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Comparative Study of Current Methods and Novel Methods of AM Technologies

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Abstract - *Additive manufacturing (AM), widely known as 3D printing, is a method of manufacturing that forms parts from powder, wire or sheets in a process that proceeds layer by layer. Many techniques (using many different names) have been developed to accomplish this via melting or solid-state joining. In this paper, these techniques for producing metal parts are explored, with a focus on the novel methods and current methods of AM technologies. The various metal AM techniques are compared, with analysis of the strengths and limitations of each.*

Key Words: *Additive Manufacturing (AM), Solid-state joining, Metal AM techniques*

1. INTRODUCTION

Additive manufacturing (AM), also known as three-dimensional (3D) printing, has grown and changed tremendously in the past decades since researchers in Austin, TX, started development of the first machine in the family of metal AM: a laser used to selectively melt layers of polymer and, later, metal.[1] The development of metal AM techniques has made major progress since then, but faces some processing and materials development issues. Understanding the various processes used to make metal AM parts, and the issues associated with them, is critical to improving the capabilities of the hardware and the materials that are produced.

This metal AM history is more concisely presented as a timeline (Fig. 1).

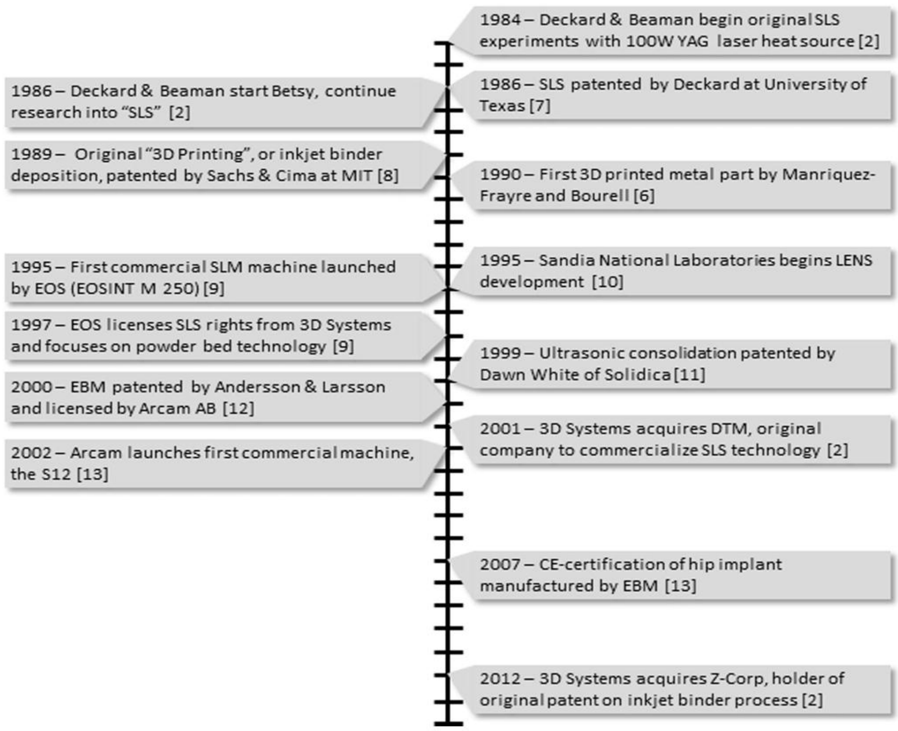

Fig1: Timeline of significant events in metal AM development

These techniques employ raw material in the form of powder, paste or liquid and are applicable to polymers, ceramics and metals. However, the most adoptable commercial RP processes are used for polymer, paper, plastic, wax and metal powders. Unluckily, the properties of these materials are far from those required in the end use material products especially densification of metallic products. The dimensional accuracy and surface finish of the part depend on the uniformity and repeatability of the clad height and width. Clad height and width may vary during the operation due to system parameters. During AM process, a focused laser beam scans the surface of the substrate to generate a molten pool into which alloy powders are injected through powder nozzle. Powders are trapped by moving molten pool and then rapidly melted and solidified after which a cladding layer is formed line-by-line. The fabrication of thin-walled metal parts is a very important research topic for DMLF technology especially in aviation and aerospace industry. For example, integral rib structures with large pockets or structures with high aspect ratio are the most common features which can be found in the aircraft applications because these structures can greatly lighten the aircraft weight with no damage to the desired strength. AM process involving rapid solidification and is used to build near-net-shape fabrications with good mechanical properties especially tensile strength and the microstructures. However, due to rapid solidification it causes the residual stresses to be induced which could lead the part to propagate the crack formation during cladding process.

II. Literature Review

The first experiments directly related to metal AM started by forming polymer powder into 3D parts.[2–5] This research focused on powder-bed laser sintering, which was patented and copyrighted as selective laser sintering (SLS). One of the earliest prototypes of SLS, 'Betsy', consolidated the first automated powder distribution system. Arguably, the first reported metal '3D printed' part was made from metal alloy powders (copper, tin, Pb–Sn solder) in an SLS process in 1990 by Manriquez-Frayre and Bourell.[6] Today, systems used to make metal parts are typically referred to by selective laser melting (SLM) because full melting of the metal powder is achieved, whereas the term SLS is mostly used to refer to polymer powder-bed processes only. Metal powder-bed processes have been called SLM, direct metal laser sintering, etc. depending on vendor. The term SLM is used throughout this work to refer to all metal powder-bed processes which use a laser as a heat source. This process is under license by EOS GmbH, though other companies have entered the market with laser powder-bed hardware for metal production (SLM Solutions, Concept Laser, Renishaw, 3D Systems). Shortly after SLS was patented, a group of researchers at MIT patented a process called 'three-dimensional printing', which used inkjet printing to deposit binder. The use of '3D printing' has evolved in popular media to describe all forms of AM, while the MIT method has become known as Binder Jetting. Binder Jetting can be used to create metal parts, in addition to other materials. Another class of printers relies on depositing feedstock directly into a molten pool, as opposed to selective melting of a powder bed. Known as direct energy deposition (DED), some of these machines are fed by wire and trace their history to welding technologies. In 1995, Sandia National Laboratories developed a different approach to feed powder feedstock into DED with a laser heat source. This technology was first commercialized and trademarked as laser engineered net shaping (LENS), a sub-set of DED. The final major category of metal AM, Sheet Lamination, welds together sheets of feedstock to form 3D parts. A process uses ultrasonic welding and computer numerical control (CNC) milling to accomplish this was originally developed and patented by Dawn White of Solidica in 1999. In 2000, research in Sweden conducted to the patent of another powder-bed technique: electron beam melting (EBM). This process was later licensed and developed by Arcam AB.

Since the invention of the various metal AM processes, meticulous R&D and industry efforts have found some functional applications. Aerospace structures, part repairs, biomedical implants and high-temperature components highlight some of the current production use of the technologies. Despite rapid advances in hardware and software for AM, some big questions remain: What are the current limitations of the technology? Can those limits be over-come through comprehensive research and development? Are the governing physics different of the same as that of traditional manufacturing?

III. Classification of technologies

A diverse set of processes has been used to form feedstock (powder, sheets or wire) into 3D objects. All metal AM processes must consolidate the feedstock into a dense part. The consolidation may be achieved by melting or solid-state joining during the AM processes to achieve this. In order to discuss well defined classes of machines, the ASTM F42 Committee on Additive Manufacturing has issued a standard on process terminology.[7] Of the seven F42 standard categories, the following four pertain to metal AM:

- Powder bed fusion (PBF)
  - Selective laser melting (SLM)
  - Electron beam melting (EBM)
- Direct energy deposition (DED)
  - Laser vs. e-beam
  - Wire fed vs. powder fed
- Binder jetting

- Infiltration
- Consolidation

Sheet lamination

- Ultrasonic additive manufacturing (UAM)

The other three categories specified in the standard do not currently apply to metal technologies: material extrusion, material jetting and vat photo-polymerization. There are unique uses, strengths and challenges for each process. In this review, each category for metal AM is briefly explored; however, more focus is given to DED and PBF due to the large volume of publications about these processes. Additionally, it should be noted that the term 'SLM' is used to refer to all laser PBF processes throughout this paper. This is the most widely used term for the process, so was adopted herein as convention.

3.1 Powder-bed fusion

PBF includes all processes where focused energy (electron beam or laser beam) is used to selectively melt or sinter a layer of a powder bed. For metals, melting is typically used instead of sintering. The use of laser sintering has been previously reviewed, but much progress has been made since this work to include the use of full melting. Re-melting of previous layers during the sintering of the current layer allows for adherence of the current layer to the rest of the part. Schematic representation of PBF laser melting (SLM) and EBM machines are shown in Figs. 2 and 3, respectively. Although both systems use the same powder-bed principle for layer-wise selective melting, there are significant differences in the hardware set-up.

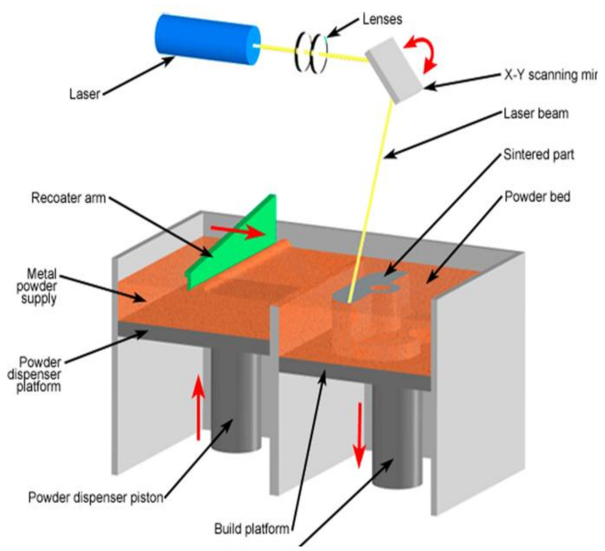

Fig2: SLM system schematic

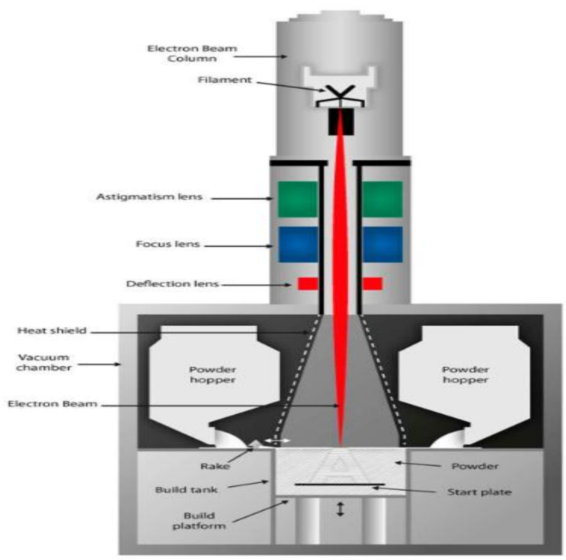

Fig3: EBM system schematic

PBF processes almost exclusive process pre-alloyed (PA) materials, directly achieving high densities. Prior work has been done to examine infiltration of more porous PBF materials.[8] For example, bronze infiltration of laser sintered PBF parts has been demonstrated, with significant focus on porosity and the amount of infiltration.[9]This is not typically desired, as intrusion alters the chemistry of a material and limits the range of available alloys and properties.

3.2 Direct energy deposition

DED encircles all processes where focused energy generates a melt pool into which feed stock is deposited. The process can use a laser, arc or e-beam heat source. The feed stock used can be either powder (see Fig. 4) or wire (see Fig. 5). The origins of this category can be traced to welding technology, where material can be deposited outside a build environment by flowing a shield gas over the melt pool.

One of the most studied and commercialized forms of DED is consummated using a laser heat source to melt a stream of powder feed stock (powder-fed). This DED subset was developed at Sandia National Laboratories and originally patented as the LENS process.[10,11]

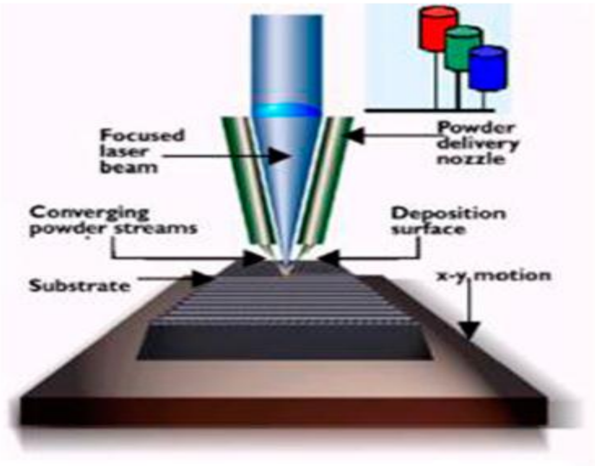

Fig4: Laser, powder-fed DED system (LENS)

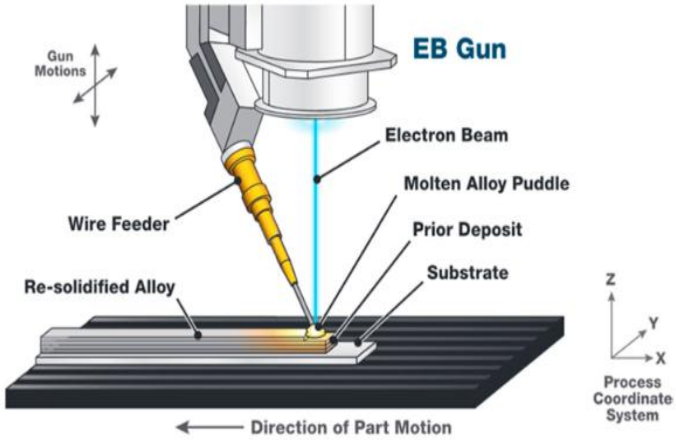

Fig5: Electron beam, wire-fed DED system

Other DED processes feed wire into a molten pool (wire-fed), and are originally extensions of welding technology.[12,13] In fact, the use of modified welding machines to make DED parts via multi-pass welding is presently being explored.[14] Applications of wire-fed, arc heat source DED have shown potential for successfully build some large geometries[15] by making use of lower heat input values that can typically lead to porosity generation in this process.[16]

As in PBF, a finished DED part is typically attached to the build substrate. Parts are then post-processed both thermally (to reduce residual stress and improve properties) and mechanically to achieve the desired final geometry (parts produced using DED are typically near-net shapes with a rough finish). Parts may be removed from the substrate using the same processes for an adhered PBF part. Surplus powder from machine operation is vacuumed during clean out of the machine. Depending on the operating procedure, this powder may be recovered or disposed. Disposal is usually a costly option, as powder costs are typically high. When paired with post-process machining, DED can be a powerful technique for repairing damaged parts (this is addressed further in the 'Surface finishing' section along with surface finishing and hybrid processing).

3.3 Binder Jetting

Binder Jetting works by depositing binder on metal powder, curing the binder to hold the powder together, sintering or consolidating the bound powder and (optionally) infiltrating with a second metal. A schematic of the binder deposition process is shown in (see Fig. 6). ExOne is currently the main manufacturer of Binder Jetting printers, so discussion of these devices is focused on this hardware.

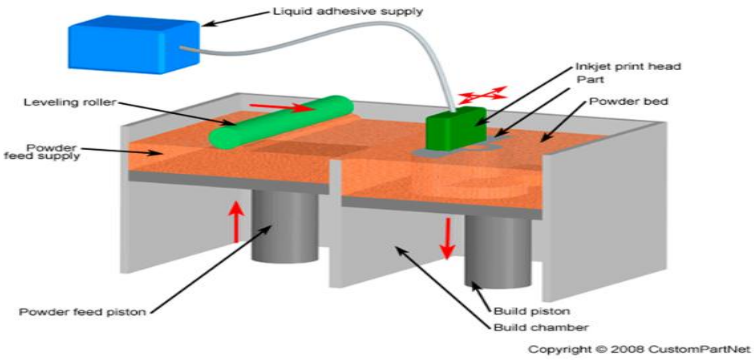

Fig6: Binder Jetting process schematic

The most common process used by these printers has focused on bronze infiltration of porous iron produced using a binder-sintering process. Binder Jetting printers selectively deposit liquid binder on top of metal powder using inkjet print head. When the binder dries, a fragile binder–metal mix (also refer to as a 'green body') can be removed from the powder-bed system.

3.4 Sheet Lamination

Sheet Lamination make use of stacking of precision cut metal sheets into 2D part slices from a 3D object.[17,18] After stacking, these sheets are either metallurgically bonded or adhesively joined using brazing, diffusion bonding,[19] laser welding,[20] resistance welding[21] or ultrasonic consolidation. A key feature of Sheet Lamination hardware is the order in which sheets are applied and cut/machined. Sheets may be either cut to the specified geometry prior to adhesion or machined post-adhesion.

The UAM process is one of the most used technologies for metal Sheet Lamination, so essential technical details are included to illustrate the technology (see Fig 7).

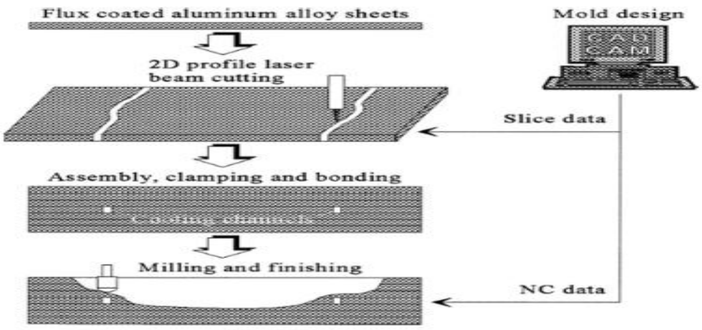

Fig7: Schematic illustration of sheet lamination process to make injection or metal forming moulds

IV. Novel methods of metal AM

Having discussed current technologies in this paper, there are some AM methods for producing metal parts that have not been as fully explored: physical vapour deposition (PVD), chemical vapour deposition (CVD), liquid metal material jetting and friction stir AM. Machine modifications to existing systems offer the chance to improve material properties, speed up deposition rates or both. Either by development of novel methods or incremental improvements to existing technology, innovation will continue to change the metal AM landscape.

4.1 PVD and CVD

Vapour deposition has been used for many decades to deposit coatings, among other applications. CVD is accomplished via a chemical reaction at the deposition surface with the particles in a vapour stream. PVD is accomplished uniquely through the condensation of metal vapour on the substrate and requires vacuum, whereas CVD may operate within a range of atmospheres. Though CVD and PVD are mostly used for coatings, the use of CVD for metal AM has been considered using an e-beam[22] or laser-jet.[23]

4.2 Cold spray

Another purely physical process investigated is cold spray and is being studied for use in AM.[24] Cold spray technologies typically work by acceleration of powder particles in a high-speed gas stream. This powder adheres to a substrate via plastic deformation, forming a deposit.[25] Correspondingly, residual stresses in cold spray deposits are primarily due to impact and are compressive in nature. Residual stresses have not been reported for bulk deposits, which may be a significant material defect to address considering the large amount of deformation put into the deposit. The technology also appears constrained to simple, near-net shapes at present. There have been recent success stories in demonstrating cold spray techniques as shown in (see Fig.8),[26] and deposition rates are expected to be faster than existing metal AM processes. Though microstructures are not well characterised for cold spray processes, recent work has noted abnormalities in the precipitation kinetics of Inconel 625; typical phase precipitation was inhibited or sluggish within ranges expected to form precipitates in traditional materials.[27]

Fig8: (Left) Operator setting up cold spray AM system, which operates outside of a controlled environment and (right) cold spray deposit forming on the tip of a substrate tube that is rotated

4.3 Material jetting & other methods

Metal material jetting deposits droplets of liquid metal that either solidifies when deposited to form a part[28] or remain liquid at room temperature to form arrays of liquid metal.[29] Demonstration has been limited to micron-scale or smaller structures, and no other technique has been demonstrated for millimetre-scale parts. A thermal spray method for forming parts was developed in the early 1990s and employed a mask in the shape of each layer to form 3D geometries.[30] This method has not seen widespread adoption since, but it may provide useful methods for applying masks to generate parts in other processes. Friction stir welding has been proposed for AM,[31] which operates by the method of sheet lamination. Forming of an actual part using friction stir welding has not been demonstrated either and would require pairing with CNC tools to machine of each layer of deposited material before subsequent deposits are made.

V. Open source and low cost

3D printing is a mainstay of the open-source hardware movement, centred on the RepRap project famous for its plastic material extrusion process. The use of open source hardware to make research cheaper and better over a wide range of disciplines is promising.[32] A major constraint of current open-source hardware is the lack of a widely used 3D metal printer. The most exciting developments in low-cost metal AM are comes under the DED category. Michigan Tech University researchers have demonstrated a stationary welder that deposits metal on top of a moving substrate (see Fig. 9).

The welding machine used is a gas metal arc welding (GMAW) or metal inert gas (MIG) machine. The machine is reported to cost <$2000.[33] The problem is that weld deposition has poor resolution, producing only near-net shapes. Promisingly, researchers in India have demonstrated a low-cost CNC mill to machine near-net shapes produced using a welder.[34] Using a welding machine as a desktop printer may be limited due to safety issues, but the combination of open-source weld deposition with CNC milling could be an important step for open-source hardware development. PBF SLM machines capable of finer resolution may develop in the future, as related patents continue to expire.

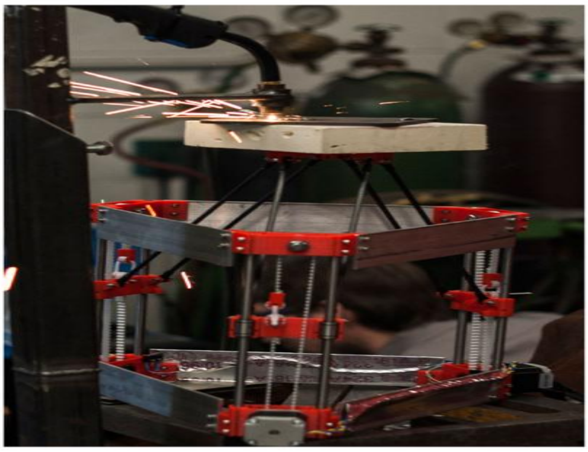

Fig9: Open-source DED system designed with a stationary GMAW/MIG welder and moving stage/platform.

VI. Conclusion

Slow deposition rates, high feed stock costs, limited build volumes and high machine costs limit the current use of the technology. With these constraints, AM technologies are mostly limited to uses in low-volume production, material use reduction and cases of necessity.

The general processing science of metal AM has been surveyed; this background can be used to compare the technical aspects of existing technologies. A tabulated comparison of SLM, EBM, powder-fed DED, wire-fed DED, Binder Jetting and Sheet Lamination is given in Table.

Table: Comparison of defects and features across platforms

Defect or Feature	LM	EBM	DED-Powder fed	DED-Wire fed	Binder Jetting	Sheet Lamination
Feedstock	Powder	Powder	Powder	Wire	Powder	sheet
Heat Source	Laser	E-beam	Laser	Laser / E-beam	N/A; Kiln	N/A; Ultrasound
Part repair	No	No	Yes	Yes	No	No
New parts	Yes	Yes	Yes	Yes	Yes	Yes
Porosity	Low	Low	Low	Low	High	At sheet interface
Cracking	Yes	No	Yes	Yes	Fragile Green body	No
Surface finish	Medium-rough	Rough	Medium-poor	Poor but smooth	Medium-rough	Machined

Process speed, or deposition rate, is a major limitation of current metal AM techniques.

The complexity of part geometry is critical in determining the point at which AM becomes an economically viable production pathway. Process improvements and quality controls may help to lower the costs associated with AM production in the future.

VII. Future Scope

Machine modifications to existing hardware typically support incremental improvements, but several developments could make large gains in the development of current technologies.

The use of multiple heat sources can reduce deposition times or be used to help reducing residual stresses and preheating of material.

Multiple small power lasers have been combined to produce a cheaper power source for laser systems. Another technique is to heat the feed-stock prior to deposition; wire-fed can be modified to heat the wire (using an arc) while creating a molten pool with a laser.

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