hot Isostatic Pressing Parameters on the Microstructural Evolution of Ti-6Al-4V and Inconel 718 Fabricated by Electron Beam Melting*
[44] Murr L E, Gaytan S M, Ramirez D A, Martinez E, Hernandez J, Amato K N, Shindo P W, Medina F R and Wicker R B 2012 *J. Mater. Sci. Technol.* **28** 1–14
[45] Rangaswamy P, Griffith M L, Prime M B, Holden T M, Rogge R B, Edwards J M and Sebring R J 2005 *Mater. Sci. Eng. A* **399** 72–83
[46] Klingbeil N W, Beuth J L, Chin R K and Amon C H 2002 *Int. J. Mech. Sci.* **44** 57–77
[47] Shiomi M, Osakada K, Nakamura K, Yamashita T and Abe F 2004 *CIRP Ann. - Manuf. Technol.* **53** 195–8
[48] Baumers M 2012 *Economic aspects of additive manufacturing : benefits , costs and energy consumption* (Loughborough University)
[49] Kinsella M E 2008 *Additive Manufacturing of Superalloys for Aerospace Applications*