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REVIEW

Issues in Resolution and Build Size Scaling of Additive Manufacturing Technologies

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Abstract:

In this review, scaling issues in additive manufacturing (AM) processes are discussed based on multiple factors. Scaling issues arise mainly due to design and control of the AM system and also while attempting to achieve desired accuracy. Based on current AM systems available commercially, we identified scaling issues that can potentially challenge the build feasibility and accuracy while moving in geometrical and build resolution length scales. Inherent limitations of multiple AM processes are discussed based on these aspects and challenges while implementing these technologies in multiple length scales are identified through this work. Potential remedies for such scaling issues are also presented based on current progressing research in AM.

Keywords: Additive manufacturing (AM), Resolution scaling of AM, Build size scaling of AM, Scaling issues in AM, Remedies for scaling issues in AM

Introduction

Additive manufacturing (AM) can be considered as groundbreaking technology due to versatility and adaptivity. AM so far has been identified as a rapid prototyping (RP) approach since it enables fast visualization or prototyping of engineering as well as aesthetic designs. More importantly, AM enables the flexibility to create parts with complex geometries where fabrication through conventional manufacturing will be highly challenging or infeasible[1].

Most conventional manufacturing techniques are based on subtractive technologies. Therefore, AM can be considered as a non-conventional approach since the part will be produced by adding material in a subsequent process. The general technique in AM is building a part layer by layer which is predetermined by its original computer aided design (CAD) file. Current AM technologies can be categorized mainly into seven processes as presented in figure 1. In brief the dependent technology of each process is also given. Vat photopolymerization (VPP) works based on curing a photosensitive resin to build the final solid geometry. Powder bed fusion (PBF) utilizes melting of solid particles initially in the form of a bed and fused together by an external energy source (laser/electron beam) to build the final solid geometry. Directed energy deposition (DED) techniques utilize directing the feedstock material towards the energy source while moving both energy source and material feed mechanism in multiple build planes. Material extrusion (ME) process applied melting the feedstock material at the nozzle while extruding it to produce the solid part. Material jetting (MJ) processes work by ejecting the build material in the form of droplet using a nozzle. The droplet will be converted to solid material by specific mechanisms (evaporation/condensation). Similarly, binder jetting (BJ) operates in the principle of jetting a liquid binder material on powder bed producing binding effect between powder particles to build the solid geometry. Direct write (DW) processes, contrary to jetting technology, directly release the build material in the form of liquid or gas and will be solidified on build substrate to create the desired geometry [2]. Finally, sheet lamination (SL) works in the principle of solid state welding of two thin sheets that are pre-shaped or in initial form [2]. Here in we do not discuss specific operating principles and in-depth details of such AM techniques, since it is beyond our scope. We inform reader to refer references elsewhere for detailed information about AM processes[3].

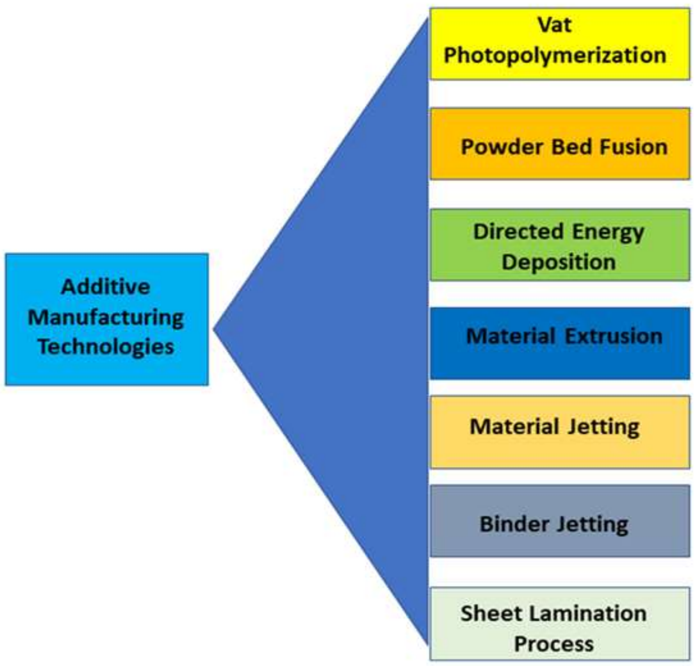

Figure 1: The major seven AM processes

Scaling issues in AM originates while approaching towards the needs of the desired build. A definition for scalability for AM process can be concisely given as the ability of the process to satisfy the desired accuracy (resolution), build size, build speed and production volume. Like conventional manufacturing processes, scaling issues arise in AM due to technology and underlying physics of the approach itself, form and availability of the feedstock and form of the geometry. Therefore, it is crucial to implement solutions to overcome such challenges to project AM technologies to the current understanding of conventional manufacturing processes. As a brief definition for scalability of AM processes, is that the ability of an AM process to sustain satisfying major requirements of fabrication (Build resolution, build speed, build size etc.).

While discussing scalability challenges in AM methodologies, Ngo et al. [4] reviewed the challenges in current AM technologies based on the aspects of material, methods and applications. They focused their discussions on structural homogeneity, mechanical anisotropy, geometrical accuracy, mechanical property, and aesthetic qualities as common drawbacks of any AM process. Former studies based on specific AM process, Bochove et al.[5] discussed general challenges in VPP methods by attempting to produce components by poly(trimethylene carbonate) which is a bio implantable material. Zhang et al. [6] studied the resolution, energy and time dependency on layer scaling of laser PBF (L-PBF) through finite element models. They have concluded that, the final powder bed temperature and temperature trajectories are strongly dependent on layer scaling. Also, cooling time per layer is another dominant factor affecting the temperature and stress which impact resolution of L-PBF process. Gan et al. [7] studied the universal scaling laws of keyhole stability and porosity in L-PBF. They have discovered an inherent quantitative relationship between keyhole stability and porosity formation in L-PBF which affect process parameter settings in L-PBF. Svetlizky et al. [8] reviewed the challenges in directed energy deposition (DED) techniques. They focused on incorporating hybrid AM system along with DED, multimaterial printing, metallurgical challenges, and more importantly resolution-based scalability challenges. They proposed multiple remedies to mitigate such challenges in DED in their discussion. Ziaee and Crane [9] discussed about shortcomings of binder jetting (BJ) based on powder material, binder type, post processing, and production scalability. They have extracted aspects from sources of process variation and defects while introducing factors that can improve such issues. Shen and Naguib [10] addressed issues in material jetting (MJ) when the process limitations due to "jettability" of materials and its effects of this property on scalability. Their analytical and experimental approach aided in producing jettable materials that fall to MJ feasibility range.

Based on all previous studies, there is a lack of a comprehensive study purely focusing on scalability of AM methods. Therefore, as the objective in this work, focus was weighted to identifying scaling limitations of most standard AM technologies and to address them more closely. By closing this research gap, will aid future researchers to implement solutions for such issues. Therefore, scope of this review is to identify the resolution and geometrical scalability-based bottlenecks in each standardized AM processes that are introduced so far. It is vital to have a solid understanding of the extent of resolution on many AM processes that are currently available under research and in the industry. By identifying the extent of the resolution, this helps the reader to select the most feasible AM process under multiple processes that fit to produce desired part geometry with expected material properties. Figure 1 shows the hierarchy of scalability expanding to subatomic level resolution and build sizes to macroscopic resolutions and build sizes. The analysis was performed to identify the limitations of the typical AM process based on size of the final build while maintaining the highest build resolution which is ultimately pertaining to the accuracy of the process based on the application. The issues are identified while walking in the path of highest to lowest (and vice versa) in geometrical length scales while preserving optimal resolutions. In addition, the main two categories that affect scaling of any AM system are based on design of the process, process control and associated hardware. Firstly, Design of the process determines the associated physics of the AM approach that limits the scalability due to laws of nature. Secondly, process control and associated hardware decides the maneuverability of components and variability of process parameters of the system based on highest technology currently available. These three factors can act as the bottlenecks in either direction of scaling reaching to the limits of sub nanometer resolutions to macroscale part sizes. Figure 2 shows the main aspects that fall into the scope in this discussion [11]. The inherent issues in scalability can be extracted efficiently while moving left on resolution scale bar while analyzing maintainability of build size in a higher length scale of a typical AM process as presented in figure 2(bottom).

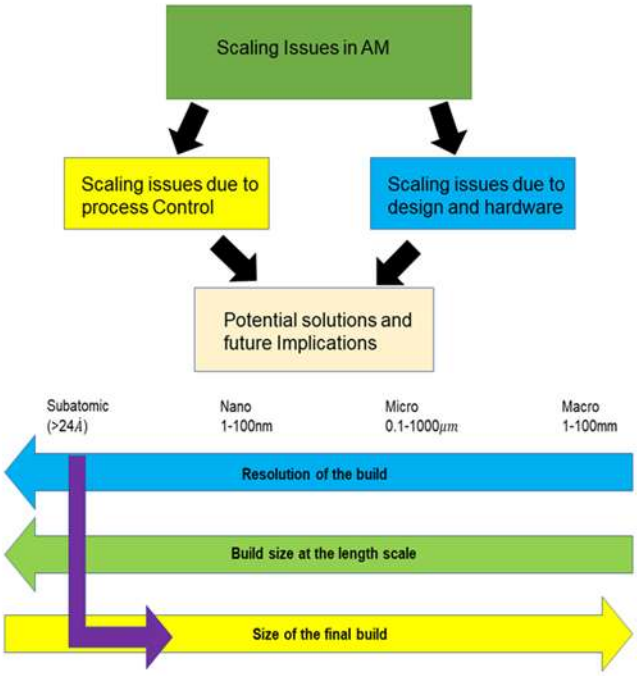

Figure 2: (Top) Main twofold categories that affect the scalability of any AM system, (Bottom) Scalability of AM processes spanning from subatomic levels to macroscopic levels while maintaining greater process resolutions

Outcome of any analysis is the utilization of the technology to achieve the desired product. Therefore, selecting an AM process based on scaling perspectives can be divided mainly into five aspects as represented in figure 3. While analyzing the five aspects, threefold requirements based on build accuracy, speed and size will reflect as interrelating parameters either extending the utilization or limiting for a typical AM process.

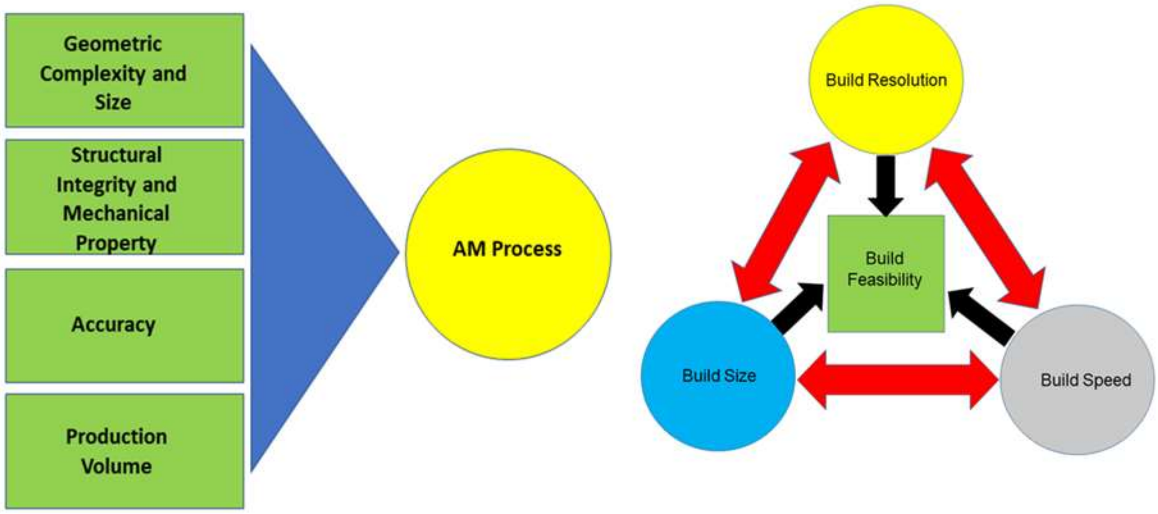

Figure 3: (Left) Identifying an AM process based on multiple aspects, (Right) Threefold interrelationship between accuracy, size, and speed

Vat photopolymerization processes

The VPP AM processes are based on by transforming the build material which is initially at liquid form to a solid form using an external energy source. The most common and widely utilized method is the liquid vat photopolymerization (VPP) which is known in many categories such as stereolithography (SLA), digital light processing (DLP) and continuous digital light processing (CDLP). In addition to these processes liquid jet-based PP (LJPP) methods are also present. However, LJPP methods are separately discussed under material jetting approaches since they are distinct from liquid vat approaches [12].

The underlying principle of photopolymerization is based on curing of a photosensitive polymer exposed to ultraviolet radiation. The exposed region of the photopolymer gets solidified by creating a solid part from continuous multilayers. The exposure can be a focused, projection or a continuous processes based on the process approach [12]. Currently, photopolymerization techniques carry the flagship on highest resolution among all AM processes reaching up to several nanometer scale resolutions(~100nm) specifically based on two photon lithography (2PL) approaches [12].

Liquid vat photo polymerization (VPP) process is the first introduced AM methodology in the hierarchy. The first commercial 3D printer was introduced by 3D systems in 1996. As the name suggests VPP systems differ from LJPP is since, the photopolymer is in a flooded form in a tank where the part is being built, while LJPP utilizes jetting of photopolymer to the built platform based on requirement. LVPP methods can be further classified based on methods of exposure of the photopolymer as vector scan, mask projection and two photon approaches. Distinctively vector scan VPP (VSVPP) utilizes focused beam moving from point-to-point basis in a typical built layer, therefore, curing the photopolymer layer in the form of bead while in continuous motion. Mask projection methods also known as DLP processes expose an entire layer to the energy source thus building the part in an individual layer wise approach. CDLP methods can also be considered as an improved DLP process with the only difference in the projection method while using LEDs and oxygen permeable windows instead of glass windows in DLP. Furthermore, 2PL can be considered as the finer resolution-oriented approach which can produce build resolutions below the diffraction limit [12]. In addition to the above distinct categories, VPP systems can be further classified based on the development of their subsystems. Initially, based on material feed systems currently they can be condensed to deep dipping, top feeding, and bottom feeding approaches. In deep dipping the entire part is built under a flooded pool of liquid photopolymer and the part is built in upright position. In the bottom feed approach, part is built-in upside-down direction with the help of a special fixture while supplying liquid photopolymer only to build the desired layer. Therefore, exposure is achieved from the bottom of the build platform using a transparent window. On the other hand, top feeding supplies the material as a thin layer from the top bed. Furthermore, recoating processes also play an important role in the build quality. Therefore, owing to effects related to viscosity and surface tension properties of the liquid resin, parameters associated with recoating process also demonstrate a crucial importance.

Issues in resolution scaling of VPP process

Based on the development of subsystems of vector scan approach-based VPP, the focus can be given to the methodologies of manipulating the laser to achieve desired curing geometries. Currently, the main methods of beam manipulation are galvanometric and flying optics techniques[13], [14]. Galvanometric techniques utilize a stationary optics system with a movable mirror (galvanometer) to deflect the beam. In contrast, flying optics manipulate the laser beam by moving the entire optics system in the 2D plane. Therefore, flying optics systems can direct the UV beam in a pure vertical direction to the resin where galvanometric techniques focus the beam on an angle to the surface of the resin on locations far away from the galvanometer core. Since angle of incidence plays a great role in determining the curing profile in vector scan process, therefore, beam deflected by a galvanometer, a curing position far away from the galvanometer core, will produce a different curing profile compared with a location near to the galvanometric center by limiting a build size while maintaining homogeneous resolution [12]. In contrast, flying optics utilize the entire optics system to move with beam travel. Since an entire optics head is moving in the 2D plane, flying optics systems require large servo mechanisms that can compensate for the weight of the moving system. Therefore, compared to soft beam manipulation using galvanometers, such mechanisms in flying optics contribute to the reduction in print resolution as well as print speed [15]. Finally, implementing flying optics systems can be highly costly compared to galvanometers which also results in low accuracy.

Issues in build speed and size scaling of VPP process

As the dimension of the build gets larger (>100mm), the build time becomes a significant constraint due to relative slow process in VSPP [5]. Resolution of the VPP process is a dependent of exposure time. Therefore, scanning speed must be tailored to a specific region to facilitate accurate exposure based on requirement while low exposure time results in incomplete curing. Figure 4 presents the analysis of working curve for a typical photo polymer, based in this curve, it is evident that the cure depth is limited between under exposed region to the overexposed region of exposed energy to avoid distortion of the build. A potential remedy to reduce the build time is sacrificing the resolution to increase the build speed by higher scanning speeds. However, higher scanning speeds resulting in low curing depths due to exposed low energy [16].

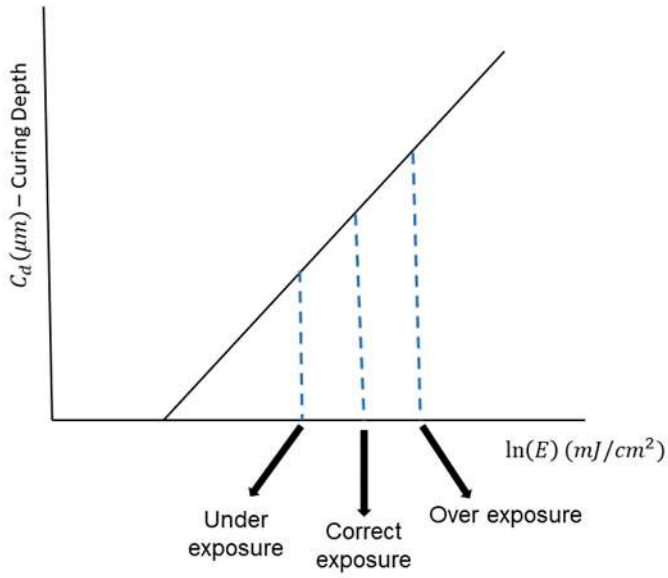

Figure 4: Restrictions imposed on exposed energy to avoid distortion due to overcuring (Reconstructed from [16]).

Another potential remedy is increasing the laser spot diameter. However, as with increasing the laser spot diameter, intensity of the beam will be reduced for the same applied power rating. Therefore, high power consumption will take place to achieve similar curing depth. One must consider tradeoffs between resolution, build speed and power consumption to determine optimum build conditions as the increase of geometrical dimensions.

Mask projection liquid vat photo polymerization

Mass projection photopolymerization (MPPP) technique works based on curing an entire layer of photopolymer with a help of a projection device. MPPP herein capable of producing large build size due to its convenient approach.

Issues in resolution scaling of MPPP process

Resolution scalability of MPPP systems is currently limited to the minimum mirror size of DMD. As the name itself suggests, in most commercially available projection devices consists of microscale mirrors with microscale actuators. Production of DMD devices with resolutions falls to microscale is a currently well-established process [17].

Issues in build size and speed scaling and potential remedies of MPPP process

Build size of an MPPP process is mainly limited due to the size of the DMD. Producing a DMD device expanding to large build size can result in a heavy principal cost [18]. However, as a solution, multiple DMD devices can assembled in array to increase the projection space. In similar fashion, producing a DMD device with ultra-small mirrors is another technological can be a high cost process, since synthesis of individual mirrors in nanoscale resolution is a current potential challenge [19] along with nanoscale mirror actuation mechanisms. If nano scale mirrors are applied, then the technology will be entirely replaced to digital nano-mirror devices. Due to such reasons, size scalability of MPPP is limited to a feasible span. MPPP process in general consists of number discrete steps including projection and curing, step dipping or recoating etc. Can result in large time consumption while maintaining ultra-low layer thicknesses inhibiting scaling traditional MPPP for large parts [20].

Two photon based PP (2PL)

Issues in scaling of build size and speed in 2PL process

Compared with vector scan VPP, the main difference or the improvement in 2PL is the increased resolution of the process. Traditional vector scan methods as discussed before, utilizes the single photon approach where transmittance is limited by the diffraction phenomena. More generally, single photon absorption transmittance light is dependent on linear absorption coefficient (α) whereas in two photon absorption, absorption coefficient behaves non-linearly. Compared to vector scan UV photolithography, 2PL involved extremely intense laser radiation in the order of terawatts per cm2. This high intensity facilitates the multiphoton absorption [21]. The increased transmission of the light photon producing further accuracy and resolution in the curing phenomena. Since 2PL utilizes two photon absorptions, the exposed energy required for the process is significantly higher than VPP. This issue creates a large energy drain while moving to higher build sizes limiting 2PL as viable application for large scale builds. While maintaining large energy absorption, build speeds in 2PL becomes inherently low compared to VPP due to increased exposure time while demonstrating all build speed issues associated with VPP.

Potential remedies to expand scalability of VPP processes

Photo polymers with higher curing depths with small exposure or with greater limits of over exposure can provide potential solutions to increase build speeds [22]. Hofstetter et al. [22] studied nine photopolymers with different with different working curves under similar exposure. They have established that curing speed and curing depth are some of key determinants of the speed of VPP process. Researchers have attempted to increase penetration depth of photopolymers by multiple approaches. Van Bochove et al. [5], studied the effects on adding a congruent dye to a photopolymer resin to increase the curing depth. It has been demonstrated that increasing the dye concentration in the photo resin has increased the depth of penetration [5].

One of the main issues that adds additional build time to MPPP process compared to VPP process is discrete steps in MPPP process where, mainly due to layer wise resin refilling. Compared with VPP process layer filling is occurring automatically with platform movement without the requirement of further controls. A remedy to reduce build time in a MPPP is introduced by Manapatt et al. [23] which is known as continuous liquid interface projection (CLIP). CLIP processes address the increased build time issue due to discontinuous or discrete process steps which are mainly laser scanning, platform moving and resin refilling. As in figure 7, in CLIP process, the resin is continuously cured by eliminating the discrete nature of layer refilling.

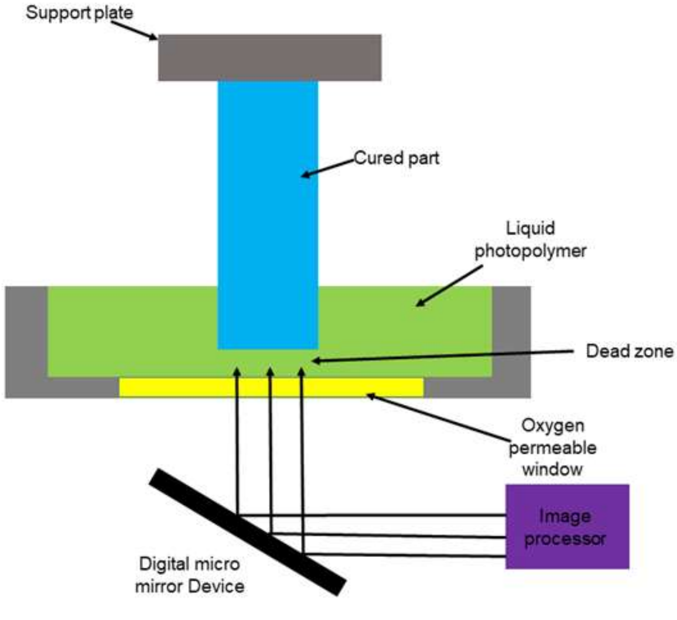

Figure 5: Schematic of the CLIP process [23]

The CLIP process utilizes the implementation of a dead zone which is an uncured photopolymer between cured part and reservoir bottom. The dead zone is formed via a specially designed UV transparent and highly oxygen permeable window used as the base of the reservoir, below which pure oxygen is continuously supplied. UV transparency ensures laser penetration for resin curing, while oxygen permeability allows oxygen to penetrate the resin reservoir to inhibit polymerization. This "dead zone" is fundamental for continuous printing as it ensures that a fresh layer of resin is always present below the printed part. Therefore, CLIP processes are ensuring that overall printing is done in a continuous manner which is reducing build speeds from hour scale to minute scales for while fabricating similar geometries using traditional MPPP and CLIP processes [23].

Like previously discussed aspects, though 2PL processes have a remarkable printing resolution compared to VPP and MPPP processes, it is limited by the slow build speeds that inherently limits expanding to large build sizes. As remedy to slow building speeds of 2PL, as well to utilize maximum potential of 2PL, Schmidt et al. [24] introduced hybridization of vat photopolymerization as a potential solution. The approach is the collaboration of MPPP and 2PL methods to produce cm scale parts with sub micrometer resolution. Figure 6 represents where large scale was achieved using MPPP and the small length scales are achieved using 2PL enabling the feasibility of multiscale printing. Schmidt et al. [24] utilized the approach to fabricate multiscale woodpile structures as presented in figure 6. The mm scale wood piles are initially fabricated by MPPP process, the printed part was then mounted in a 2PL printer. Subsequently, microscale woodpile features are now fabricated on top of the mm scale woodpile structure. They have concluded the success of the process by validating that two components fabricated by different processes are satisfactorily bonded to each other after post cleaning steps.

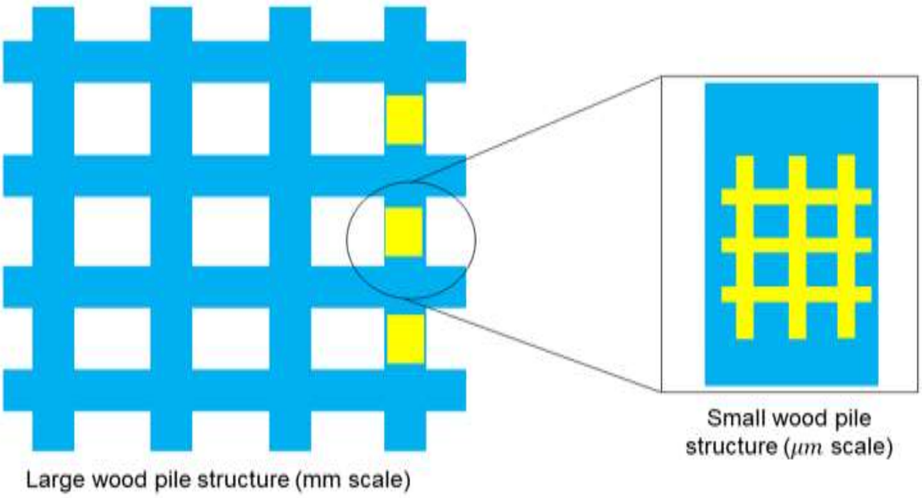

Figure 6: Printed microstructures with the combination of MPPP and 2PL methods (Schematic constructed based on [24])

Powder bed fusion

Powder bed fusion (PBF) processes can be considered as one of the most sophisticated and well-established AM technologies. The general principle of the technology includes melting or sintering the material of the build part which is initially in powder form. On the other hand, powder can be supplied using a nozzle to the fusing location which falls to the directed energy deposition (DED) category. To efficiently identify scaling issues in PBF, current PBF processes are condensed to the areas of selective sintering (SS) and direct melting (DM). SS focuses on heating or melting a constituent in the powder mixture selectively to produce interparticle bonding. The part obtained after the SS step is referred to as the sintered part and the sintered part will be further processed in operation as complete sintering and debinding to allow diffusion in main constituent. However, SM approach is based on purely melting the low melting point constituent in the mixture and allowing the bondage in the liquid state. One step further, DM works on purely melting the entire constituents in the powder mixture allowing joining in the powder bed itself. Therefore, parts made by DM processes do not require further post processing as the latter [25, p. 3], [26]. From scaling perspective, post processing of PBF sintered parts either by sintering or debinding will produce distortions in geometrical dimensions due to part shrinkage due to loss of material as well as reduction in porosity. While scaling the process to high resolutions and low build sizes such issues become detrimental on final product [27].

Focusing on subsystems of PBF processes, the energy source to melt the powder can be multiple such as use of a laser or an electron beam. Secondly, depending on movement of the energy source, we can categorize PBF beam manipulation like VPP as galvanometric optics settings. Thirdly, based on material feed mechanisms, mainly top or bottom feeding approaches can be given. Fourthly, as in some VPP processes, recoating systems also play an important role in the topology of the build. Finally, the form of the feed material can also be a limiting factor on the resolution of fusion process. [28]–[30]

Issues in resolution scaling of PBF process

Like beam manipulation in VSPP process, the use of galvanometers produces inhomogeneities in melt pool dimensions while moving away from galvanometric center producing challenges in maintaining constant resolution [31].

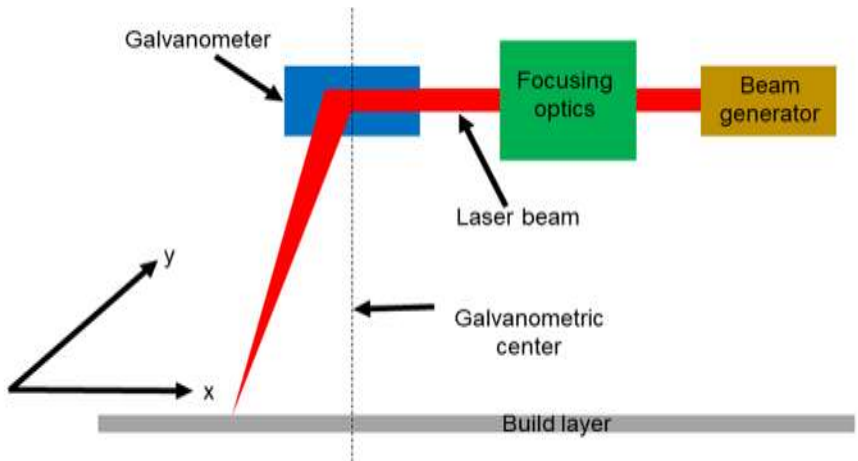

Figure 7: Galvanometric beam manipulation in PBF

Resolution scaling of PBF processes is also limited while avoiding process instabilities. Most common instabilities are keyhole formation, balling and swelling, lack of fusion, porosity, and spatter. Such issues can only be minimized by controlling or inhibiting laser parameters and process parameters. Figure 8 shows the ideal working zone that can reduce or eliminate such micro defects [31, 32].

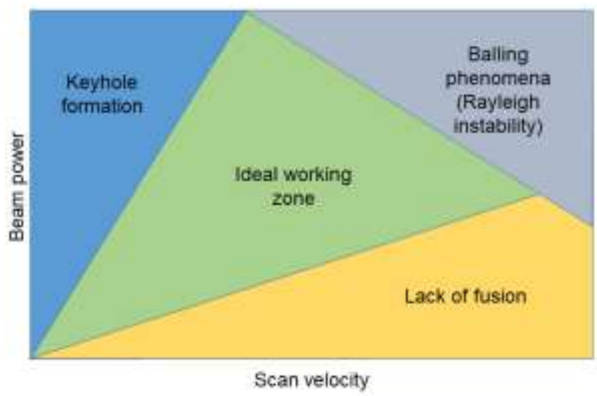

Figure 8: Identification of ideal zone for laser powder bed fusion[34]

To initiate satisfactory bonding between particles, laser spot diameter must cover multiple particles to initiate multiparticle fusion. For a low laser diameter (50-80µm) the size of the largest particle must be order of magnitude lower than laser diameter to satisfy this requirement[33]. Producing ultra-low size particles are a technological challenge as well as high-cost operation while producing in large quantities [35].

Issues in build size and speed scalability of PBF processes

For large scale builds utilizing galvanometric manipulations becomes challenging to continue with maintaining higher resolutions which limits the scalability of build size. Therefore, one is limited with these two aspects on first size scaling analysis of PBF.

Gheysen et al. [36] studied on identification of process window for a PBF process based on single bead analysis where process instabilities are minimized. Such process window creates challenges in geometrical scaling to small build sizes with high resolutions. To avoid keyhole formation, low laser power with small spot size can be used. However, as the decrease of laser power, required scanning time has to increase to produce required energy for fusion. If both laser power and scanning speed are increased, the build track results in balling effects. Increasing laser spot diameter for same power will reduce the laser intensity. To maintain required intensity for large diameter laser, high energy supply has to be simultaneously maintained. Therefore, for material specific application, one is limited with the freedom on setting laser powers, laser spot diameters and scanning speeds. While According to the characteristic curves of scanning speed and laser power [36].

Potential remedies to expand scalability of PBF processes

Galvanometric systems in PBF can be mainly divided into passive and active optics approaches. Working area is limited in passive optics due to constant focal length. But by active optics, focal length can be dynamically changed based on beam travel distance. A solution is to implement galvanometric calibration to adjust the beam power as it moves from galvanometric center also with active optics [37].

To increase the scalability of PBF processes, research groups have introduced solutions based on new or altering the traditional approach in PBF. Tsai et al. [38] introduced multispot scanning strategy to reduce scanning time and improve print quality. They have used traditional galvanometric scanning system and diffractive optical element (DOE) to build their laser PBF based AM system. A DOE device can split an incident single laser beam to multiple laser beams by inbuilt optics arrangement [38]. They were able to achieve a satisfactory surface roughness of 3.2µm while maintaining reduced scan time of 38.1% that to the single spot method.

In addition to multispot scanning strategy, to increase the build speed, research and implementation has also done on multiple laser beam scanning strategies. Zhang et al.[39] implemented duel laser beam scanning strategy where, laser beams produced by two individual sources are parallelized to increase processing flexibility. Such implementation can reduce the build times of large components with limited resolution where, single beam PBF pose build speed challenges.

Directed energy deposition

Among all AM process up to present, directed energy deposition (DED) techniques demonstrates the capability for large scale build sizes starting from sub mm to multiple meters in geometrical length scales. Currently, DED techniques can be categorized based on powder and wire approaches. Where in powder based DED, a stream of powder is directed towards the energy source which can be a laser or an electron beam or an arc or a plasma. In wire based DED, the feed material is directed towards the energy source which is in wire form. The design of DED processes allowed them to expand up to large build sizes where other AM processes not able to achieve since entire material feed mechanism and energy source in the 3D space using traditional CNC or custom robotics [4]. DED processes are generally demonstrates low resolutions, however, eliminates bottlenecks in printing large length scales allowing print sizes up to large aerospace applications [8].

From the basis of process control, the main two aspects that influence the scalability of the process are manipulation of the energy source and feedstock feeding mechanism. As the name suggests DED works by moving the entire bulk mass of energy source and material feed mechanism by the help of servo system typically incorporating computer numerical control (CNC) or with advanced robotics. Even with multiaxial approaches, manipulating such mass in very low length scale becomes challenging due to application of bulky servo mechanisms [8]. Reducing the mass of the entire assembly will limit required source power and powder flow rate subsequently reducing build speed.

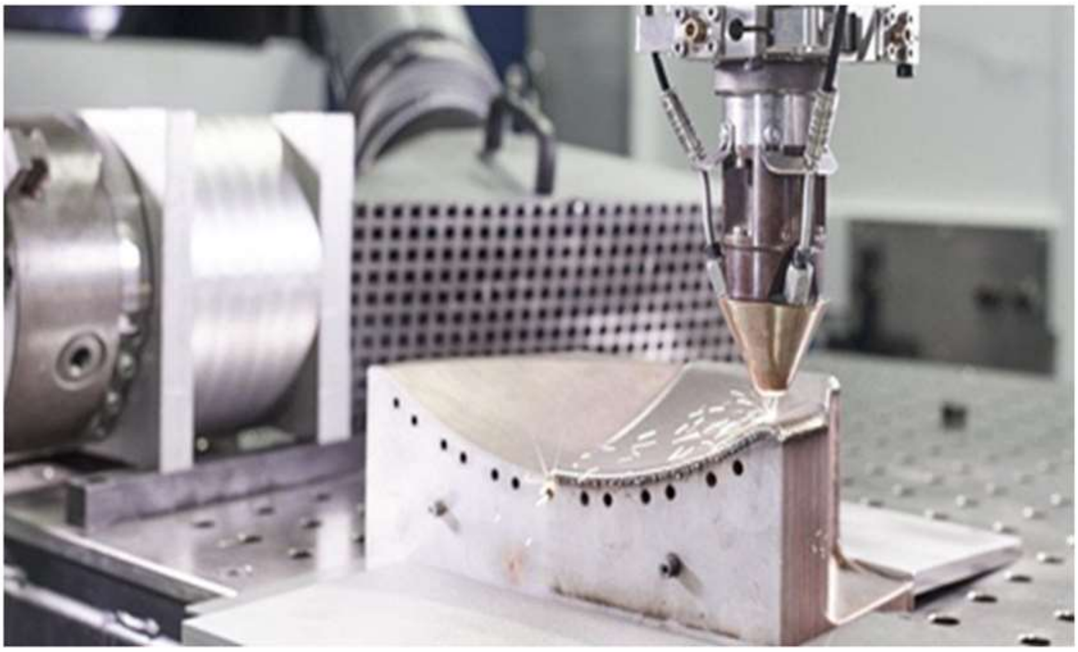

Figure 9: DED laser cladding process

Powder based directed energy deposition

In powder based DED, the stream of powder particles is directed towards the energy source either uniaxially or with an angle to the direction of the energy source. Currently laser based DED has the advantage of focusing the energy in small spot sizes like PBF processes. However, due to small spot size, the interaction area between particles and laser becomes limited. To balance with laser spot size, particle stream diameter also must be in the order of spot size [40]. However, it is challenging to ultimately reduce particle nozzle diameters that facilitate such small length scales to avoid powder clogging[41].

Issues in resolution scaling of powder DED process

The main limiting factor for resolution scaling of powder based DED process can be given as the parameter called catchment efficiency [42]. Catchment efficiency is initially defined as the amount of powder captured by the melt pool and can be effectively scaled to the ratio between melt pool diameter and area of the powder stream striking on the melt pool [43]. It is always expected to have a value of catchment efficiency greater than a minimum of 5%. Due to the catchment efficiency and satisfying ideal values, the laser spot diameters of powder DED becomes larger compared to PBF. While laser spot diameters of PBF processes can be as low as 50-80µm, while laser spot diameters for powder DED can vary from 1-4mm which is an order of magnitude higher. For a large melt pool with low nozzle diameter with respect to melt pool size can produce a good catchment efficiency. However, due to low material feed rate by low diameter nozzles, can increase the build time. Therefore, such application will inherently limits reaching powder DED for high resolutions [43].

The reachability of powder based DED is limited again due to parametric constraints based on laser powder interactions and avoiding process instabilities similar to PBF processes. Influence on material thermophysical properties, residence time, particle size, impact velocity, melt pool conditions and surface tension are such parameters and must be optimized as discussed in previous processes. Melting temperature of the material constraints in time of fusion where, high residence time is needed. Depending on melt pool dimensions, impact velocity has to be tailors to satisfy a good value in catchment efficiency [44]. Therefore, such constraints on parametric aspects will further limit the resolution scalability of powder DED.

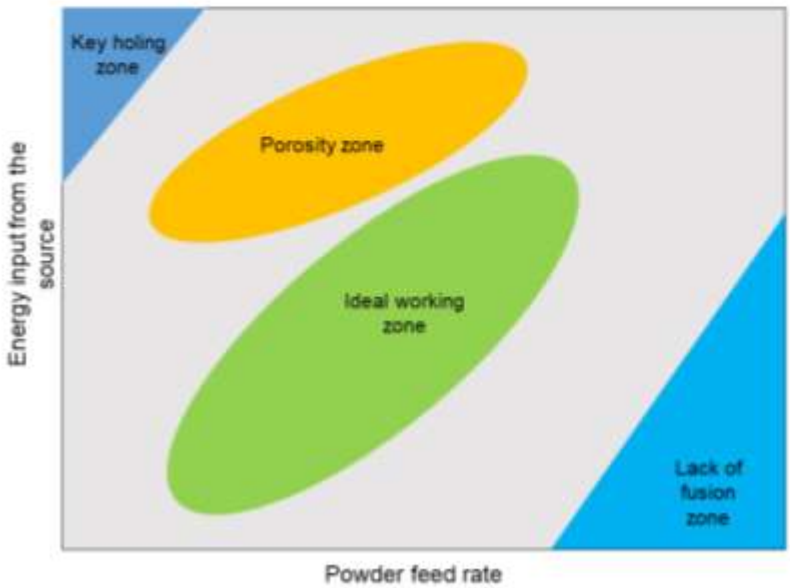

Figure 10: Identifying working zones for metal DED avoiding macro and micro defects for a typical material (Sketch approximated based on Dass et al. [45])

Issues in resolution scaling of wire DED process

While achieving higher resolutions wire diameter must compensate with laser spot or electron beam diameter. As maintaining high resolution with smaller laser spot sizes with ultra-low diameter wires, DED build speed will be considerably low and will not meet desired build criteria.

The main drawback in metal inert gas (MIG) DED processes is the poor control of energy source. Generation of arc requires an overcome of threshold current to facilitate electron transport between substrate and electrode. Due to these limitations sizing of the melt pool lies in the macroscopic length scales demonstrating high melt pool dimensions limiting the reach to lower resolutions [47].

Contrary to the approach in wire arc AM, plasma AM focuses on applying a high voltage between electrode and substrate to create a plasma to melt the feedstock. Like arc creation, plasma creation requires a threshold value in voltage difference between the substrate and electrode. Furthermore, plasma width increases with respect to welding current and similarly plasma temperature is also a dependent on welding current [48]. Based on the temperature that requires to melt the feed stock and size of the plasma limits the plasma method reaching to lower melt pool dimensions hindering higher resolutions [49].

Issues in build size and speed scaling of DED process

Scaling issues on build size of DED processes mainly arises while moving to smaller build sizes. Due to the physics limited low resolution of the process and high material feed rates associated, it is challenging to tailor DED processes to fabricate complex geometries at low size scales [46].

Potential remedies to increase accuracy of DED processes

Modern day DED systems commonly utilizes hybrid additive manufacturing approaches (HAM) where cooperation between additive and subtractive processes takes place in the same setup. Since DED unit can be mounted in the same CNC machine, HAM becomes convenient. Assuming a part with low resolution is built by DED and post machining is done using CNC milling operations, the external resolution and the surface roughness of the build is now decided by the capability of post machining process [50], [51].

Binder jetting

Binder jetting (BJ) is based on selectively depositing a liquid binder in a bed of powder to create the desired layer geometry like layer wise building approach as discussed before. If metal, ceramic or a specific polymer part is required, green part will be sintered and debinded as post processing steps[52]. The main parameters to consider while utilizing BJ process are, powder characteristics, binder characteristics, print processing parameters and design features[52]. In detail, powder characteristics are focused on shape or morphology (circularity or sphericity), mean particle size, flow and spreadability, packing density and surface chemistry. Binder is a crucial factor in BJ processes since it fills the free spaces in the powdered material. Therefore, there are certain requirements that the binder needs to be satisfied. Mainly there are three types of binders available based on acid-based, metal salts and aqueous-based binders[52]. Acid based binders produce the powder bonding using an acid-base reaction. Metal salts works based on salt crystallization and salt displacement reactions. Aqueous based binders work based on solvent evaporation technique [52]. Since almost all binders are based on polymers and monomers, the jetting process can be limited by the rheology of the binder.

Issues in resolution scaling of BJ process

Viscosity (η) of the fluid binder is important in binder jetting, since it provides are metric in flowability of the polymer. Secondly, surface tension (γ) provides information on droplet formation of the binder. These two parameters are assed based on Re (Reynolds number) and We (Weber number).

$$Re = \frac{\rho dV}{\eta} \quad (1)$$

And,

$$We = \frac{\rho dV^2}{\gamma} \quad (2)$$

Where, d is the droplet diameter, ρ is the density of binder, and V is the velocity of jetting.

Jettability of a fluid is an important aspect while scaling BJ. Jettability can be initially defined as the ability of a fluid to form droplets while overcoming inertial, viscous and surface tension forces, which is also dependent on flow geometry [52]. Based on Re and We numbers, the factor, jettability can be defined for a fluid as,

$$\frac{1}{Oh} = \frac{Re}{\sqrt{We}} = \frac{\sqrt{\gamma \rho d}}{\eta} \quad (3)$$

Where, Oh is the Ohnesorge number. For compatibility for jetting, Oh number must be in between 0.1 and 1. When 1/Oh value is less than 1, dominance of viscous forces comes to effect creating difficulties in ejecting. On the other hand, if 1/Oh is greater than 10, then surface tension forces dominate creating continuous flow of liquid without producing bubbles. Therefore, at these extremes the binder is not considered as jettable [53]. When focusing on resolution scaling of a typical BJ process, the diameter of the droplet must be tailored to fall in to the jettable region. Since Oh number is a function of Re number and We number, which are functions of nozzle diameter, to satisfy the printable fluid requirement as in figure 18 and based on the jetting technique therefore, a tradeoff between nozzle diameter and type of binder that is used limits the allowable size range of droplet diameter.

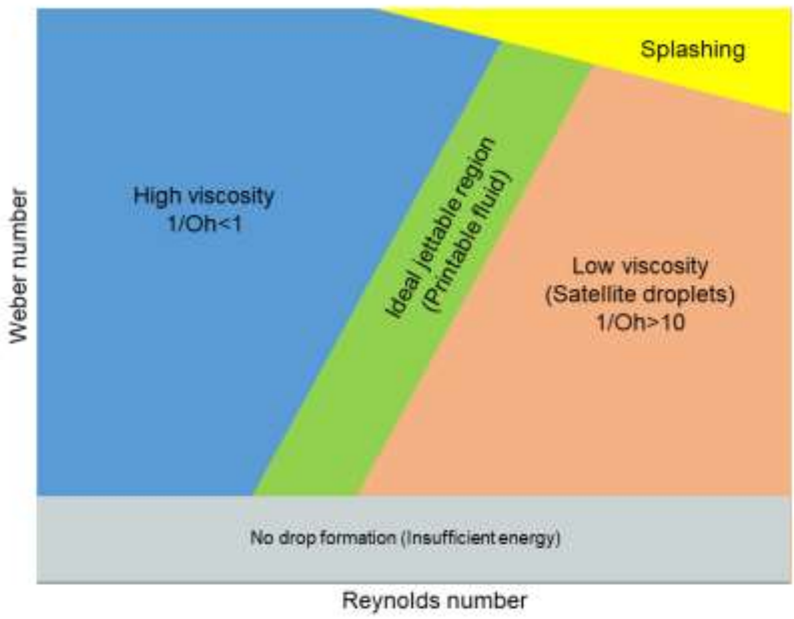

Figure 11: Identifying the printable fluid region in BJ (Reconstructed based on Dini et al. [53])

Droplet spacing, which is the distance between two successive ejected droplets by a single nozzle or spacing between adjacent droplets ejected by multiple nozzles, is another area to focus while scaling of a BJ process in the aspect of process resolution. The main parameters that can affect droplet spacing and line spacing are deposition rate of the print head, rate of binder permeability in the powder, drop to drop distance and line spacing itself. Deposition rate is mainly dependent on capillary pressure and gravity on droplets. Secondly, diffusivity is based on powder morphology, surface chemistry, powder bed compactivity and droplet impact velocity. Higher droplet velocity will produce more droplet momentum resulting further depth of penetration. Also, a powder with satisfactory void fraction will increase the binder diffusion in the powder bed. Droplet spacing, droplet size and frequency of droplet generation and line spacing must be tailored to prevent oversaturation or under saturation of the binder in the bed [54]. Exploring further, large droplet sizes and high frequencies can produce oversaturation. Similarly, smaller droplet and line spacing incongruent with droplet size will also result in binder saturation.

Issues in build speed and size scaling of BJ process

Jetting velocity of the binder is a crucial parameter that determines the speed of BJ process. Jetting velocity can be defined as the speed of ejection of the droplet from the binder nozzle [55]. Higher jetting velocity will produce higher droplet velocity increasing the impact momentum of the droplet with powder bed. However, jetting velocity is controlled to an optimum value mainly to avoid splashing and binder saturation. Splashing threshold (f(R)) for BJ is defined based on the relation,

$$f(R) = We^{1/2}Re^{1/4} \qquad (4)$$

Since f(R) is a function of Re and We numbers, Re and We number are functions of droplet velocity f(R) becomes directly proportional to droplet velocity v. Therefore, splashing threshold, asses the influence of jetted binder on the powder bed based on droplet velocity. Higher droplet impact forces produce inherent surface roughness of the layer due to splashing. Therefore, jetting velocity is constrained due to this factor limiting binder release thus constraining overall build speed. In addition, We number of the binder is also restricted to a higher value than 4 to overcome barrier in fluid air surface tension to form liquid droplets [52].

While focusing impact on build speed due to BJ print parameters based on materials aspect, layer thickness is limited by the size of the powder. In general, layer thickness is considered as three times the largest particle size to attain convenient powder flow spread ability [56]. However, further increasing the layer size will decrease the powder bed density [56] simultaneously reducing the green part strength due to reduced capillary bonding phenomena, therefore, producing challenges while fabricating large build sizes with high aspect ratio overhang structures. Powder size can also be considered as one of the main parameters that decide part features and dimensional capabilities. Also, further increasing layer thickness will result in higher diffusion times and large droplets. [57]. Binder saturation parameter can also be addressed based on binder saturation, S as [56],

$$S = \frac{1000 \times V}{(1-(\frac{PR}{100})) \times X \times Y \times Z} \qquad (5)$$

Where, V is the volume of the droplet, PR is the powder packing rate, and X and Y are the planner spacing between binder droplets and Z is the layer thickness. To attain sufficient mechanical strength of the green part, an optimum S value is a necessity. The optimum S value is set based on the requirement of the green part, however, which is constrained by the factors discussed before [58].

Material jetting

The main difference in material jetting (MJ) compared to BJ is that the material, which is used to build the 3D printed part, will be directly deposited through the printhead nozzles. While identifying scaling issues, the first aspect is the jettability of the material or the composite. MJ can be challenging compared to BJ, since specialty materials or mixtures must be deposited and they may not directly jettable as many commercial binders [59]. However, MJ is one of the most promising AM processes that facilitate reaching up to higher resolutions [60]. It is important to note that MJ contains all the limitations and scaling issues so far compared to BJ, except few inherent issues associated only with BJ (powder particle interactions, pore diffusion etc.).

Issues in resolution scaling of MJ process

A specific type of material jetting can be introduced as jet photopolymerization (JPP). In JPP, a liquid photopolymer is jetted through a print head and simultaneously cured by a focused UV beam at the droplet location. Based on this criterion, resolution of JPP can be lower than pure VPP methods [61]. In addition, synchronization droplet timing and curing timing must precisely be controlled. Such synchronization process may add additional relaxation time to the curing process compared to VPP may results decreased build speeds. Since the polymer is in liquid form at the initial phase, curing must be achieved before it flows to an unexpected area. Therefore, based on these two aspects, scaling limitations of JPP can come from while reaching lower resolutions as well as reaching high geometrical sizes due to large build times which is imposed due to jetting technology [62]. Jetting technology initially constraints the minimum droplet diameter to a certain region limiting minimum resolution. Scaling issues on build sizes of MJ processes can be similarly attributed to that of BJ processes except large size parts are limited in BJ due to green part strength, however, in MJ such issues can be eliminated.

Remedies to increase scalability of binder and material jetting processes

As with the previous approaches discussed with other AM methods to increase scalability, most common implementation to increase scalability of BJ process is the hybridization. Popov et al. [63] hybridized BJ with cold isostatic pressing where a more dense green parts can be obtained. Increase density of the parts resulted in increased scalability and more refined microstructure with large scale builds that can withstand further bending stresses. Secondly, most convenient method to increase the scalability of BJ and MJ processes are optimization of process parameters based on multiple practical aspects. Shrestha and Manoharan [64] utilized Taguchi method to optimize process parameters in BJ. Such optimization resulted in efficient control of binder saturation, while identifying critical parameters that dominates the control of the process. They have further identified that powder-binder interaction can be improved by allowing densification of powder layer at a high ratio of feed to layer thickness with higher binder percentage. Such findings are directly obtained from the input of common process parameters such as saturation percentage, layer thickness, roll speed and feed to powder ratio from the optimization method eliminating further complex diffusion experiments.

Direct write processes

Direct write (DW) processes can be introduced as the technology that bridges the gap between nanoscale and microscale which is ultimately referred to as a mesoscale technology. The common DW processes can be categorized as ink based, laser transfer, thermal spray, beam deposition and liquid phase DW processes. Ink based DW processes are further expanded into the technology that is based on as, nozzle dispensing, quill type, inkjet, aerosol projection processes. In inkjet processes, dispensing of the ink can either take place from liquid or gas phase. Laser transfer DW works on the principal of ablating the build material and allowing the deposition of such vaporized material in substrate. Thermal evaporation DW works in the same principle of ablation but producing the energy for ablation is supplied by thermal energy. The melted plume created by the process is bombarded on the substrate. On the other hand, beam deposition DW processes work based on sending multiple precursors to the deposition chamber in gaseous form while and external energy source (laser or an electron beam) will initiate a reaction between precursors which ultimately deposit on the substrate. It is convenient to consider that bean deposition DW is an integration of traditional CVD process [3].

Issues in resolution scaling of DW process

Behera and Cullinan [65] thoroughly studies scaling issues in three direct write processes on direct ink deposition (DI), electrohydrodynamic deposition (EHD) and aerosol jet (AJ). Electrohydrodynamic processes can produce droplets on a submicron scale. The resolution of the process is mainly constraint by the nozzle size. For low nozzle diameter, particle loading must be reduced to overcome clogging issues which results in inhomogeneous particle size distribution while working with high viscosity fluids. Parallel to EHD process, resolution of the AJ process is also limited by avoiding process instabilities. Additional constraints that limit resolution of an AJ process are also due to avoiding poor edge quality, line discontinuity and overspray can be extracted. Finally, aerodynamic focusing approach also plays a vital role on deciding AJ resolution. Poor aerodynamic focusing can lead to inhomogeneous spray diameters further reducing resolution [65].

Issues in build size and speed scaling of DW process

While reaching to high resolutions, application of low nozzle head diameters produces extremely low deposition rates due to rheological aspects and well as fluid dynamics aspects. Fluid dynamically low nozzle diameters inhibits the ejection of the fluid due to fluid viscosity and surface tension properties. While loaded with particles, nozzle diameters must be sufficiently larger than largest particle size in the distribution. The throughput of a typical EHD process with a sub nanometer resolution scale is reported as 0.00036mm3/h. Also throughput of 200mm3/h is reported for AJ process according to Behera and Cullinan [65]. Under such low building rates, it is highly challenging to implement EHD and AJ processes for large size builds that typically falls to macro scale. In addition to low building speeds, DW processes may produce challenges in producing complex geometrical structures with high aspect ratios due to material and technological limitations. Since DW poses a relaxation time between liquid to solid phase transformation, subsequent layer shift has to rigorously tailored to avoid process instabilities while fabrication of overhangs [66].

Remedies to improve scaling of DW process

Medina et al. [67] demonstrated hybridization of stereolithography processes with DW technology to improve scalability of DW process based on functional printing of electrical circuits. A hybrid stereolithography/DW apparatus was fabricated, and high resolution required conductive material paths were produced by DW nozzle head while bulk material capsuling is achieved by fast stereolithography process. Such approaches can increase total throughput tremendously while projecting DW processes as a viable large scale future application.

Extrusion based additive manufacturing processes

Extrusion based methods mainly utilize the technique where the build material is fed in the form of a filament, and it is extruded through a nozzle to a substrate while moving in X-Y plane or Z plane (in special cases) to produce the build. The filament, while forcing through the nozzle by the feed mechanism, is melted using inbuilt heaters in the nozzle where build material deposits in the substrate in liquid form. Among all of AM technologies available, extrusion-based methods became highly popular due to its versatility and expandability up to obtaining as a domestic 3D printer and can be considered as the most popular form of AM technology. Among the multiple extrusion-based methods, discussion at this point is limited to FDM for conciseness [68].

Material extrusion is a 3D printing process that uses a continuous filament of a thermoplastic material. Filament is fed from a large spool through a moving, heated extruding head, and is deposited on the growing part. One of the major concerns is the scale limitation of the printed parts with the scale issues with the material extrusion hardware itself. With owning and operating a large format ME 3D printer, the owner would prefer to get the largest possible build volume for the smallest possible footprint; where footprint is the volume of space that must be allocated to the printer and can be expressed as an imaginary cubic bounding box around the outside of the printer. The main issue with scaling a ME system is having to increase the size of the build plate [68].

It is expected that a large size scale 3D print will require large amount of filament material to build the entire geometry. The bed of the printer itself must be robust enough to carry mass relative to the size of the build without warping. Build times on a large size scales will be challenging by desktop small scale printers. The biggest limiting factor for build time is the rate at which the filament can be heated and extruded. A powerful hot end will be required to produce sufficient thermal energy to facilitate material extrusion which could help in reducing print time for larger scale [68].

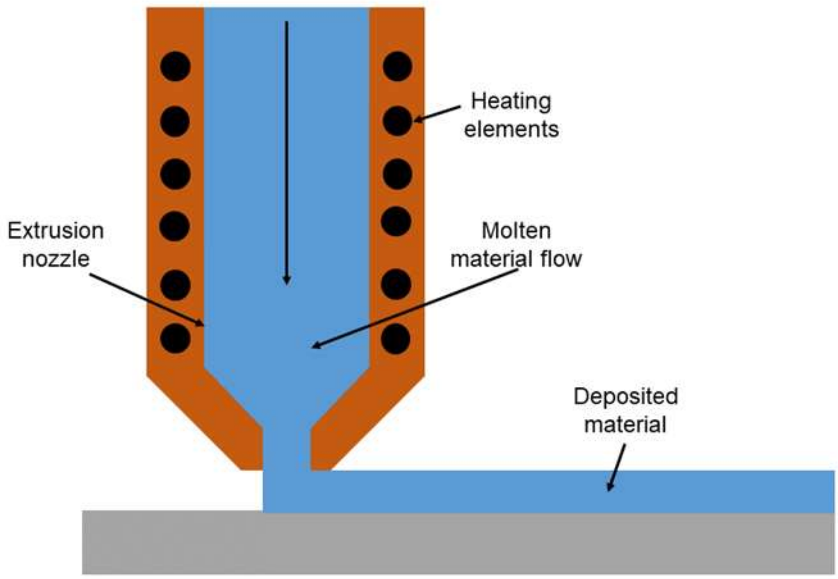

Figure 12: Schematic of FDM process

Issues in resolution scaling of material extrusion process

Ideal scale for material extrusion printing:

In general, the average-size ME printer can print models approximately 120 mm x 120 mm x 200 mm while some printers can print as large as 500 mm x 500 mm x 500 mm. For the average size of such ME printer, many process parameters can be controlled as extrusion rate, print head movement speed, deposited layer height etc. such process parameters can be resulted on the final geometry mainly based on resolution scaling of the process.

Syrlbayyev et al. [68] showed material extrusion print process parameters change dramatically based on the type of material but in order to achieve good acuracy for a small scale geometry a layer thickness of 0.15 mm and print speed of 15 mm/sec were found to be ideal according to Syrlybayev et al. of material extruded ABS printed parts. Such process parameters can increase the time of build for a great extent. As an example, fabricating a small cube of 2 cm x 2cm with these process parameters can take up to 20 minutes without considering the pre printing preparation time . A detailed research had covered the basics of how to optimize scalability of material extrusion and the process parameters of the fused deposition modelling (FDM) process using the Grey-based Taguchi method per the follwoing paper Parametric optimization of fused deposition modelling process using Grey based Taguchi and TOPSIS methods for an automotive component by comparing print time estimation from G-cod slicer softwares for different process parameters [68].

Issues in build size scaling in FDM process

The combination of process parameters ideal for FDM printing with its built size depends on process parameter and hardware limitations. Building a large FDM printer would require redesigning and new configuration for the current FDM hardware for the most effective results. Same goes for micro and nano scales material extrusion 3D printing. A good example for small scale 3D printing is 3D printing bolts with threads. Geometries made of thermoplastics with thread features has very tight tolerances and currently being produced using conventional injection molding due to its capability of tight tolerances [68].

There are multiple influencing factors for the accuracy of FDM. Syrlybayev et al. used FDM desktop 3D printer to print PLA products under different parameters. The influences of bottom/top thickness, filling density and placement position on printing accuracy is studied. They have concluded that each parameter has a certain influence on the fabricated parts resolution in relation to its scale, however, the influence is relatively minor. The work piece has a certain degree of shrinkage in all directions, while having a certain directivity. Plotting the parameters on a three dimensional graph to observe the multi-dimensional effects of parameters on resolution showed that increase nozzle size and speed reduced the resolution for such scale sizes [69],[70]. Interpreting these results for a larger scale would lead to identifying further scaling limitations.

The selected diameter of the nozzle represents a suboptimal compromise between the highest possible level of detail and a large flow rate to shorten the fabrication time. Other new concepts of print heads can be considered as concept of a rotatable print heads with slot-shaped nozzle openings. Such print heads gained wide implementation in modern FDM machines. The innovative concept presented here opens new possibilities for the free adjustment of line widths to be printed and thus also with variable layer heights in a wide range.

Potential remedies to increase scalability in FDM process

Experiments with the new nozzle concepts to capture high detailed features such as curves are analyzed. Where it showed high resolution to generate small scale features and large scale features without sacrificing time or resolutions. work on high volume 3D printing with the variable nozzle size to accommodate for different throughput requirements merged multiple resolutions as well as throughput scales in a same setting. [71], [72]. The problem between build time and resolution of FDM parts was further addressed by researches [71], [72]. An application with a rotatable printing nozzle with a slot-shaped opening was successfully introduced and a fully working prototype of the print head was applied in an FDM system, allowing a variable adjustment of line width during the printing process. Such approachs can accomodate the tradeoffs between resolution and build speeds simultaneously in large scale build while facilitating a dynamic spatial resolutions and opening pathways for new scales with the current techniuqe [73].

Introduction of innovative extruder concept is another approach to increase the thruput in FDM. The current technology to produce 3D printed components with the FDM process allows the use of one or two printing nozzles with fixed diameters. For large-scale 3D printing of ultra-high-performance concrete – a new processing route for architects and builders was researched. the research project introduced in the present publication deals with the large-scale additive manufacturing of selective deposition for ultra-high-performance concrete (UHPC). The 3D involved printing process is based on an FDM-like technique, in the sense that a material is deposited layer by layer through an extrusion print head. The present work also explores the possibilities offered by computer aided design (CAD) and optimization, and their integration within the product design process in the case of large-scale AM. They have revolutionized the concept and hardware of FDM printers by utilizing a 5-axis robotics which acts as the extruder and 3 axis stepping motors in a normal FDM process. Such approach made possible since FDM printing with concrete does not require heated bed requiring less hardware modification. The utilization of 5-axis robotic arms is applicable to material extrusion with other materials to generate large scale geometries. It also adds in another advantage as it could eliminate support structure which improves resolution with increasing the scale of printing.

Sheet lamination processes

Sheet lamination process (SL) is an additive manufacturing (AM) methodology where thin sheets of material (usually supplied via a system of feed rollers) are bonded together layer-by-layer to form a single piece that is cut into a 3D object. Laminated object manufacturing (LOM) and ultrasonic consolidation (UC) are both examples of sheet lamination techniques.

SL can use a variety of materials such as paper, polymer, and metal - but each requires a different method to bind the sheets of material together. Paper sheets are commonly bound using heat and pressure to activate a layer of adhesive that is pre-applied to the sheets. Metal sheets are bound together with ultrasonic vibrations under pressure (aka: ultrasonic welding), as opposed to melting or sintering. The bonding mechanism in UC process is based on producing adherence between crests and voids due to inherent surface roughness of adjacent metal sheets [74].

Issues in resolution scaling of SL process

SL is one of the limited-resolution AM methods, Industries utilize SLM as a fast and low-cost way to fabricate non-functional prototypes, casting molds, and geometries with low complexity using readily available materials. Since the approach allows build-materials to be swapped out in the middle of printing, SLM also facilitates on producing composite structures [75].

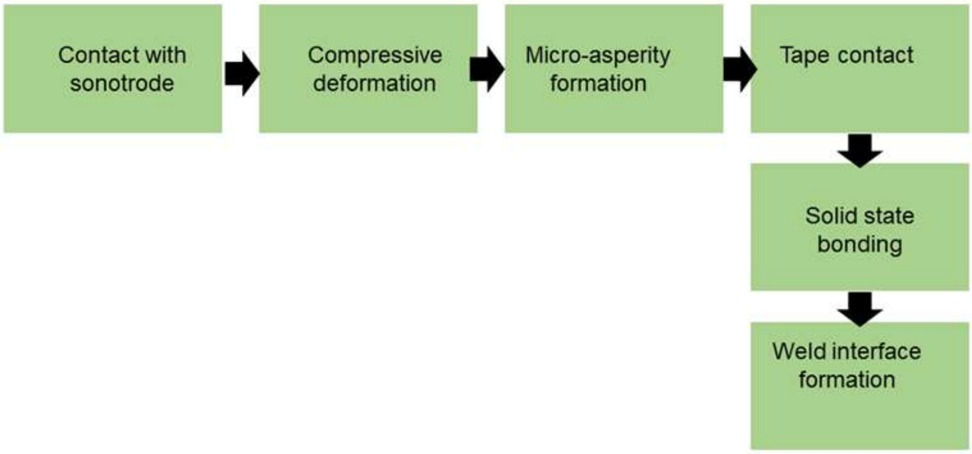

Figure 13: Steps in bond formation process between two adjacent sheets in UC process [75]

Focusing on UC, which can be considered as the most widely used SL process by industries, resolution of the build is mainly limited due to the limited thickness of the metal sheets. To initiate the ultrasonic weld, an accurate vibrational mode must be satisfied. While achieving a specific vibrational mode, an interrelationship between height, width and sonotrode frequency arises [74]. Therefore, from sheet manufacturing perspective with different thicknesses, constraints to discrete values also inhibiting the production of sheets with ultra-low thicknesses while fine tuning of sonotrode [74]. In addition, application of ultra-low thickness sheets with thickness values near the surface roughness will result in sheet penetration.

From process approach itself, the geometrical complexity is largely limited in UC. Therefore, resolution of the build is also dependent on the pre and post machining processes. Either pre-machined shapes of sheets are welded layer by layer or sheets with uniform geometries are welded together and post machined to the desired geometry, or both approaches are utilized simultaneously. For high strength materials crafting narrow 3D internal contours will produce challenges using conventional machine tools limiting reaching UC process that to the capabilities of other AM processes.

Issues in size and speed scaling of SL process

SLP, while specifically focusing on UC, is a discrete step process like PBF processes. Where discrete step process comprises of layer generation, ultrasonic welding, post machining mainly for UC. Such discrete steps increase the building time inherently while comparing with continuous AM processes (VPP, ME). For a typical spot weld of 10cm2, with an amplitude of 20-60µm, a welding time can vary between 0.1-2s based on material type and sheet thickness [76]. Therefore, welding of sheets with very large areas can be highly time consuming and will not meet the required build speeds that match the production requirements. Therefore, previous studies have concluded that UC processes widely friendly process to utilize for sheet areas up to 200cm2 surface area based on build speed [77]. In addition, incorporation of post and pre-machining steps can further increase the production time.

Remedies to increase scalability of SL, UC process

The most significant remedy to increase the scalability of UC process is incorporating hybrid techniques as introduced with previous AM processes. Incorporating post machining, facilitated UC fabricated parts to reach certain design freedom [78]. Furthermore, post machining is further contributing to UC process when multimaterial laminations are considered. Application of hybrid techniques can increase the build speed also while maintaining build resolution utilizing the inherent advantages of SL (versatility, multimaterial products, non-fusion approach etc.).

Discussion

This paper discusses the scaling limitations of AM processes in a holistic approach. The issues are identified with respect to current widely accepted and applied AM processes to extract their inherent challenges. Issues arise in almost every AM process introduced herein while moving from either side of geometrical dimension scale bar while maintaining optimal resolution. The limitations ultimately end in infeasibility of the process for certain geometrical length scale, lower accuracy, exponentially high build times that limits the scalability of certain AM approach.

Flashing back on scaling limitations of each of the seven major AM processes, focusing on threefold triangular relation of build accuracy, size and speed, approach, technology, materials aspects, and physics of the problem can be identified as the main factors that limits their scalability beyond their favorable resolution and build size length scales.

Build resolution of the VPP processes are limited due to parametric and technological constraints (laser spot diameter, beam manipulation etc.). Resolution of MPPP systems is limited mainly due to the pixel size of the DMD device while 2PL process facilitates high resolution but creating high build times constraining applying 2PL for large scale part sizes.

Resolution and build speed of a PBF processes are initially constrained to a specific region while avoiding micro and macro defects. Material limitations also play a major role while considering the fusion mechanism. Interaction between powder bed and laser is another limiting factor that decides the minimum melt pool dimensions.

Melt pool dimensions of powder DED systems are order of magnitude higher than the same of PBF processes due to large laser/electron beam diameters to capture the bombarding powder stream more effectively. Also, to create sufficient metallurgical bonding, the minimum size of the deposited bead is limited. Arc/plasma DED processes are producing large melt pools which inherently fall to macro length scales (mm) while overcoming thresholds in current to initiate the plasma. Like previously discussed processes, all parameters in a typical DED processes are constrained to a working window based on material to avoid defects of the build. However, DED allows to expand to large build sizes where other AM processes are not allowed due to its technological approach.

Build resolution of ME processes are mainly limited due to extrusion nozzle diameters while facilitating rheological requirements of the extruded material. Material limitations are another bottleneck while resolution scaling of a ME process.

Resolution of MJ and BJ processes are mainly limited due to the technological approach, to produce liquid droplets. The fluid and nozzle diameter contains an interrelationship based on rheological properties constrains the jet nozzle diameter limiting reaching to a smaller droplet size. Particle size distribution of the powder bed in a BJ process must adhere to a certain span that can facilitate effective capillary bonding between binder and particles while producing a satisfactory binder diffusion. Speed of BJ process are limited while avoiding process instabilities (splashing, binder saturation etc.).

Resolution of DW processes is also limited while satisfying rheological requirements of the fluid or gas stream. Build speed of DW processes are constrained similarly as in the processes before while avoiding process instabilities (rapid deposition etc.). As an intermediate conclusion, geometrical complexity, materials aspects, technological approach and laws of nature inherently limits the scalability of any AM process.

Finally, SL processes lack scalability in both resolution and size due to its underlying technology. Thickness of the laminated sheet either in metal or paper SL process can be considered as a main bottleneck. Producing metallurgical bonding on a large surface area is highly challenging while maintaining sustainability of the process (Ultrasonic SL).

Conclusion

Figure 14 presents a summary of a few common AM processes that fall to seven major categories and their applications restrictions on resolution and build size scale bars. Current research groups have attempted to solve the issue for satisfactory level by adding multiple remedies to implement a certain AM method that can utilize in a desired length scale conveniently which will preserve the definition of AM as “Rapid Prototyping”. The most common remedy to improve scaling of many AM processes are utilizing the hybridization approach where capabilities of a specific AM process can be utilized to a maximum at its most favorable working scale. However, a complete solution for inherent scaling issue due to the design and working principal of the technology is still not eliminated. The main reason for this bottleneck is the limitations in governing physics of the approach it self and current technological limitations. Therefore, herein we conclude that a specific AM process is versatile to be utilized in a restricted geometrical length scale and a resolution span.

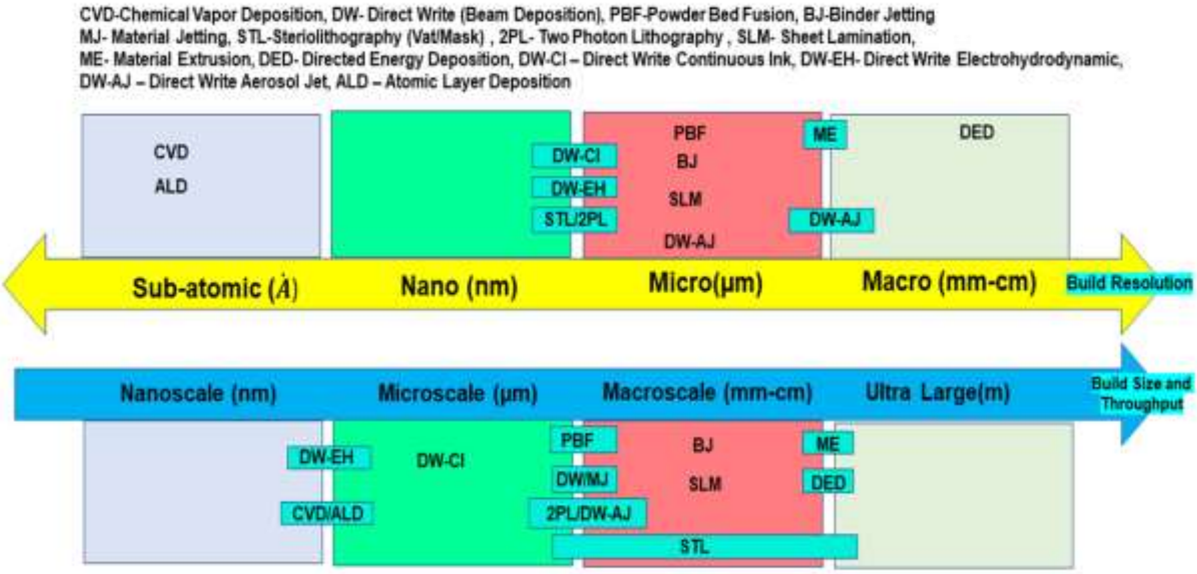

Figure 14: Identifying resolution and size restrictions in common AM processes

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