International Journal of Rapid Manufacturing, Volume 9, Issue 2/3, 2020, pp. 194 - 211
DOI:10.1504/IJRAPIDM.2020.10019230

A comparison framework to support the selection of the best additive manufacturing process for specific aerospace applications

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Abstract: Additive Manufacturing (AM) is a cutting-edge technology that provides up to 100% of material efficiency and significant weight reduction which will positively impact aircraft fuel consumption in addition to high design freedom. Consequently, many aerospace companies are considering implementing AM thanks to these benefits. Therefore, the aim of this research is to assist aerospace organisations with a selection among different AM technologies. To enable this, primary data from (8) experts in the field of AM was collected through semi-structured interviews and cross-referenced with secondary data to identify the key factors for consideration in the selection of AM equipment for aerospace applications. Four AM technologies Laser Powder Bed Fusion (LPBF), Electron Beam Powder Bed Fusion (EBPBF), Wire Arc AM (WAAM) & Laser Metal Deposition (LMD) were highlighted by the experts as the most appropriate for aerospace applications. The main outcome of this study is the development of a comparison framework that helps companies select their AM technology depending on their main business or specific application.

Keywords: Additive Manufacturing, aerospace, business drivers, decision-making

1 Introduction

Additive manufacturing (AM) processes are based on the principle of exporting a digital model from a CAD file to build components by adding material layer upon layer (Dutta & Froes 2017; Uriondo et al. 2015). AM freedom of design, jointly with its promising buy-to-fly ratio[1] of up to 1:1 (Bhavar et al. 2014), might especially benefit the aerospace sector, due to the difficulty of machining high performance alloys such as titanium, and given that as little as 5% of the raw material may remain in the finished parts (Kumar & Nair 2017). Amongst the different AM technologies on the market, only a few offer the potential to produce fully dense metal components (Murr et al. 2013; Uriondo et al. 2015; Sun et al. 2013) with similar mechanical properties as traditional methods; thus being suitable for aerospace applications (Joshi & Sheikh 2015; Uriondo et al. 2015). These AM technologies are shown and classified in Figure 1.

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[1] Buy-to-fly is the ratio between the quantity of the starting raw material and that left in the finished component.

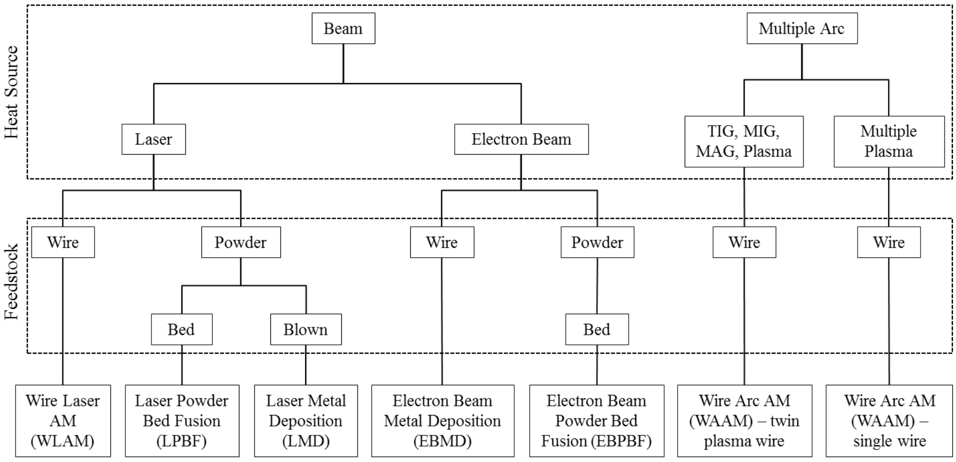

Figure 1: Classification of the metal AM processes regarding the power source and mechanism of adding the raw material - Edited from (Martina 2014).

Among the different technologies presented in Figure 1, powder-bed fusion systems (both laser and electron beam) jointly with Wire Arc AM (WAAM) and Laser Metal Deposition (LMD) have been selected for the purposes of this study since these were the most mentioned by experts when carrying out the semi-structured interviews.

Powder Bed Fusion (PBF) Processes

In these processes, the power source (laser or electron beam) is used to locally melt a layer of powder previously spread according to the data obtain from the CAD model. Once a layer has been scanned, the build station piston moves downwards by a fixed amount (equal to the layer thickness), and a new layer of powder is spread by the coater (Bhavar et al. 2014) as shown in Figure 2.

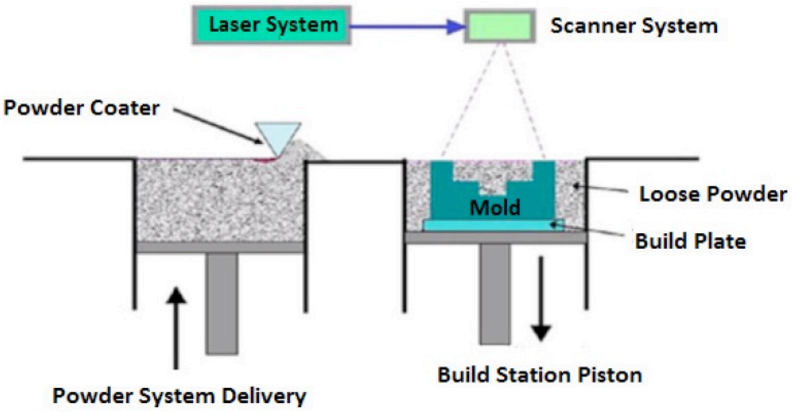

Figure 2: Schematic of PBF processes (Dutta & Froes 2017)

These processes use a chamber under vacuum or filled with inert gas, to protect the powder particles from humidity and oxygen in order to avoid oxidation and consequent degradation of the mechanical properties. The maximum build volume available in PBF systems is limited due to the difficulty of managing large amounts of powder hence, the size of the parts that can be built is also limited (Joshi & Sheikh 2015; Vaezi et al. 2013; Williams 2016). Additionally, in some PBF processes the powder is preheated at elevated temperatures to minimise the development of residual stresses caused by the rapid heating and cooling experienced by the material (Bhavar et al. 2014; Uriondo et al. 2015).

Laser Powder Bed Fusion (LPBF)

LPBF processes potentially enable production of fully dense components and might achieve complete solidification of parts by completely melting the powder; in practice though this is rarely achieved and most of the components built by LPBF still need Hot Isostatic Pressing (HIPing) (Bhavar et al. 2014; Gu 2015; Song et al. 2012). Moreover, LPBF also provides high levels of accuracy and surface finish which enables the production of complex shaped parts with high resolution (Brandl et al. 2012). However, the application of locally concentrated energy potentially results in residual stresses which could aid crack initiation (Zaeh & Branner 2010).

Electron Beam Powder Bed Fusion (EBPBF)

EBPBF provides higher energy density and more efficient energy transfer since the powder is melted using electrons, which are nearly absorbed by the metal powder, as compared to LPBF in which some energy is lost due to the reflectivity of the metal powder (Sames 2015; N. Williams et al. 2016a). Secondly, the deeper absorption experimented in EBPBF enables a higher energy density than LPBF without large amounts of vaporisation; although this contributes to deeper layer thickness as compared to LPBF (Trevisan et al. 2017; Ghouse et al. 2017) This contributes to higher build rates, although at the cost of poorer tolerances and surface finish than LPBF (Guo & Leu 2013; Bhavar et al. 2014; Moiduddin et al. 2016).

Additionally, the powder is pre-sintered in EBPBF processes which avoids powder particles spreading due to the high electric and magnetic fields in EBPBF as compared to LPBF; which on the other hand makes it more difficult to remove the loose powder (Sames 2015). Moreover, while LPBF processes pre-heat the powder bed up to 200ºC (Bhavar et al. 2014); EBPBF technology maintains the pre-heating close to the melting point (Price et al. 2014), which benefits the union of powder particles and leads to better mechanical properties (Price et al. 2014; Murr et al. 2013).

The presence of vacuum atmosphere in EBPBF favours slower cooling rates; smaller grain sizes (Uriondo et al. 2015) and lower residual stresses (Bhavar et al. 2014; Uriondo et al. 2015) as compared to LPBF which uses inert gases such as Argon or Nitrogen (Bhavar et al. 2014). Lastly, the higher energy efficiency achieved in EBPBF as compared to LPBF is conducive to reductions in operating costs (Gibson et al. 2015; Uriondo et al. 2015). Nonetheless, LPBF processes are widely used in industry due to their lower machine costs, higher accuracy, and higher available build volume (Bhavar et al. 2014).

Directed Energy Deposition (DED) Processes

These processes build the component by melting the raw material while it is being deposited in form of blown-powder (LMD) or wire (WAAM) (Uriondo et al. 2015). In this case, both processes are assisted by shielding gas (normally argon) to minimise the oxygen presence when melting the feedstock (Gu et al. 2017; Bhavar et al. 2014).

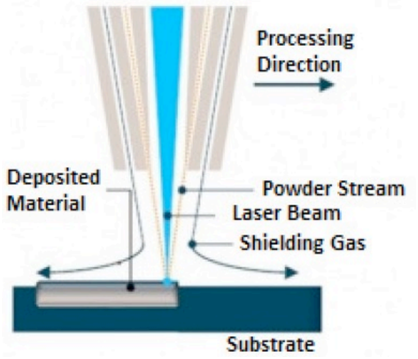

Figure 3: Schematic of DED processes – LMD (Geyer 2016)

While WAAM uses an electric or plasma arc to melt the wire and deposit it at a controlled rate onto the previous layer (Zhang et al. 2016; Wang et al. 2013); LMD uses an integrated powder feeder system which directly deposits the blown powder, employing a high power laser of up to 3 kW (Graf et al. 2012; Gu et al. 2017). Table 1 shows a comparison between powder-feed and wire-feed AM technology.

Powder-feed technology (LMD and PBF)	Wire-feed technology (WAAM)
Lower deposition rates (Colegrove 2010)	Higher deposition rates (Dilip & Ram 2012)
Lower material efficiency (~50%) (Colegrove 2010; D. Ding et al. 2015b)	Higher material efficiency of the process (90% - 100%)(Colegrove 2010; D. Ding et al. 2015b), although finish-machining might be required (D. Ding et al. 2015a; S. W. Williams et al. 2016b).
Possible quality and flaw issues (Colegrove 2010)	No inherent defects (Colegrove 2010)
Very high part cost (Colegrove 2010; D. Ding et al. 2015b)	Low part cost (Busachi et al., 2017, Busachi et al., 2018, Colegrove 2010; D. Ding et al. 2015b)
Higher complexity levels achieved (Colegrove 2010)	Lower to medium level of complexity achieved (Colegrove 2010)
Higher accuracy achieved (Gibson et al. 2015)	Lower accuracy achieved (Szost et al. 2016; Zhang et al. 2016)
Smaller particle size and higher geometrical accuracy (D. Ding et al. 2015b)	Bigger feature size and lower geometrical accuracy (D. Ding et al. 2015b)
Potential risks of contamination issues (Martina et al. 2012)	Cleaner and more environmental friendly (D. Ding et al. 2015b)
Safety issues - Needs to be confined and presents fire hazards (Williams et al. 2017)	No powder handling required (Zhang et al. 2016)

Table 1: Characteristics of powder and wire feed technologies

Although LMD is capable of producing more complex components due to its higher dimensional accuracy; WAAM has higher deposition rates enabling it to significantly reduce cost and lead times compared to conventional manufacturing methods (Olakanmi et al. 2015; Williams 2016). Moreover, WAAM provides potentially unlimited build volume since it is not limited by a chamber, especially if local shielding solutions are deployed (J. Ding et al. 2015; Williams 2016; Dilip & Ram 2012). DED technologies are characterised by their high freedom of design due to the flexibility of their devices (Dutta & Froes 2017); which makes especially LMD unique in the sense that can be used not only to build components, but also to repair high value parts as turbine blades, blisks, and engine combustion chambers (Dutta & Froes 2017; Liu et al. 2017).

2 Research Methods

Although some technical data on AM equipment can be gathered from the literature; there is still lack of knowledge on how to assess the selection of these technologies for aerospace applications (Gibson et al. 2015). Hence, an exploratory study was carried out to determine the main factors involved in this selection process. Thereby, a non-probabilistic judgement sampling of eight AM experts from Spanish and British academia and manufacturing organisations (Appendix 1) were selected; within this cohort five semi-structured one-to-one interviews and one multi-person focus group (Kvale 1996) were recorded. The interview data was subjected to a structured thematic analysis. The quantitative findings from the literature review were combined with the qualitative gathered from the interviews. Two spider-diagrams were generated to summarise these results. A score of 10 would have been given to a process meeting all requirements in a particular category.

3 Results

Comparison between all processes based on literature

Table 2 summarises the characteristics of all the aforementioned technologies, thus comparing them with regards to the different technical parameters that must be considered in AM.

Parameter	LPBF	EBPBF	LMD	WAAM
Energy (W)	100 - 1000 (Bhavar et al. 2014)	~ 3500 (Baumers et al. 2016)	~500 - 3000 (Cao & Gu 2015)	2000-4000 (D. Ding et al. 2015b)
Overall Process Efficiency[2]	2% – 5% (D. Ding et al. 2015b)	15% – 20% (D. Ding et al. 2015b)	2 – 5% (D. Ding et al. 2015b)	~ 70% (Ríos et al. 2018)
Dimensional Accuracy (mm)	± 0.04 (Gu 2015)	± 0.05 (D. Ding et al. 2015a)	± 0.13 (D. Ding et al. 2015b)	± 0.2 (D. Ding et al. 2015b)
Build Rates (for Ti6Al4V) (Kg/h)	0.1 – 0.18 (Bhavar et al. 2014)	0.26 – 0.36 (Dutta & Froes 2017)	0.1 – 1.41 (Dutta & Froes 2017)	0.5 – 4 (Williams 2016b)
Maximum Build volume (mm x mm x mm)	500 x 350 x 300 (Bhavar et al. 2014)	200 x 200 x 180 (Bhavar et al. 2014)	900 x 1500 x 900 (Frazier 2014)	Potentially unlimited (Williams 2016b)
Layer Thickness (μm)	20 – 100 (Gu 2015; Ruban et al. 2014)	~ 100 (Murr et al. 2012)	500 – 1000 (Dutta & Froes 2017)	1000 – 2000 (S. W. Williams et al. 2016)
Surface Roughness (μm)	4 – 11 (Vayre et al. 2012; Gu 2015)	25 – 35 (Vayre et al. 2012)	20 – 50 (Gu 2015; Dutta & Froes 2017)	500 (S. W. Williams et al. 2016)
Minimum feature Size (μm)	40 – 200 (Bhavar et al. 2014)	100 (Bhavar et al. 2014)	150 – 200 (Mahamood et al. 2013)	2000 (Williams 2016)

Table 2: Technical Comparison among metal AM technologies used in the Aerospace industry

Based on some parameters shown in Table 2 a method can be derived to assist in process selection. It is desirable in all AM processes to maximise the build rate in order to reduce build time and cost. It can be seen from Table 2 that the build rate increases with layer height. Through consideration of melt pool dynamics this can be expected, if the layer height is increased then the melt pool width will also increase. In fact, for a single axisymmetric heat source the build rate will increase with the square of the layer height as shown schematically in Figure 4a with the four processes overlaid. However, because the melt pool width also increases with the layer height the minimum resolvable feature size achievable will also increase. In this case a linear dependence of the minimum feature resolution on the layer height will occur, as shown in Figure 4b. Hence, for any application the starting point for process selection should be what is the minimum required feature

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[2] Dimensionless ratio of workpiece net heat-input to the electrical energy provided to the power source

size? This will determine the layer height and therefore the required process with the maximum build rate for that feature size.

A further consideration could be the surface finish in the as built condition. Due to the effect of the natural shape of the weld pool when building a component in a layer wise fashion leads to scalloping effect in the outside surface - (ignoring any effects due to particulates). The size of the scallops will depend linearly on the layer height as shown schematically in Figure 5. Therefore, if the component is to be used in the as built condition then, in addition to resolution, surface finish could also be a consideration in process selection.

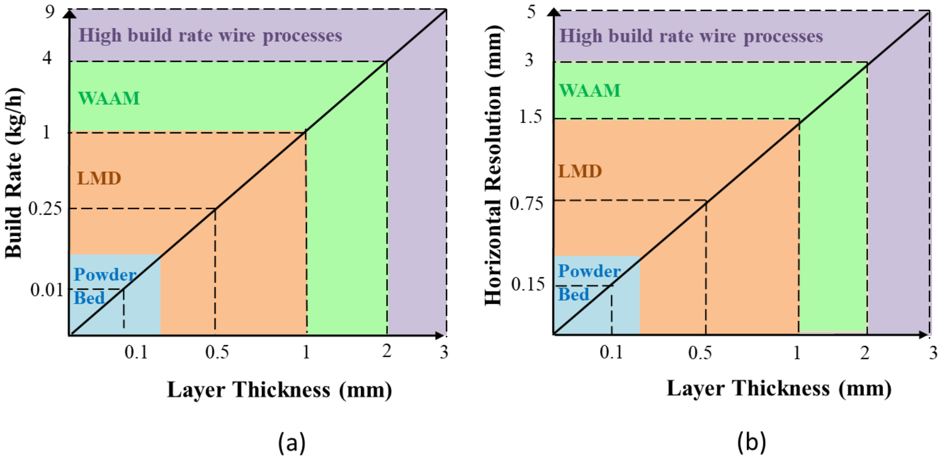

Figure 4: Relationship between layer thickness and build rate (a); and layer thickness and horizontal resolution (b)

Similarly, a relationship between the surface topology (quantitative features) and the layer thickness can be determined. Thereby, the surface topology will depend linearly on the layer thickness as shown in Figure 5.

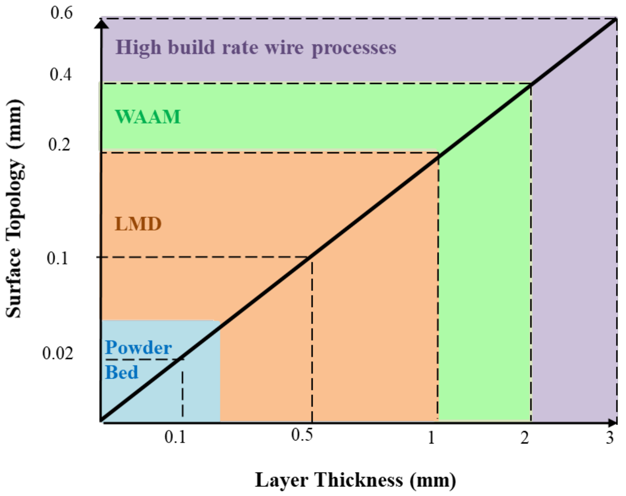

Figure 5: Relationship between layer thickness and surface topology

4 Discussion

Those results obtained from the interviews were cross-referenced against Table 2 and the secondary data obtained from OEMs to create a comparison framework for the selection of AM technologies according to company's business drivers. The factors involved in the selection of AM equipment will be discussed in this section.

Materials

Mix material capability is referred to by Participant 4 as a major driver for WAAM technology since "it is straightforward to feed one or more wires at a time…". Similarly, Participants 6 and 7 see it as a limitation of PBF equipment; where using multiple materials might enhance contamination risks. Hence, it is often needed to match material with machine, or even conditioning different rooms for each alloy; resulting in a considerable increase in costs. Furthermore, Participant 7 states that "you wouldn't use aluminium in EBPBF since it evaporates because the temperatures achieved are too high, so, in this case you'd use laser. You could do it by decreasing the power, but you then lose efficiency". In addition, the fact of EBPBF being under vacuum contributes to decrease the boiling point so materials such as Aluminium do evaporate more easily.

Complexity

It is widely agreed among participants that PBF technologies will provide more freedom of design than DED processes. Moreover, Participant 7 specifies that "laser PBF machines allow very good complexity compared to EBPBF because the particle size and laser spot size are much finer". In addition, Participants 1, 2, and 3 point out that "you will use PBF processes if you want to reduce the number of assemblies in the outcome".

Maximum Volume Available

It is agreed that PBF processes limit the production of big components; DED being more suitable for this purpose. Indeed, Participant 4 states this would be a major driver to choose WAAM technology. Participant 7 specifies that “laser technologies tend to have bigger chambers than in EBPBF”. Table 3 shows secondary data extracted from OEMs regarding their limited build chamber.

AM Process	Technology	Maximum build size	Source
Laser PBF	Renishaw; RenAM 500M	250mm x 250mm x 350mm	(Renishaw Plc. 2017)
Laser PBF	E.O.S; EOS M400	400mm x 400mm x 400mm	(EOS Manufacturing Solutions 2015)
Laser PBF	AddUp; FormUp 350	350mm x 350mm x 350mm	(AddUp Global Additive Solutions 2017)
Laser PBF	Concept Laser; X Line 2000R	800mm x 400mm x 500mm	(GE Additive n.d.)
Laser PBF	GE Additive; BETA	1100mm x 1100mm x 300mm	(GE Additive 2017)
EBPBF	Arcam Q10plus	200mm x 200mm x 280mm	(Arcam EBM 2017)
EBPBF	Arcam A2X	200mm x 200mm x 380mm	(Arcam EBM 2017)
LMD	Optomec; LENS 800R	900mm x 1500mm x 900mm	(Optomec 2017)

Table 3: Limited maximum build size of different PBF OEMs

Quality

Participants 5, 6 and 7 agree that the quality of the outcome is a decisive factor in such critical sector as the aerospace. They also agree that PBF processes provide better surface finish and accuracy than DED. Participant 6 says that “with the current technologies there is an inevitable trade-off between surface finish and component size”. Moreover, Participant 7 also states that “laser processes give better surface finish than EBPBF; although EBPBF is more efficient”. Furthermore, Participants 5 and 7 argue that the thinner the layer; the more accurate and the better the resolution, in agreement with what previously stated in Figure 4.

Mechanical Properties

Participant 4 states that WAAM is much less prone to porosity and that “all AM processes will give origin to residual stress”. However, “if buckling during build is avoided, stresses can be dealt with through a relatively short heat-treatment”. Participant 5 also choose the equipment that guaranties higher mechanical properties when manufacturing Ti6Al4V; while Participant 8 selects the one which provides better fatigue properties.

Build Rates

All participants consider it an important factor when evaluating the equipment in aerospace. Participants 4, 5, and 8 state that DED processes enable high deposition rates at economical way. Moreover, Participant 5 and 7 agree that EBPBF is faster than laser technologies due to their bigger particle sizes and higher energy power. Furthermore, Participant 7 points out that “the bigger chambers in EBPBF allow to make more parts at a time than laser PBF”. Additionally, it can also be deducted from Table 2 that layer thickness impacts build rates.

Costs

When selecting AM equipment, not only will machinery costs be considered; but also raw material, operating, and maintenance costs. Regarding machinery costs, Participant 4 states that “we don’t have commercial equipment yet, we buy welding equipment and we put it together ourselves”. Participant 7 relates the low price of laser PBF processes compared to EBPBF to the higher range of suppliers in laser technologies. Table 4 shows the capital investment required in some AM machines.

Machinery	Costs
ARCAM (EBPBF)	£0.6M – £1.6M (Dahlbom 2013)
EOS M270/M280 (LPBF)	£800,000 (Rengers 2012)
Renishaw AM250 (LPBF)	£750,000 (Nelson 2013)
WAAM	£90,000 - £210,000 (S. W. Williams et al. 2016b)
LMD	£250,000 (Optomec 2016)

Table 4: AM Equipment: Capital Investment Required (per machine)

Participant 6 and 7 consider material costs when breaking down the costs associated to AM machinery. For instance, Participant 7 states that “EBPBF powder is 3 times cheaper than laser powder due to its higher particle size distribution”. Table 5 compares the cost of different AM alloys depending on the material feedstock used.

Material Feedstock	Ti6Al4V	Inconel 625	Stainless Steel 316
Wire – 1.1mm Diameter	$119/Kg	$51.30/Kg	$10.2/Kg
Wire – 1.6mm Diameter	$110/Kg	$48.83/Kg	$10/Kg
Wire – 3.2mm Diameter	$99/Kg	$46.3/Kg	$10.46/Kg
Powder AM Grade	$264.3/Kg	$105.7/Kg	$22/Kg

Table 5: Comparison between AM wire and powder in the US market (Sciaky 2015)

Participant 4 mentions the operation costs and energy efficiency as major factors when choosing WAAM equipment; stating that large cost savings can be achieved compared to machining from solid. Moreover, although electricity is considered as a relatively minor factor of the total cost, WAAM processes achieve much higher energy efficiencies (70%) than EBPBF (20%) and laser technologies (5%) as shown in Table 2. Moreover, Participant 7 points out that “it is much cheaper to operate in EBPBF than laser PBF because you melt thicker layers”. Participant 6 also consider “the best maintenance price that the supplier can provide us”. Thereby, it is considered that powder-feed equipment will require more maintenance than wire-feed (Sames et al. 2016); to maintain the levels of humidity, shielding gas, temperature, etc., and the chamber will need to be cleaned regularly to avoid powder contamination issues.

Figure 6 shows a cost comparison among the AM equipment considering these four sub-factors.

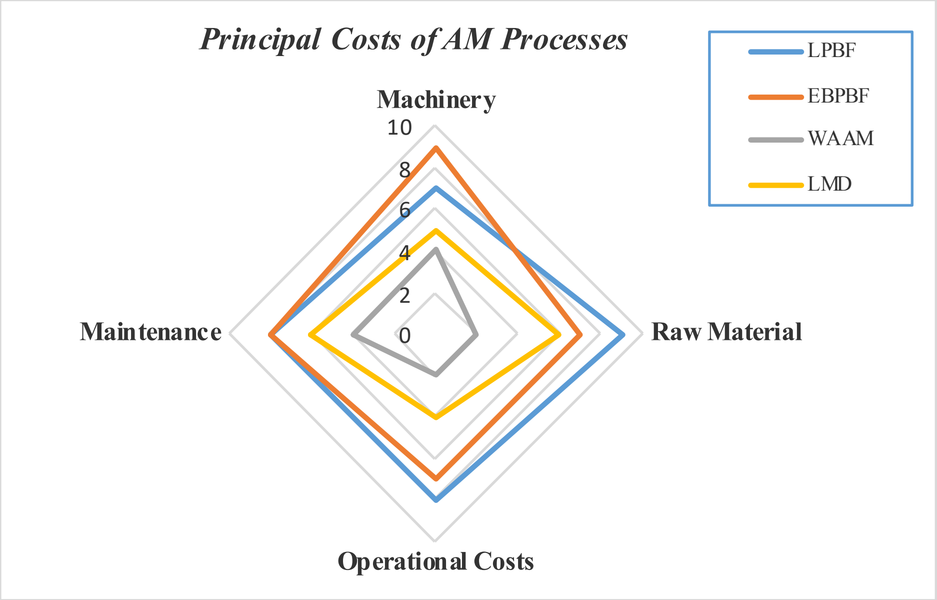

Figure 6: AM Technologies: Cost Comparison Framework

The data obtained in Figure 6 was cross-referenced with the primary and secondary data obtained and used to create a new category called ‘overall cost’ which was integrated in the metal AM comparison framework represented in Figure 7.

Regarding Figure 7, it is evident that a trade-off is inevitable: between build rates, maximum volume available, accuracy, surface finish and complexity. Hence, the component specifications will influence the technology chosen as shown in Table 6.

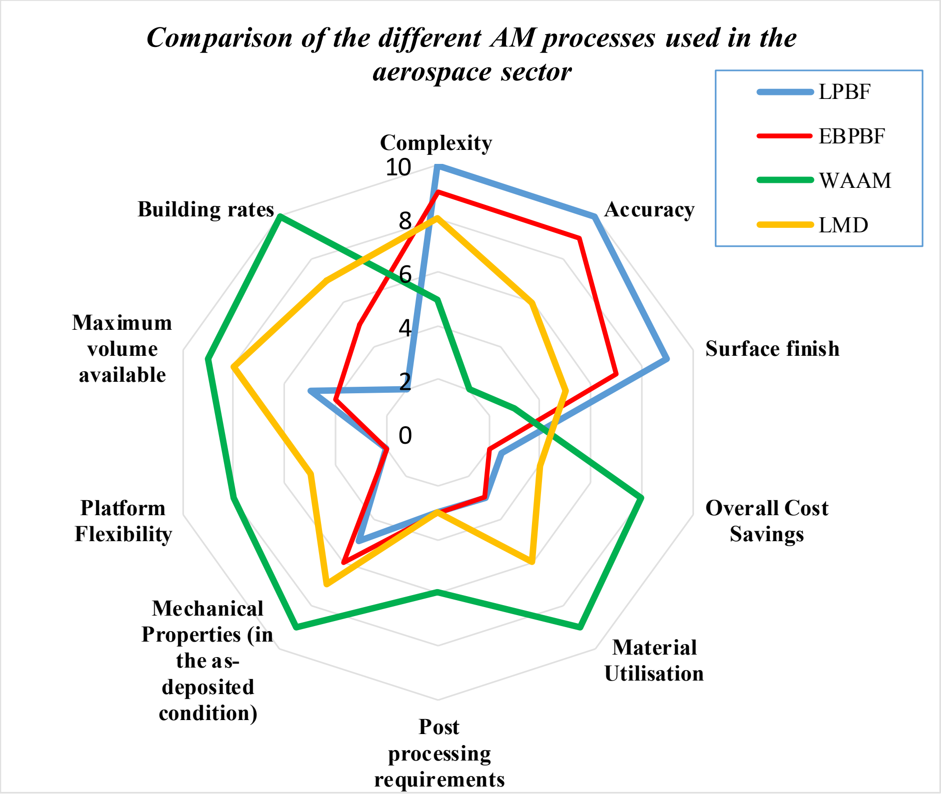

Figure 7: Comparison framework among different metal AM technologies used in the aerospace industry

Main Business Drivers		
DED	WAAM	Cost reduction Manufacture big and not overly complex components Lead time reduction Repair applications Reduction of material wasted E.g. wing ribs, flanges, stiffened panels, cruciform, etc.
	LMD	
PBF	LPBF	Manufacture small and complex components High resolution needed High accuracy needed E.g. turbine blades, complex engine components, etc.
	EBPBF	

Table 6 : Business drivers for the different metal AM equipment used in the aerospace industry

As it can be seen in Table 6, the main business drivers to select WAAM equipment are the lead time reduction, buy-to-fly ratio reduction, and costs. Its excellent mechanical properties after post-processing jointly with its capability of reducing the buy-to-fly ratio have made DED technologies, and WAAM in particular, suitable to build medium to large aircraft components such as cruciform, flanges, stiffened panels, wing ribs, etc.; since they have buy-to-fly ratios of 10-20:1 as they are normally machined from billets or large forgings (Joshi & Sheikh 2015; S. W. Williams et al. 2016b). Similarly, titanium parts often present buy-to-fly ratios up to 40:1 and are highly difficult to machine costing nearly $2,200/Kg machined. This cost can be reduced by 50% using AM technology, especially WAAM processes since they promise buy-to-fly ratios below 2 (Dutta & Froes 2017).

Furthermore, the lower thermal input of DED technology, especially in LMD, results in lower distortion and thermal damage in the base material; which jointly with its high platform flexibility also enables their application in maintenance activities (Graf et al. 2012; Liu et al. 2017). For instance, not only has Optomec used LMD to manufacture gas turbine parts in the Bell Helicopter (Guo & Leu 2013); but it has also used it for the repair of gas turbine engine parts such as aerofoils, blisks, caners, stators, rotors, or diffusers (Guo & Leu 2013). Indeed, it has been argued that expensive aerospace titanium components such as blades, casings, or flanges could be repaired by using this technology at 20% - 40% of the cost of the new part by using LMD (Dutta & Froes 2017; Mahamood et al. 2013). Nevertheless, EBPBF is also used for critical repairs in turbine blades; since residual stresses might appear in DED processes due to the uneven cooling and heating rates (Wong & Hernandez 2012).

On the other hand, it is advised to use PBF technologies to produce aircraft lightweight components due to their capability of producing complex shapes with thin walls (Gibson et al. 2015). This might be critical in aerospace applications since it is argued that for each kilogram reduced; it is possible to save $3,000 per year in fuel consumption (Beyer 2014;

Forbush & Edwards 2014). For instance, EOS produced a steel nacelle hinge bracket for an Airbus 320 using LPBF; which contributed to achieve 10 Kg weight reduction per aircraft and a decrease in raw material consumption by 75% (Joshi & Sheikh 2015; Warwick 2013). Furthermore, Airbus has also used Concept Laser LPBF technology to save 30% of weight in a bracket connector for the A350 XWB (Liu et al. 2017). In addition, EBPBF has also been used to create lattice structures; which enabled reduced weight with increased stiffness (Guo & Leu 2013).

Moreover, Arcam EBM (prior to being acquired by GE) was used to produce the GE LEAP engine fuel nozzle that enabled it to reduce 20 assemblies into a single unit and reduce weight by 25% (Tomas Kellner 2017). Siemens also used LPBF to manufacture an Inconel turbine blade which reduced lead times by 2 or 3 months while adding complex inner channels to improve cooling (Siebert 2017). Similarly, Concept Laser LPBF (prior to being acquired by GE) has also been used to produce turbine blades to achieve thin wall parts with complex inner channels (Guo & Leu 2013). Moreover, PBF technologies are commonly used to produce small but highly critical aircraft engine components where high resolution, surface finish, and accuracy are needed (Lyons 2012; Williams 2016).

5 Conclusion

In conclusion, among the four AM processes selected for this study, there is not a unique AM technology that suits every metal aerospace application. Instead, there is a significant trade-off between build rates, volume available, and buy-to-fly ratio reduction (DED processes); and accuracy, surface finish, and shape complexity of the outcome (PBF equipment). Thereby, a framework for comparison among metal AM technologies is provided; in which the selection of equipment is assessed depending on the company's business drivers. Hence, the complexity achieved in PBF processes benefit the business drivers of improving the component functionality, assembly reduction, or weight reduction. On the other hand, buy-to-fly ratio reduction, cost reduction, and possibility of build big components (which also reduce the assembly function) are drivers easily met through DED. Lastly, LMD technologies might be chosen for repair applications due to the high flexibility provided, or for the manufacture of net-shape components of medium size.

6 Limitations and Recommendations for Future Research

The main limitation of this research resides in the small sample size used; which limits the generalisation of the results across the aerospace industry. Furthermore, although the materials are shown as an important factor by participants when selecting AM equipment; their choice is not represented in the comparison framework. Therefore, it is recommended for further study to enlarge the sample size and include participants from OEMs in order to enhance internal reliability of the research. Further research is underway to develop an improved decision framework considering other factors involved in the decision-making including selection of metal alloys, preferred aerospace applications and other supply chain factors. A follow-up paper is expected.

7 Acknowledgements

We would like to thank the Warwick Manufacturing Group from the University of Warwick and the Welding Engineering and Laser Processing Centre from the University of Cranfield for the support and resources provided to carry out this research. Furthermore, we acknowledge the University of Warwick for giving this research the ethical approval required to carried out the interviews and the experts who accepted to take part in the research and contributed to its outcome.

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Appendix 1

Participant	Job Title	Organisation
Participant 1	AM Research Engineer	University Research Centre
Participant 2	AM Research Engineer	University Research Centre
Participant 3	AM Research Engineer	University Research Centre
Participant 4	AM Senior Lecturer and Programme Manager	Engineering Research Centre
Participant 5	Associate Professor	Manufacturing Research Centre
Participant 6	Head of Additive Manufacturing	Aerospace Tier 1 Company
Participant 7	Principal Engineer	Industrial & Technology Centre
Participant 8	Technical Sales Manager	Aerospace Tier 1 Company

Table 7: Interview Participants' Job Roles

A comparison framework to support the selection of the best additive manufacturing process for specific aerospace applications

Garcia-Colomo, Alberto

2020-05-31

Garcia-Colomo A, Wood D, Martina F, Williams S. (2020) A comparison framework to support the selection of the best additive manufacturing process for specific aerospace applications. International Journal of Rapid Manufacturing, Volume 9, Issue 2-3, June 2020, pp.194-211

https://doi.org/10.1504/IJRAPIDM.2020.10019230