NATIONAL CENTRE ADDITIVE MANUFACTURING

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Understanding the opportunities and challenges building large parts in PBF LB

CATAPULT High Value Manufacturing

About Us

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Figure 1 (Cover Image): Launcher rocket nozzle produced in CuCrZz Alloy On EOS AMCM 4K. Courtesy of AMCM and Launcher.

The MTC is the home of the UK's National Centre for Additive Manufacturing (NCAM), which is the UK's independent AM body supporting supply chain companies adopt and mature additive manufacturing. One of NCAM's focus areas for research is enabling large PBF-LB components. Current research topics include: Bench marking state of the art 'large' PBF-LB machines, understanding build stoppages, evaluating multi laser melting strategies, and design for 'large' components. This is in addition to the multiple other research strands across metal, polymer. and ceramic AM.

1. Introduction

Commercial Metal Powder Bed Fusion – Laser Based [PBF-LB] machines have existed since the mid-1990s. One of the earliest examples of a commercial offering is the EOSINT M250, which was launched in 1995 [1], with a 250x250x200 build volume and a 100W laser [2]. Since this time there has been a marked acceleration in the development and uptake of machines, materials, and end applications. However, one major constraint in the use of this technology is the size of parts that can be manufactured.

One method of overcoming part size limitations is to initially section parts during the design process, build those sections and finally join at a later point downstream, possibly by a conventional process such as welding [3]. In some applications this is not practical, complex heat exchangers or thrust chambers for instance. In applications where size of build volume is the limiting factor, this can often be the end of the road for the application, assuming no other manufacturing technique can produce the component.

This paper will explore the recent growth in 'large' PBF-LB machines which are enabling larger parts to be manufactured in metal additive manufacturing. The paper will discuss each stage in the PBF-LB build process and will investigate how large parts affect them, including discussing challenges, solutions, and areas for further work.

Figure 2 Welding together tidal turbines sections produced using PBF-LB. Courtesy of Biome Renewables/Nova Scotia Community College.

To discuss this topic, it is necessary to define what constitutes a “large” PBF-LB machine. Although somewhat arbitrary it is useful to be able to categorise AM machines into the build volume size allowing a comparison. This paper defines a “large” machine to be a build volume which has a dimension greater than 400 mm in either of the X, Y, Z axes. The value of 400 mm was chosen in this paper as it relates to the EOS M400, a machine which has an installed base of over 370 units worldwide [4]. To date, as far as these authors are aware, there is no other platform of this build volume or larger which has achieved this level of adoption. Given the widespread adoption of this machine and the growing number of machines with build volumes beyond this value, it was decided for the purposes of this report that an M400 would be considered a “medium” sized build volume.

Similarly for the purposes of comparison “small” and “medium” are also defined below. It should be noted that this categorisation has been adopted for the purposes of this report and is not formally recognised.

Machine Build Volume Categories

If a machine has a build volume that exceeds any of the following ranges in 1 or more build volume dimensions (X, Y, Z) then it will fall in the following categories:

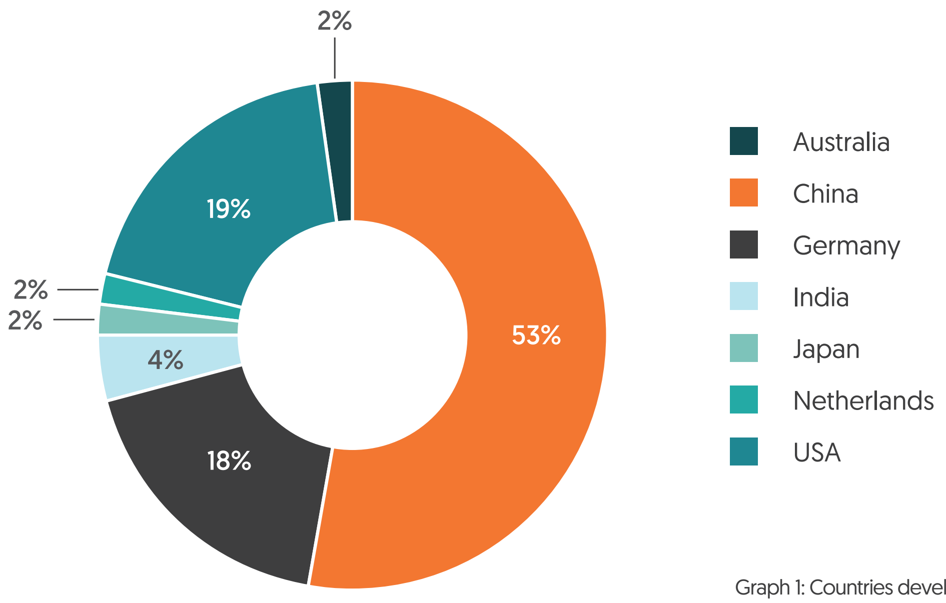
Dimension in (X, Y, Z)	Build Volume Category
<200mm	Small
=>200-400mm	Medium
>400mm	Large

Table 1: Build volume categories

2. Market Overview

One challenge that is continually faced by AM users is being able to fit parts within the constraints of the build volumes they have at hand. Solving this issue is now a hotly contested race between manufacturers. From 2020 to 2022 there has been a 100% increase in the number of 'large' PBF-LB machines on the market, with 50 different 'large' PBF-LB models now available from 18 different manufactures (Table 1).

Typical machines within this category of 'large' PBF-LB machines use multiple lasers to either span a larger bed size and/or improve the build rate. To achieve this, different manufacturers have taken different multi-laser approaches. These can be broadly covered in two overarching categories: 'full field' and 'sector-based melting'. Full field lasers can melt at any point within the build area, resulting in the ability for all lasers to be utilised regardless of the component position on the plate. The second approach is 'sector-based melting' where the platform is segmented into sections where each laser predominantly melts, with defined overlap regions set to connect the different laser sectors. Other methods that manufacturers are taking to increase the size of the build volume, include extending the build volume in one or two axis, such as increasing the height of the Z-axis (and thus not requiring a different laser arrangement) or extending the X-axis and mostly likely adding additional lasers using a sector-based melting approach.



Graph 1: Countries developing 'large' PBF-LB systems in 2022.

Size category of PBF-LB Machines	No. of PBF-LB Machine Models in 2020	No. of PBF-LB Machine Models in 2022	Delta	% Increase
Small (<200mm)	56	67	11	20%
Medium (=>200-400mm)	65	75	10	15%
Large (=>400mm)	25	50	25	100%
Total No. of PBF-LB M/Cs	146	192	46	32%

Table 2: Change in number of different models of PBF-LB machine from 2020 to 2022, sorted into size categories. Data pulled from publicly available sources.

Within this new market segment, industry leaders such as AMCM [5], SLM Solutions [6], and Velo3D [7] have capitalised on fast moving markets such as the space sector to fuel new growth. New entrants such as Velo3D are making significant inroads into this marketplace, recently launching their Sapphire XC machine to meet customer demand in this sector, fuelled by one of their main customers SpaceX, who by 2021 had acquired 22 Velo3D systems [8]. SLM Solutions launched the NXG XII 600 machine in November 2020, equipped with 12 x 1 kW lasers with the aim of improving build rate, across a 600 x 600 x 600 mm build chamber [9].

Developments in China have largely gone unreported in western AM media, however, market entrants like Bright Light Technologies (BLT) [10], Farsoon [11], HBD3D [12], and Eplus3D [13], have launched a collection of 'large' PBF-LB machines to the market. It has been widely assumed that a wide selection of major PBF-LB manufacturers are working toward developing platforms that are 1 m in build volume dimension, this has been verified by multiple different industry sources and public examples such as SLM Solution NXG XII 600 E [14], GE ATLAS [15] or Renishaw LAMDA projects [16].
Currently, at the time of publication (October 2022) The Eplus3D EP-M1250 machine is currently the largest build volume with dimensions of 1258 x 1258 x 1350 mm (X, Y, Z). With a build volume of 2.14 m3. Currently this machine comes in 9 laser 500W, 700W, or 1000W configuration. This is followed by the S1000 machine with dimensions of 1200 x 600 x 1500 mm (1.08 m3). One additional development in this space includes SLM Solution's "Large part machine" concept which aims to produce cylindrical parts with a diameter of 1.8 meters and a height of 1.6 meters or alternatively long parts with a dimension of up to 3.0 x 1.2 x 1.2 meters. Further details are not yet available for this machine.

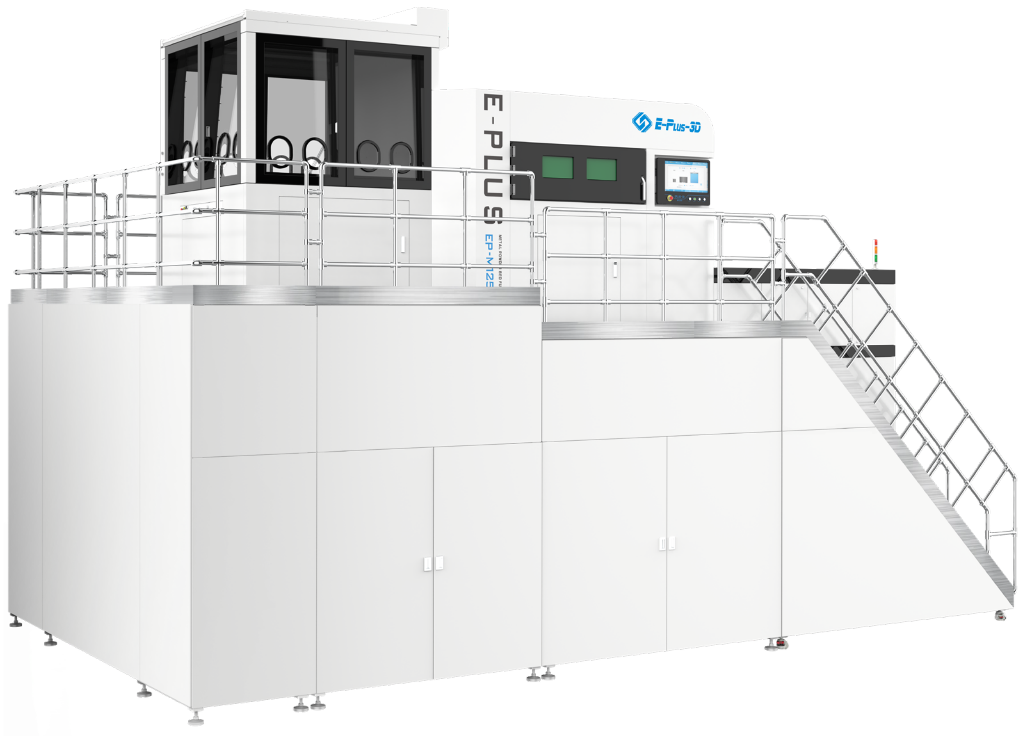


Figure 3: Eplus3D EP-M1250 representation the largest PBF-LB machine by build volume at 1258 x 1258 x 1350 mm (X, Y, Z). Image courtesy of Eplus3D.

One notable machine, using laser optics mounted on an XY gantry system, is the Adira Add Creator which has a build envelope of 1050 x 1050 x 500 mm [16]. This system is described as a tiled laser melting system. A similar system was developed by Aeroswift [17]. For the sake of comparison these systems have not been included in this comparison as their optical systems differ.

Typically, machines in the 'large' PBF-LB category, sell within the range of £1M to£4M.

Manufacturer	Machine Model	Build Volume Dimensions (mm)	Build Volume (mm^3)
Eplus3D	EP-M1250	1,258 x 1,258 x 1350	2,136,461,400
BLT	S1000	1,200 x 600 x 1,500	1,080,000,000
SLM Solutions	NXG XII 600E	600 x 600 x 1,500	540,000,000
Farsoon	FS621M	620 x 620 x 1,100	422,840,000
Farsoon	FS621M-4	620 x 620 x 1,100	422,840,000
BLT	S800	800 x 800 x 600	384,000,000
HBD	HBD-1000	600 x 600 x 1,000	360,000,000
Eplus3D	EP-M650	650 x 650 x 800	338,000,000
3D Mectronic	3DM AMS 800	800 x 800 x 500	320,000,000
HBD	HBD-1500	460 x 460 x 1,500	317,400,000
Velo3D	Sapphire XC 1Mz	600 x 1,000	282,743,339
Eplus3D	EP-M450H	455 x 455 x 1,080	227,727,500
BLT	S600	600 x 600 x 600	216,000,000
SLM Solutions	NXG XII 600	600 x 600 x 600	216,000,000
AMCM	AMCM 4K-1	450 x 450 x 1,000	202,500,000
AMCM	AMCM 4K-4	450 x 450 x 1,000	202,500,000
Matsuura	LUMEX Avance-60	600 x 600 x 500	180,000,000
Zrapid	iSLM500D	500 x 400 x 800	160,000,000
GE Additive	X Line 2000R	800 x 400 x 500	160,000,000
Velo3D	Sapphire XC	600 x 550	155,508,836

Table 3: Top 20 'large' PBF-LB machines sorted into decreasing build volume.

3. Large PBF-LB Applications

Applications within 'large' PBF-LB components are typically heavily protected by IP during development and deployment. Few companies have openly declared their use of 'large' PBF-LB, however it is assumed that there has been significant demand to warrant the large number of machines developed by machine OEMs. Companies that have publicly announced their use of such machines include names such as: Mann Energy solutions [19], Collins Aerospace [20], Morf3D [21], Divergent [22], Orbex [5], Sintavia [23] and Launcher [24].

A user may choose to utilise a larger build volume for different reasons including allowing for more parts to be built within the same build volume, increasing productivity, or for making larger components. The second, and more pertinent to this text, is that the designer has more freedom to explore the possibility of building larger parts within that build volume. For example, a wider range of potential applications could be manufactured using PBF-LB technologies, that were previously limited by the size of the build chamber [25]. This can add further benefits when designers are able to consolidate many parts into fewer or only one part. Simplifying the manufacturing process, usually with performance benefits in tow. Nowhere is this better demonstrated than in space componentry. Gradl et al demonstrated across a variety of components schedule reductions up to 45%, part count reduction of 252 to 6, and cost reductions of 30%[26]. It should be noted that consolidation of parts does come with trade-offs in certain applications such as increasing the complexity of repair and maintenance and limiting possibilities for end-of-life recycling.

The following examples of components have been collated from different industries, demonstrating how manufacturers and private companies are pushing the boundaries of what is possible when using 'large' PBF-LB.

Figure 4: Impellor component produced on SLM Solutions NXG XII 600. Dimension: ~Ø550 mm x 300 mm Z-height. Build Time:~7 days. Material: Nickel Superalloy. Courtesy of Sintavia.

Large PBF-LB Applications

BLT - Engine Integration Component

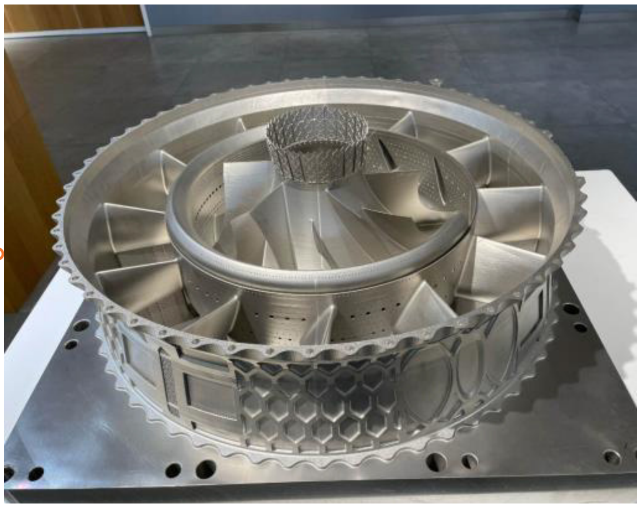
Machine: BLT-S800

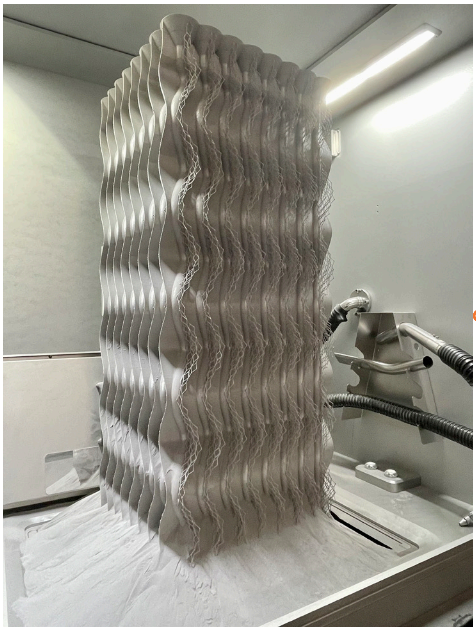
Dimension: Ø800 x 400 mm

Build Time: 175 hours

Material: Inconel 718

Application: Aircraft engine integration component





Sintavia - Heat Exchanger

Machine: AMCM M4K-4

Dimension: ~406 x 406 x 990 mm

Build Time: ~ 288 hours

Material: Nickel superalloy

Application: Seawater heat exchanger

GE Aerospace - Turbine Centre Frame

Machine: GE Additive ATLAS (In Development)

Dimension: Ø1000 mm

Material: Inconel 718

Application: Turbine Centre Frame for narrow-body aerospace engines. This parts reduces weight by 30%, combines 150 parts to 1, reduces lead from 9 months to 2.5 months.

Velo3D - Stator Ring

Machine: Velo3D Sapphire XC

Dimensions: Ø535 mm

Build Time: 80 Hours

Material: Inconel 718

Application: Stator Ring featuring low angle blades and internal cooling channels

Velo3D - Rocket Nozzle

Machine: Velo3D Sapphire 1MZ

Dimension: Ø280 mm x 1000 mm Z height

Build Time: 150 hours

Material: Inconel 718

Application: Rocket Nozzle Chamber with 20 injectors and optimised internal thin wall regenerative cooling (Sectioned view)

Eplus3D - Disc Brake

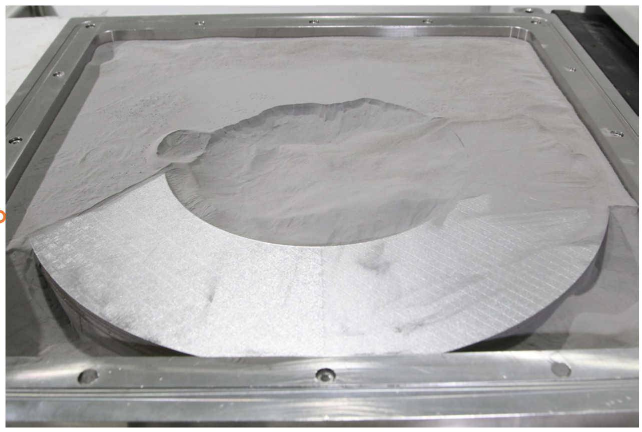
Machine: Eplus3D EP-M650

Dimension: Ø648 × 90 mm

Build Time: 631 hrs

Material: 24CrNiMo

Application: Railway disc brake



4. Large PBF-LB Parts Process Overview

The following sections will go through each stage of the PBF-LB manufacturing process chain to discuss some of the challenges and opportunities that are faced when building larger parts in PBF-LB.

4.1 - Design for AM & Data

Limited DfAM Knowledge for Larger Parts
To truly realise the benefits of AM, it is imperative that components are designed correctly, and when pushing the envelope on component size in PBF-LB, understanding of the design rules will be a key challenge. Issues around residual stresses, geometric feature rules, specific machine characteristics, multi-laser interactions and post processing challenges are exacerbated by 'large' PBF-LB parts. Overcoming these points will be key to avoid costly mistakes. For example, large circular geometries will face different challenges when building features on the external and internal surfaces due to the high hoop stresses, with external features having a higher likelihood of recoater interaction compared to the same features being built on an internal surface. Another challenge to overcome is the management of shift lines in components where one large structure joins to a smaller structure.

Scaling up of current design rules will act as a starting point for the formation of large part designs, however, the interaction of the stresses of these features at a larger scale will need to be explored. Production of comprehensive design guidelines and training courses to share knowledge on the processing of 'large' PBF-LB will be a key step to enabling this technology.

Simulation & Optimising for Larger Parts

Simulation will play a key role in de-risking 'large' PBF-LB builds. Whether it is understanding part distortion during a build, the effect of multiple heat sources (lasers), distortion during post processing activities (heat treatment and build plate removal) or analysing powder removal from part. Simulation will provide key data that designers and engineers can use to optimise their designs and processes to maximise build success.

Challenges will be faced in longer simulation times and the greater computing power required to run increasingly complex simulations. Simulations often don't account for multiple laser sources; however, thermal models are able to assess the impact of multiple lasers but require development and take significantly longer to run than mechanical simulations. Mechanical simulations can be recalibrated with changes to the model inputs through understanding of recorded data to improve the accuracy of multi-laser simulations of specific machines. Challenges will also be met in understanding different scanning strategies employed by different manufacturers.

Both machine manufacturers and 3rd party vendors are developing commercially available simulation packages that have the capability to represent different types of laser configurations that are scalable with the component size. Simulation vendors have been working to validate mechanical simulation models for multi-laser systems, this has required further understanding of how the base input to the simulation such as recorded base plate temperature and top layer temperature compare to that of a single laser build.

File Sizes & Volume of Data

Transferring data files throughout the build process chain whether it be from design, simulation, build processer, and post build data will prove to be a key challenge in enabling larger parts. For example, it is assumed that as parts become larger this will increase the size of native CAD files and in turn the build files used on machines. Slow data transfer whether inputting, receiving, or storing data will be a critical IT infrastructure challenge. If IT infrastructure cannot handle the speed or storage requirements of future processes, then the knock-on impact will be that users of the system will struggle to complete their work, either slowing down their progress or in the worst-case stopping progress. Additionally, the increasing use and reliance of in-process monitoring of builds where inspection is difficult due to size constraints adds to the data processing and storage requirements.

Mitigating these risks could come in the form of clear guidelines for high spec PC requirements and IT infrastructure specifications. Understanding the output of data from in-process monitoring and other processing steps will become increasingly hard for humans as the quantity and frequency of data output grows. The use of AI and machine learning software to process data from the build, and throughout the AM build process chain, is expected to grow in the near future to make post build analysis more manageable for the user. Thought will also have to be put into standardising output file formats, to enable seamless data flow.

4.2 - Feedstock

Increasing Powder Quantities

As machine build volumes grow as does the requirement to fill them with larger quantities of powder feedstock, ranging from 160 to >1000 kg, depending on the material type and hopper size. Larger powder batches will amplify challenges around powder cost and powder management. Typical powder feedstock ranges from €50 - 300 per kg, which becomes a significant consumable expenditure when considering the largest machines. This will likely have the effect of rendering this technology out of the reach of smaller vendors. The cost of powder and emphasis on sustainability will likely drive increased focus on powder management, ensuring that powders remain in specification, are stored in suitable environmental settings, and have a fully traceable lifespan. It is also highly likely that as powder volumes grow that in larger machines there will be less likelihood of swapping materials batches due to the possibility of cross contamination between costly powder batches. Resulting in machines which are fixed to a single material for their entire lifespan. Further to this point, a large amount of feedstock can remain (>100 kg) once the minimum viable quantity to run a large PBF-LB build is no longer met. This incurs challenges with how to combine these smaller feedstock batches to ensure economic and sustainable use of powder.

Storage and Delivery of Powder

Storage of metal powder in PBF-LB is a relatively well explored area of research [27]. Care will have to be taken in what types of containers are used to store the increased volumes of powder and the environmental conditions will be of utmost importance (both where the powder is stored and how, i.e. in inert conditions). Transferring of powder should also be heavily scrutinised (i.e. is there a chance of contamination as large quantities of powder are being transferred by pipework).

Storage and delivery of powder to the machine will also heavily depend on whether the powder is internally recycled through an in-built sieving mechanism or not. Machines with internal recycling capability (i.e. internal sieving capability) will likely only require “top up” powder added to the system, in theory this should simplify the powder handling requirements from an operations standpoint. However, this comes with traceability challenges, such as understanding the condition of the overall powder batch through a series of builds. In addition, if powder is being recirculated (due to internal sieving mechanism) from sources such as top up, overflow and the remaining powder then careful explanation and evidence will be required from machine manufacturers to demonstrate that their systems can effectively maintain powder quality.

Some AM production environments are using either gravity fed or conveying style units to move large qualities of powder efficiently. Areas for further investigation include understanding which powder management strategy is most applicable to which industry, understanding the impact of powder segregation in hoppers during long term storage & movement, if there is an impact on build properties, and a clearer consensus on batch strategies.

Figure 11: SLM Hub is an automated powder handling station. With automated transport of build cylinders with dedicated locations for pre-heating and cooling. Other features include depowdering and a centralised powder supply. Image courtesy of SLM Solutions.

4.3 - Build Process Considerations For Large Volume PBF-LB Machines

Process Parameters

Process parameters control the build process and are used to instruct the machine hardware, such as the scanning head or laser, on how and where to apply the thermal energy to produce a part. Ultimately there must be a delicate interplay between hundreds of parameters to produce a part to the required standard.

Given that there is an increasing number of possible machine configurations (with features such as variable beam size, variable layer thickness, and multiple lasers) on sale, it is essential that users of the technology have confidence that their parts meet the end users' requirements.

Currently there is limited literature, albeit a growing area of research, on the development and effect of process parameters used in multi-laser systems. Understanding the material and mechanical properties of different laser overlap strategies and variation within the build volume will be key areas of understanding for customers. Greater reliance on machine manufacturers to provide accessible and transparent data will be key to successful adoption.

Laser Overlap

Larger build volumes are likely to require multi-lasers systems to meet build speed and part quality requirements. This could take the form in either the addition of more lasers to the system, such as the SLM Solutions NXG XII 600 with 12 lasers covering a 600 x 600 x 600 mm build volume [28] or dynamic focusing systems such as nLIGHT, which alter the spot size of the beam and in turn reduce the time per layer [29]. Larger PBF-LB parts can have associated build times in excess of 10 days and therefore one of the main driving forces for using multiple lasers is to reduce the build time. However, with the increase in quantity of laser sources comes with it associated technical and commercial challenges including: Interaction of multiple laser beams (including any by-products from the melting process), maintenance of multiple optics, and the cost of the laser sources.

One of the key technical challenges is understanding the effect of multiple lasers interacting with each other to form a single part. If the 'stitching' (The action of different laser beams interacting to form a join within a part) between lasers isn't optimised this could lead to higher level of defects within that region. To mitigate this risk machine OEMs conduct extensive research and development in order to optimise 'stitching' methods. This is generally communicated to users of the technology with guidelines of how to assign relevant parameters during the build file prep in OEM training courses. However, the responsibility will generally be on the end user to determine that the 'stitching' method is sufficient to meet the requirements of the application.

Another important technical challenge is positional shift of lasers relative to each other. This could affect the dimensional accuracy of the lasers, possibly causing ridges on the edges of parts. To mitigate this risk machine OEMs have developed calibration solutions for users. These can take the form of being manually carried out before the build or automatically during the build to ensure laser calibration remains optimal. EOSYSTEM SmartCal is an example of such a system [30].

Excessive vibrations which could be generated by varying powder hopper masses or build elevator movement have the potential to affect the laser calibration of the machine. Careful industrial design will have to be considered to avoid this, whilst regular or automatic laser calibration should become the norm to provide confidence in each build. Understanding the factors that affect the rate of calibration drift will be key to setting maintenance intervals that allow serial production. Laser maintenance schedules may need to be adapted for different builds, where different components result in different levels of vibration and residual heat in the machines.

Figure 12: EOSYSTEM SmartCal calibration plate being installed on MTC's EOS M400-4. Image courtesy of The MTC.

Powder Spreadability & Recoating

Increasing growth in build volumes has amplified existing challenges around spreading powder, one such challenge is the rigidity of the recoater arm. If there is flex in the recoater arm this can cause differing angles or pressures to be imparted on the powder which is being spread. This in turn can cause variation in the powder layer thickness and could cause defects in parts.

This can be overcome through robust industrial design, for instance the use of recoater arms mounted at multiple points of the machine frame, rather than cantilever designs. An additional mitigation is monitoring the layer thickness spread on each layer to ensure the right level of dosing has been met and correcting if required.

Larger parts are likely to be subjected to higher build stresses which puts the parts at increased risk of protruding through the powder bed, potentially resulting in recoater collisions and ultimately a build stop/failure. Recoater types such as a brush recoater may be more forgiving for recoater collisions but struggle to consistently spread powder whilst harder blade materials have a higher chance of builds stops/ failures from impacting protruding parts. Velo3D has approached this challenge with a novel hardware & software approach which incorporates a "non-contact" recoater that works as part of a holistic solution including optimisation of build preparation files and in-process monitoring to mitigate possible recoater issues [31]

Greater care will also be required with setting and achieving tolerances on base plates. This will be required to prevent base radius cracking, which is where an uneven base plate causes an inconsistent first layer in the build process. This can in turn induce defects in the part to baseplate interface.
Mitigations of possible recoating issues include a better understanding of design guidelines for building larger components, with respect to recoater types, and a better understanding of simulation of potential effects that will have on the part during the build. An additional mitigation could be integrated powder bed monitoring that can adjust in-situ to recover from any short doses during a build.

Gas Flow

Shielding gas is used to remove by-products of the PBF-LB process such as metal condensate, which are carried out of the chamber in the shielding gas to reduce the risk of defects within the parts. Challenges arise when striking a balance between ensuring the entire bed is covered with the suitable gas flow and not inadvertently blowing powder from the bed. This can be caused with higher flow rates, which typically are utilised when there is a single gas source in the machine covering a large powder bed. Multiple sources of gas flow have the benefit of being able to reduce flow rate however, this may be difficult to implement and if poorly implemented could lead to varying part properties as a result of turbulence in the chamber causing inefficient removal of melt plumes. As more lasers are added to machines, the complexity of gas flow management becomes more challenging.

Interaction of a laser moving into the plume of another active laser, can cause de-focusing of the beam thus effecting the final part properties, which is especially important in platforms which utilise full field lasers. The laser-gas flow interactions in multi-laser systems can be managed in a number of different ways. Concept Laser for example have built into their laser toolpath generation software that predicts laser plume flow. This means that the melting of the layers can be managed such that the lasers that are actively melting do not stray into this area of predicted condensate flow by either melting at a different area of the build volume or pausing melting until the risk is lower.

Figure 13: An example of laser scanning strategy of 12 beams on a multi-laser system (SLM Solutions NXG XII 600). Image courtesy of SLM Solutions.

High Operating Costs

It is expected that growing part sizes will result in higher operating costs for users of 'large' PBF-LB technology, across the AM processing chain. Capital expenditure costs will likely be higher when purchasing 'large' PBF-LB machines with the general cost of machines being in the £1M to £4M range compared to £250k to £1.5M for 'medium' PBF-LB machines. Additional costs for setting up a controlled environment facility and purchasing the necessary auxiliary equipment costs, would likely be >£1M. Reducing the cost of 'large' PBF-LB builds will be a key enabler to wider adoption of the technology. To meet this cost requirement manufacturers are increasing the number of lasers used in machines to reduce build times. Build times make up a a significant portion of the cost of a build, as machines are generally charged by the hour. SLM Solutions were one of the first to introduce a 12-laser system working in parallel to melt in a optimise manner to reduce build time. Other methods of reducing build time including varying layer heights used during a build. Where thicker layer heights are used in sections of the builds with simplified geometry reducing the time per layer and ultimately the overall build time. Another method is altering the laser spot size during processing for sections that require less resolution, again reducing the time per layer and the overall build time.

With longer build times there will be a greater emphasis on mitigating possible causes of build failure especially near the end of longer builds due to the negative impact on cost and time. For instance, a 20-day long build failing on day 19, will result in 19 lost days, powder costs, utility costs, time for a route cause analysis investigation, subsequent mitigation actions, and an additional 20 days to re-run the build.

Post processing costs will likely increase as areas such as depowdering, surface finishing, and NDT may require more effort, which will also depend on the complexity of the component. For example, there may be a requirement to increase the amount of effort to manually improve the surface finish of a part with an increased amount of part support stubs or a larger part with more complex internal channels may require more time to inspect.

Finally, the effort required to analyse the data output from across the AM process chain will increase with part size. Whether it is data from in-process monitoring, indications from post-build NDT inspections, or simply analysing data from the machine build logs throughout the build. Data can quickly run into terabytes of rich information, that rapidly multiplies with subsequent builds and/or additional machines, that can overwhelm users. Key to finding value in this data will be using software to ensure that key trends are discovered, highlighted and if deemed appropriate acted upon to reduce the risk of increasing operating costs through build failures, machine breakdowns, etc. Software packages from companies such as AMFG [32] and Siemens [33] are tackling this topic.

With the increased operating costs mentioned in this section comes a greater financial risk to a company aiming to operating within the 'large' PBF-LB space. This will likely put increased scrutiny on the business cases for each application and in turn will require close collaboration between users and machine OEMs to ensure high value assets are operating correctly and continuously.

4.4 – Post Processing

Depowdering

Depowdering of parts is an increasingly important consideration when designing and manufacturing complex components. If parts cannot have powder successfully removed from internal passageways, then most likely that part will be scrapped due to unintended sintering of loose powder during heat treatments or risks of powder contamination during service. Given the high cost and time required to build 'large' PBF-LB parts this risk of scrappage could be high if not carefully considered in the initial stages of design.

Powder removal solutions historically have been ad-hoc in nature with custom built solutions for specific applications. Manufacturers like Solukon have changed the landscape through providing standardised equipment that can deal with a large variety of build sizes up to 600 x 600 x 1000 mm and maximum weights of 800kg [34]. Currently there is a limited supply chain of commercially available large

Figure 14: Large AM part installed in a Solukon depowdering system SFM-AT1000-S. Image courtesy of Solukon.

depowdering units that are available, however with time this is likely to improve. Currently it is expected that this will increase the lead time of parts. As parts grow it is expected that solutions, such as the Solukon, will scale with build volumes.

Heat treat

Heat treatment of PBF-LB parts post build is a vital step in relieving stresses built up during the build. This will become increasingly important as larger parts will have a high likelihood of greater residual stresses. These stresses can cause cracking and/or distortion within the parts. Existing heat treatment facilities have capability of vacuum furnaces that can accommodate builds and build plates into the metre scale. This includes hot isostatic pressing which can also scale into the metre scale, with the world's largest press has a hot zone diameter of more than 2 m [35]. However, challenges will arise with limited supply chains with this capability and lengthening lead times. Existing users of the technology may need to replace existing furnaces with larger units, both incurring increases capital expenditure and operating costs. In addition, upskilling in the effects of heat-treating larger parts will need to be developed and disseminated to ensure designers & engineers are competent in their application. Understanding topics such as ensuring consistent heating of multiple geometric features, within a single part.

Part Removal

Part removal from the baseplate is typically carried out using a bandsaw or a wire electrical discharge machining. There are expected to be few issues with scaling up part removal equipment. However, gaining access to such equipment may increase lead times due a limited supply chain of locations where parts can be processed.

Care will also have to be taken in the orientation that parts are removed in. Due to the increased mass of parts, it may be possible for parts to distort and/or tear off the baseplate if left free hanging whilst being removed from the baseplate.

Surface Finishing

Surface finishing of AM parts has always been an important processing step that enables the final use in the chosen application. Finishing processes such as CNC machining are likely to be able to scale with part size. However, vendors that offer this service may

Figure 15: Heat treatment furnace used post build. Image courtesy of Sintavia.

be limited due to few vendors having experience with AM parts, increasing lead times. Care will have to be taken to ensure materials (such as Titanium and Aluminium) are carefully monitored during the machining process given the tendency for movement during machining, potentially causing scrappage. Other finishing processes such as mass finishing, chemical finishing, shot blasting, and manual finishing are also expected to scale with the size of parts. Onus should be put on clearly defining the part requirements to ensure that surface finishing and machining are only required where they are needed rather than a catch all requirement, as finishing in non-critical areas has limited additional value.

Inspection of Parts

Geometrical inspection of parts to ensure they are to the required tolerances is expected to scale well with part size, using techniques such as blue light scanning or co-ordinate measuring machines (CMM). As expected, large parts will generate larger file sizes which will come with increased data analysis processing times, possibly increasing both cost and lead times. To reduce this burden targeted inspection should be carried out only where critical to application.

Inspection of parts for indications such as voids or inclusions face challenges as parts scale. If larger parts are to be inspected using X-Ray computed tomography (XCT) they may have to be sectioned for analysis to be effectively carried out on a part, as it is likely that the parts simply do not fit within existing equipment or that the resolution of the scan on the large part is too low due the part being too far from the detector. Whilst sectioning is a pragmatic approach it requires sacrificial parts and requires a level of consistent read across between identical components to draw conclusions.

Improvements in using XCT in conjunction with digital radiography to get a more complete overview of parts or MEv XCT scanning could increase resolution of larger parts. Industrial computed tomography systems, such as the Diondo D5, have scan volumes of up to Ø 850 x 1300 H mm, with options of going larger in their D7 or custom solutions [36].

4.5 – Additional challenges

Movement of Components and Auxiliary Equipment

As build volumes grow it can be seen that manual intervention such as lifting baseplates, parts, and powder containers will be replaced with automated mechanical solutions. Machines such as the MetalFab, Concept Laser M Line, and SLM Solution 800 have shown the rise of automated moving of parts through the process chain, removing manual input from the process.

It is expected that larger machines will increasingly need the use of cranes and forklifts to move relevant equipment, powder and parts for daily use. In turn this will put additional requirements on facility design to ensure there is space and infrastructure to accommodate this.

Another challenge particularly seen in facilities with multiple different PBF-LB machines is the lack of standardisation of lift trucks and auxiliary equipment used between machine suppliers. It is expected that forklift trucks will eventually replace machine suppliers specified lift trucks.

Machine Footprint

With the increase in the size of machines, the requirements for all auxiliary equipment and powder storage scales with it. This results in larger facilities being required. Currently the largest PBF-LB machine, Eplus3D EP-M1250, requires an installation space of 9 x 4.8 x 6.3 m. This will limit the locations that can install such equipment, pushing away from the original roots of AM where equipment could be installed in “lab” like settings with conventional ceiling heights and doorways. Increasing the likelihood that dedicated facilities will have to be setup to house ‘large’ PBF-LB, again pushing up the capital expenditure of adopting this technology.

5. Conclusion

This paper has explored the growing area of 'large' PBF-LB machines, documenting the general trend of increasing build volumes and discussing the challenges and opportunities of adopting large PBF-LB machines. Detail is given on the inherent challenges of building larger PBF-LB parts across every stage of the manufacturing process. However, it is expected that the majority of technical challenges presented will be overcome.

Perhaps the biggest challenge for the PBF-LB community, and ultimately to the success of these systems, relies on building confidence in the users that applications developed will be fit for purpose, to enable business cases to be developed with confidence. This confidence will have to be developed through greater understanding of aforementioned challenges such as laser overlaps, build pauses, interaction of build stresses and gas flow effects.

Gaining confidence could take the form of releasing comprehensive datasets for each material. This could include raw data regarding specimen testing detailing both mechanical properties and metallurgical analysis of key areas, such as overlap regions. This data would ideally be vetted by an independent and competent organisation. This in turn could be used to lower the barrier to entry to these machines by providing data that directly feeds into an end users business case justification and qualification processes. Other means of increasing confidence include machine manufacturers working closely with end users to prove out their applications on a case-by-case basis.

Financial viability is a key aspect of any advanced manufacturing technology and PBF-LB is no exception. Two main business models are being pursued by 'large' PBF-LB OEMs: selling machines to end users or machine OEMs operating their own machines and supplying parts to end users. If an end user purchases a machine from an OEM then they have the benefits in flexibility of use but carry burdens such as of machine maintenance and qualification requirements. If an end user purchases parts from an OEM then they will have the benefit of simplifying their manufacturing process, at the expense of possibly limiting specific application development opportunities and supply chain robustness. The majority of 'large' PBF-LB OEMs are continuing to sell machines as manufacturing tools, allowing end users to set up their own manufacturing facilities and develop for their own needs.

Ultimately if the cost of procuring and operating machines is sustainable, and those machines are repeatable and reliable it is expected that 'large' PBF-LB will become a major area for adoption given the benefits PBF-LB can offer in new applications areas.

6. References

[1] O. N. M. Shellabear, “DMLS – DEVELOPMENT HISTORY AND STATE OF THE ART,” in LANE 2004, Erlangen, 2004.

[2] N. Kretzschmar, “Economic validation of metal powder bed based AM processes,” AALTO UNIVERSITY, Espoo, 2015.

[3] National Centre for Additive Manufacturing, “Additive Manufacturing of Front Bearing Housing Aerofoils For Rolls-Royce Test Bed Engines,” 2015.[Online]. Available: https://ncam.the-mtc.org/case-studies/additive-manufacturing-of-front-bearing-housing-aerofoils-for-rolls-royce-test-bed-engines/. [Accessed July 2022].

[4] M. Kowal, “LinkedIn,” 2021. [Online]. Available: https://www.linkedin.com/posts/michael-kowal-30465a83_eos-m400-team-activity-6825361715643850752-xp84/. [Accessed July 2022].

[5] AMCM, “Orbex Commissions Largest Industrial 3D Printer in Europe for Rapid Rocket-Building,” March 2021. [Online]. Available: https://amcm.com/news/2021-03-09-orbex-commissions-largest-industrial-3d-printer-in-europe-for-rapid-rocket-building. [Accessed July 2022].

[6] “Leading Space Company Orders Two NXG XII 600s From SLM Solutions, Accelerating Its Path to Win Space Race,” Jan 2022. [Online]. Available: https://www.slm-solutions.com/company/news/detail/leading-space-company-orders-two-nxg-xll-600s-from-slm-solutions-accelerating-its-path-to-win-space-race/. [Accessed July 2022].

[7] L. GRIFFITHS, “Launcher adds second VELO3D metal 3D printer to produce rocket engine parts,” September 2021. [Online]. Available: https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/metal-additive-manufacturing-news/launcher-adds-second-velo3d-metal-3d-printer-rocket-engine/. [Accessed July 2022].

[8] “Build the impossible - Disruptive 3D Metal Printing for Mass Adoption,” June 2021. [Online]. Available: https://www.velo3d.com/wp-content/uploads/2021/07/analyst-presentation-june-23-2021.pdf. [Accessed July 2022].

[9] P. Hanaphy, “slm-solutions-launches-powerful-new-12-laser-nxg-xii-600-metal-3d-printer,” 3D Printing Industry, Nov 2020. [Online]. Available: https://3dprintingindustry.com/news/slm-solutions-launches-powerful-new-12-laser-nxg-xii-600-metal-3d-printer-178966/. [Accessed August 2022].

[10] “BLT-S1000,” [Online]. Available: https://www.xa-blt.com/equipments/blt-s1000/. [Accessed July 2022].

[11] “Introducing FS621M - Industrial Scale Metal Laser Sintering System,” July 2020. [Online]. Available: http://en.farsoon.com/news_detail/newsId=146.html. [Accessed July 2022].

[12] “HBD 1000,” [Online]. Available: https://en.hb3dp.com/product/23.html. [Accessed July 2022].

[13] “EP-M650 METAL 3D PRINTER,” [Online]. Available: https://www.eplus3d.com/Additive-Manufacturing/Metal/EP-M650-Metal-3D-Printer.html.[Accessed July 2022].

[14] C. T. Corporation, “Releases,” 22 September 2022. [Online]. Available: https://www.ctc.com/public/newsandmedia/releases.aspx?ID=182. [Accessed 23 September 2022].

[15] “GE Additive unveils first BETA machine from its Project Atlas program,” Nov 2017. [Online]. Available: https://www.ge.com/news/press-releases/ge-additive-unveils-first-beta-machine-its-project-atlas-program#:~:text=Project%20A.T.L.A.S%20(Additive%20Technology%20Large,company's%20existing%20portfolio%20of%20products.. [Accessed July 2022].

[16] “Large-scale Additive Manufacturing for Defence & Aerospace (LAMDA),” Dec 2020. [Online]. Available: https://gtr.ukri.org/projects?ref=75888.[Accessed July 2022].

[17] ADIRA , “ADIRA LARGE METAL PRINTER SOLUTION,” [Online]. Available: https://adira.pt/wp-content/uploads/AddCreator-AC210_EN.pdf. [Accessed July 2022].

[18] AEROSWIFT, “THE AEROSWIFT TECHNOLOGY,” [Online]. Available: https://www.aeroswift.com/technology/. [Accessed July 2022].

[19] R. Mitchinson, “Large LPBF Machines V1.0,” Coventry, 2022.

[20] “MAN Energy Solutions Invests in an NXG XII 600,” SLM Solutions, Feb 2022. [Online]. Available: https://www.slm-solutions.com/company/news/detail/man-energy-solutions-invests-in-an-nxg-xii-600/. [Accessed July 2022].

[21] “Collins Aerospace Expands Additive Capability with Addition of SLM Solutions NXG XII 600 at Engine Nozzles Facility in West Des Moines,” SLM Solutions, Feb 2022. [Online]. Available: https://www.slm-solutions.com/ir/corporate-news/detail/collins-aerospace-expands-additive-capability-with-addition-of-slm-solutions-nxg-xll-600-at-engine-nozzles-facility-in-west-des-moines-1/. [Accessed Feb 2022].

[22] S. Davies, “Morf3D to install SLM Solutions NXG XII 600 metal 3D printing system at new headquarters,” TCT Magazine, September 2021. [Online]. Available: https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/metal-additive-manufacturing-news/morf3d-to-install-slm-solutions-nxg-xii-600-metal-3d-printin/. [Accessed July 2022].

[23] S. Davies, “Divergent Technologies purchases three more SLM Solutions NXG XII 600 metal 3D printers,” TCT Magazine, October 2021.

[Online]. Available: https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/metal-additive-manufacturing-news/divergent-technologies-three-slm-solutions-nxg-xii-600-metal-3d-printers/. [Accessed July 2022].

[24] "Sintavia acquires M4K-4 printers from AMCM," Aerospace Manufacturing, Jan 2021. [Online]. Available: https://www.aero-mag.com/sintavia-acquires-m4k-4-printers-from-amcm/. [Accessed July 2022].

[25] "LAUNCHING INTO SPACE WITH 3D PRINTED ROCKET ENGINES," AMCM, [Online]. Available: https://amcm.com/success-stories customized-large-frame-system-for-launcher-aerospace. [Accessed July 2022].

[26] P. Gradl, S. E. Greene, C. Protz, B. Bullard, J. Buzzell, C. Garcia, J. Wood and K. Cooper, "Additive Manufacturing of Liquid Rocket Engine Combustion Devices: A Summary of Process Developmentsand Hot-Fire Testing Results," 54th AIAA/SAE/ASEE Joint Propulsion Conference 2018, p. 4, 2018.

[27] P. Gradl, O. Mireles and N. Andrews, "Introduction to Additive Manufacturing for Propulsion Systems," 2019.

[28] K. Riener, S. Oswald, M. Winkler and G. J. Leichtfried, "Influence of storage conditions and reconditioning of AlSi10Mg powder on the quality of parts produced by laser powder bed fusion (LPBF)," Elsevier - Additive Manufacturing, vol. 39, 2021.

[29] SLM Solutions, "NXG XII 600," SLM Solutions, [Online]. Available: https://www.slm-pushing-the-limits.com/specs#optical-system. [Accessed August 2022].

[30] Metal AM, "nLIGHT, Optoprim and TUM collaborate to push the limits of powder bed fusion processes," June 2021. [Online]. Available: https://www.metal-am.com/nlight-optoprim-and-tum-collaborate-to-push-the-limits-of-powder-bed-fusion-processes/. [Accessed August 2022].

[31] EOS GmbH Electro Optical Systems, "EOSYSTEM SmartCAL - The service tool for an accelerated calibration workflow," Nov 2018. [Online]. Available: https://www.youtube.com/watch?v=mzHSAr6_UAA&ab_channel=EOSGmbHElectroOpticalSystems. [Accessed July 2022].

[32] G. Miller, "Clash of the Recoaters: Overcoming Failed AM Builds," Velo3D, April 2022. [Online]. Available: https://velo3d.com/clash-of the-recoaters-overcoming-failed-am-builds/. [Accessed August 2022].

[33] AMFG, "AMFG," [Online]. Available: https://amfg.ai/. [Accessed August 2022].

[34] Siemens, "Produce quality parts at scale with industrial additive manufacturing software," [Online]. Available: https://www.plm.automation.siemens.com/global/en/products/manufacturing-planning/additive-manufacturing.html. [Accessed August 2022].

[35] Solukon, "SFM-AT1000-S," [Online]. Available: https://www.solukon.de/en/depowdering-metal/sfm-at1000-s/#tab-id-4. [Accessed August 2022].

[36] Quintus Technology, "Hot Isostatic Presses," [Online]. Available: https://quintustechnologies.com/hot-isostatic-pressing/products/hot-isostatic-presses/#:~:text=The%20world's%20largest%20press%20has,to%20grow%20their%20competitive%20advantage.. [Accessed August 2022].

[37] Diondo, "diondo dx," [Online]. Available: https://www.diondo.com/en/products#diondo_04. [Accessed Sept 2022].

[38] Sintavia, "LinkedIn - Sintavia Post," Sintavia, April 2022. [Online]. Available: https://www.linkedin.com/posts/sintavia_sintavia-3dprinting-additivemanufacturing-activity-6917071278193405952-rbx-?utm_source=linkedin_share&utm_medium=member_desktop_web. [Accessed July 2022].

[39] Sintavia, "Linkedin - Sintavia," May 2022. [Online]. Available: https://www.linkedin.com/posts/sintavia_sintavia-sintavia-advancedpropulsion-activity-6927215705343864833-RgzR?utm_source=linkedin_share&utm_medium=member_desktop_web. [Accessed July 2022].

[40] E. Duan, Interviewee, BLT Interview. [Interview]. May 2022.

[41] Eplus3D Additive Manufacturing, "LinkedIn Eplus3D Additive Manufacturing," May 2022. [Online]. Available: https://www.linkedin.com/posts/eplus3d-additive-manufacturing_train-two-eplus3d-activity-6924977342507356160-qEkA/?utm_source=linkedin_share&utm_medium=member_desktop_web. [Accessed July 2022].

[42] SLM Solutions, "Welcome to the new era of Additive Manufacturing," [Online]. Available: https://www.slm-pushing-the-limits.com/. [Accessed July 2022].

7. Appendix A

Machine Model	Manufacturer	Build Volume (X, Y, Z)	No. of lasers	Power of laser	Layer Thickness	Integrated sieving	Machine Dimensions	Country
3DM AMS 400	3D Metronic	400 x 400 x 500mm	4	1 kW	10-120 µm	Y	12000 x 2500 x 2500mm	Germany
3DM AMS 800	3D Metronic	800 x 800 x 500mm	4	1 kW	10-120 µm	Y	12000 x 2500 x 2500mm	Germany
DMP Factory 350	3D Systems	275 x 275 x 420mm	1	500 W	Adjustable, min. 5µm, typical: 30, 60, 90µm	Y	-	USA
DMP Factory 350 Dual	3D Systems	275 x 275 x 420mm	2	500 W	Adjustable, min. 5 µm, typical: 30, 60, 90 µm	Y	-	USA
DMP Factory 500	3D Systems	500 x 500 x 500mm	3	500 W	Adjustable, min. 5 µm, max. 200 µm, typically 60µ	N	3010 x 2350 x 3160mm	USA
DMP Flex 350	3D Systems	275 x 275 x 420mm	1	500 W	Adjustable, min. 5 µm, typical: 30, 60, 90 µm	N	-	USA
DMP Flex 250 Dual	3D Systems	275 x 275 x 420mm	2	500 W	Adjustable, min. 5 µm, typical: 30, 60, 90 µm	N	-	USA
MetalFABG2	Additive	420 x 420 x 400 mm	1 to 4	500 W	20 -100 µm	Y (In Continuous production option)	-	Netherlands
STLR-400	AMACE	410 x 410 x 450mm	2	1 kW	30 to 100 µm	N	3200 x 2400 x 3200mm	India
AMCM 4K-1 1 kW	AMCM	450 x 450 x 1000mm	1	1 kW	-	N	6340 x 3450 x 3500mm	Germany
AMCM 4K-4 1kW	AMCM	450 x 450 x 1000mm	4	1 kW	-	N	6340 x 3450 x 3500mm	Germany
AMCM M450-1 1kW	AMCM	450 x 450 x 400 mm	1	1 kW	-	N	4880 x 2440 x 3308 mm	Germany
AMCM M450-4	AMCM	450 x 450 x 400 mm	4	400 W	-	N	4880 x 2440 x 3308 mm	Germany
SP500	AmPro Innovations	500 x 250 x 260 mm	2	500 W	20 - 100 µm	N	3540 x 1160 x 2580 mm	Australia
BLT-S1000	Bright Laser Technologies	1200 x 600 x 1500 mm	8,10,12	500 W	20 - 100 µm	N	10150 x 6500 x 5525 mm	China
BLT-S450	Bright Laser Technologies	400 x 400 x 500 mm	1	500 W	20 - 100 µm	N	6100 x 4050 x 3400 mm	China
BLT-S450Q	Bright Laser Technologies	450 x 450 x 500 mm	4	500 W	20 - 100 µm	N	6100 x 4050 x 3400 mm	China
BLT-S450T	Bright Laser Technologies	400 x 450 x 500 mm	2	500 W	20 - 100 µm	N	6100 x 4050 x 3400 mm	China
BLT-S510	Bright Laser Technologies	500 x 500 x 1000 mm	4	500 W	20 - 100 µm	N	4700 x 5100 x 3800 mm	China
BLT-S600	Bright Laser Technologies	600 x 600 x 600 mm	4	500 W	20 - 100 µm	N	4700 x 5100 x 3800 mm	China
BLT-S800	Bright Laser Technologies	800 x 800 x 600 mm	6,8,10	500 W	20 - 100 µm	N	5700 x 5000 x 4400 mm	China
EP-M450	Eplus3D	455 x 455 x 500 mm	1 or 2	500 W / 1000 W	20 - 120 µm	N	5700 x 3220 x 3090 mm	China
EP-M450H	Eplus3D	455 x 455 x 1100 mm	1 or 2	500 W / 1000 W	20 - 120 µm	N	8250 x 3850 x 4750 mm	China
EP-M650	Eplus3D	655 x 655 x 800 mm	4	500 W	20 - 120 µm	N	5880 x 3840 x 3630 mm	China
EP-M1250	Eplus3D	1258 x 1258 x 1350mm	9	500 W / 700 W/ 1000 W	20 - 130 µm	N	9000 x 4800 x 6300 mm	China
M300	Eplus3D	305 x 305 x 450 mm	1 or 2	500 W / 1000 W	20 - 120 µm	N	2990 x1320 x 2590 mm	China
FS421M	Farsoon	425 x 425 x 420 mm	1	500 W	20 - 100 µm	N	2700 ×1290 ×2290 mm	China
FS421M-2	Farsoon	425 x 425 x 420 mm	2	500 W	20 - 100 µm	N	2700 ×1290 ×2290 mm	China
FS621M	Farsoon	620 x 620 x 1100 mm	1	1 kW	20 - 100 µm	N	5800 x 3300 x 4000mm	China
FS621M-4	Farsoon	620 x 620 x 1100 mm	4	500 W	20 - 100 µm	N	5800 x 3300 x 4000 mm	China
FS721M	Farsoon	720 x 420 x 420 mm	2	500 W	20 - 100 µm	N	5200 x 2800 x 2400mm	China
FS721M-4	Farsoon	720 x 420 x 420 mm	4	500 W	20 - 100 µm	N	5200 x 2800 x 2400 mm	China
M Line	GE Additive	500 x 500 x 400 mm	4	400 W	20 - 100 µm	Y (Need Material Handling Station)	4245 x 4300 x 3525 mm	USA
Xline 2000R	GE Additive	800 x 400 x 500 mm	2	1000 W	30 - 150 µm	N	5235 x 3655 x 3604 mm	USA
HBD-1000	HBD3D	600 x 600 x 1000mm	4	500 W / 1000W	30 - 120 µm	N	-	China
HBD-1500	HBD3D	460 x 460 x 1500mm	2 or 4	500 W / 1000W	20 - 120 µm	N	-	China
HBD-500	HBD3D	400 x 435 x 435 mm	1	500 W	30 - 100 µm	N	-	China
HBD-500T	HBD3D	400 x 435 x 435 mm	2	500 W	30 - 100 µm	N	-	China
iFusion LF	Intech Additive	450 x 450 x 450 mm	1	500 W	-	N	-	India
Dimetal-500	LaserAdd	500 x 500 x 400 mm	2	500 W	20 - 100 µm	N	1600 x 1100 x 2100 mm	China
LUMEX-Avance-60	Matsuura	600 x 600 x 500 mm	1	1000 W	-	Y	-	Japan
NXG XII 600	SLM Solutions	600 x 600 x 600 mm	12	1000 W	30 - 60 µm	N	-	Germany
NXG XII 600E	SLM Solutions	600 x 600 x 1500 mm	12	1000 W	30 - 60 µm	N	-	Germany
SLM Solutions 500	SLM Solutions	500 x 280 x 365 mm	2 or 4	400 W / 700 W	20 - 90 µm	N	6080 x 2530 x 2620 mm	Germany
SLM Solutions 800	SLM Solutions	500 x 280 x 850 mm	4	700 W	20 - 90 µm	-	Dependent on machine setup	Germany
Sapphire XC 1Mz	Vel3D	600 Ø x 1000 mm	8	1000 W	-	-	8.53 x 5.00 x 4.75 m (Requires 1.6m deep pit)	USA
Sapphire 1Mz	Velo	315 Ø x 1000 mm	2	1000 W	-	Y	2100 x 2100 x 2500 mm (plus 1370 mm)	USA
Sapphire XC	Velo	600 Ø x 550 mm	8	1000 W	-	Y	8530 x 3350 x 4750 mm	USA
iSLM420D	Zrapid	420 x 420 x 450 mm	2	500 W	20 - 150 µm	N	2650 x 1450 x 2700 mm	China
iSLM500D	Zrapid	500 x 400 x 900 mm	2	500 W	20 - 150 µm	N	3050 x 1900 x 3800 mm	China
iSLM600QN	Zrapid	600 x 600 x 1000 mm	4	500 W / 1000W	20 - 150 µm	N	3300 x 1650 x 4050 mm	China
iSLM800QN	Zrapid	800 x 700 x 1000 mm	4	500 W / 1000W	20 - 150 µm	N	3150 ×2550 ×3950 mm	China

Table 4: List of 'large' PBF-LB machines, collated Sept 2022

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NATIONAL CENTRE ADDITIVE MANUFACTURING

Manufacturing Technology Centre