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Solid-State VS. Fusion-Based Metal Additive Manufacturing Technologies

Haydar LİVATYALI[1] James R. CAUDILL[2]

[1] Mechatronics Engineering Dept., Yildiz Technical University, Besiktas Istanbul TR-34349 Türkiye, hlivatya@yildiz.edu.tr, https://orcid.org/0000-0002-9542-2390

[2] University of Kentucky, Institute for Sustainable Manufacturing (ISM), Lexington, KY 40506, USA, james.caudill@uky.edu, https://orcid.org/0000-0002-7185-4594

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ABSTRACT

Metal additive manufacturing (M-AM) processes are still seen as non-conventional in the industry, and they are considered for niche applications rather than mass production. The major determinant in the industry is the production time and unit cost. Casting, metal forming, and most machining processes are matured and optimized for low to medium-cost mass production; however, a large portion of manufacturing includes customization and there are also many products that are made only one or in very small quantities, where M-AM processes may be a good alternative to conventional manufacturing. Then, understanding the strengths and weaknesses of M-AM is critical in selecting the most technically and economically feasible option. Classifying the M-AM processes as fusion-based and solid-state is important in the sense that there are significant differences in the material properties and geometric precision provided by each category. Overall, fusion-based technologies yield net-shape parts with material properties close to casting. On the other hand, solid-state processes produce "near-net-shape" geometries; however, material properties may be superior. Nevertheless, almost in all cases, some post-processing including a surface finish operation is required.

Katı Hal ve Füzyon Tabanlı Metal Eklemeli İmalat Teknolojileri

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ÖZ

Metal eklemeli imalat (MEİ) süreçleri sektörde hala alışılmışın dışında görülüyor ve seri üretimden ziyade niş uygulamalar için değerlendiriliyor. Sektörde süreç seçiminde en önemli belirleyici unsurlar üretim süresi ve birim maliyettir. Döküm, metal şekillendirme ve talaşlı imalat süreçlerinin çoğu, düşük ve orta maliyetli seri üretim için olgunlaştırılmış ve optimize edilmiştir; ancak imalatın büyük bir kısmı özelleştirmeyi içermektedir ve MEİ süreçlerinin geleneksel imalata iyi bir alternatif olabileceği tek veya çok küçük adetlerde üretilen birçok ürün de mevcuttur. MEİ'in güçlü ve zayıf yönlerini anlamak, teknik ve ekonomik açıdan en uygun seçeneğin seçilmesinde kritik öneme sahiptir. MEİ işlemlerini füzyon tabanlı ve katı hal olarak sınıflandırmak, her kategorinin sağladığı malzeme özelliklerinde ve geometrik hassasiyette önemli farklılıklar olması açısından anlamlıdır. Genel olarak füzyon tabanlı teknolojiler, döküme yakın malzeme özelliklerine sahip net şekilli parçalar üretir. Öte yandan, katı hal süreçleri "net şekle yakın" geometriler üretir; ancak malzeme özellikleri daha üstün olabilir. Bununla birlikte, neredeyse her durumda, ikincil veya tamamlayıcı yüzey işlemleri de gereklidir.

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INTRODUCTION

Metal additive manufacturing (M-AM) processes are still in the development phase, 23 years after the millennium. Competing technologies offer a wide range of properties in terms of materials, geometric precision, and surface integrity. Material properties of additively manufactured (AM) metal parts do not match with the well-known data of cast and wrought alloys; besides, they differ from powder metallurgy too. Being very much related to the process, AM metal parts need some post-process surface treatments (such as milling, grinding, polishing, burnishing, etc.) and thus the performances of these processes are dependent on the material properties produced by the preceding additive process. The objective of this paper to is compare the status of fusion-based and solid-state metal additive manufacturing technologies.

HISTORY OF METAL ADDITIVE MANUFACTURING

Additive Manufacturing was introduced as free-form fabrication and the main purpose was rapid prototyping. The term 3-D printing was coined in 1984 (Turney, 2021). Among the initial additive manufacturing methods such as laser stereolithography (SLA), laminated object manufacturing (LOM), fuse deposition modeling (FDM), and selective laser sintering (SLS), none could process metals. The workpiece materials were photosensitive thermoset polymers (in SLA and SGC/DLP), thermoplastic polymers (in FDM and SLS) and paper in LOM. The first metal processing capability was commercially introduced by 3D Systems Company with the SLS process. Metal powder particles could be joined when a more powerful laser source was utilized. The main shortcoming of this process was that it required an additional sintering process in an atmosphere-controlled furnace to obtain final properties. Post-processing operations such as infiltration and impregnation were also usable depending on the final metal properties required. At this stage, metal additive manufacturing became attractive for tool and die manufacturing, aerospace applications, and rapid prototyping. Over time, the industry realized the practical and economic advantages of free-form fabrication of metals and new technologies emerged (Fig.1).

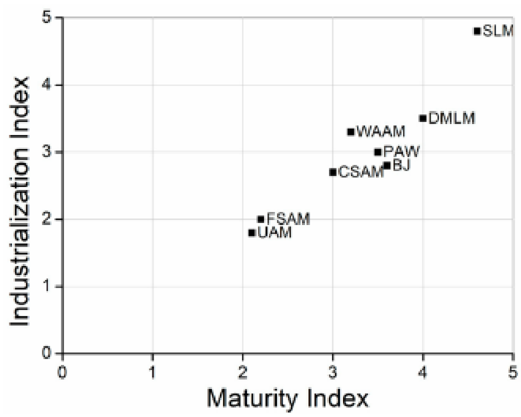

Fig. 1. Relative maturity of M-AM processes as of 2023 (Vaz et al., 2023).

FUSION-BASED METAL ADDITIVE MANUFACTURING TECHNOLOGIES

Selective Laser Melting

Selective laser melting (SLM or L-PBF: laser-powder bed fusion) is the evolved version of SLS utilizing more powerful laser beamers. SLM solved the porosity problem of SLS such that the density of current SLM products has reached 99.2-99.8% (Zhang et al., 2018). Thus, the need for sintering and infiltration is eliminated. SLM, being able to generate net-shape products, is assessed as the most mature M-AM process up to date (Fig.1) (Vaz et al., 2023). Yet, some topographic defects including weld tracks, ripples, spatters (unmelted powder particles) and surface recesses (pores) may be observed on parts made using SLM (Leach et al., n.d.). Post-processing processes are expected to eliminate these issues as well as remove the tensile residual stresses and improve subsurface hardness and microstructure.

SLM is categorized as a fusion- or beam-based method and bonding of fine metal powder is achieved by localized rapid melting and solidification. This is the cause of columnar grains and tensile residual stresses. As a variation of SLM, electron beam powder bed fusion (SEBM, EBAM or EB-PBF) is introduced (Pelin et al., 2021). EB-PBF has some advantages over L-PBF such that better geometric precision with more consistent microstructure is possible and no residual stresses due to slower cooling in vacuum; however, larger powder particles cause a rougher surface. Since the process is applied in a closed vacuum chamber, large parts are not feasible.

Directed Energy Deposition

The next mature beam-based technology is directed energy deposition (DED). In this category, the directed heat source may be a laser beam (DMLM), electron beam (DMEBM), plasma arc (PAW) or metal arc (WAAM); and the material is fed in the form of powder or wire (Özel et al., 2023). Wire direct(ed) energy deposition processes are advantageous in feedstock cost and availability. This technique is advantageous in producing large workpieces in a short time with relatively lower geometric precision and surface quality. The geometric precision is better when a laser or electron beam and metal powder are used, but the material deposition rate is much faster in WAAM where the metal wire is locally molten using an arc. Being a fusion-based technology, tensile residual stresses that are generated during rapid solidification are inevitable.

SOLID-STATE METAL ADDITIVE MANUFACTURING TECHNOLOGIES

Fusion-based M-AM processes summarized above involve the melting of metal at higher temperatures; therefore, the final microstructure has large columnar and dendritic grains as well as oxide residues that together reduce the mechanical properties of the metal alloys. In addition, tensile residual stresses that deteriorate fatigue and corrosion performance are formed on part surfaces. To obtain superior material properties with high deposition rates solid-state additive manufacturing processes are developed.

Cold Spray Additive Manufacturing

Cold spray additive manufacturing (CSAM) (Vaz et al., 2023) is like powder DED; however, the high-velocity impact of solid particles is dominant, and some of the heat needed for bonding is transferred to the particles in a special chamber via convection before spraying instead of an in-situ directed laser or electron beam. The cold spray method was initially developed for metal coating, cladding, and surface repair. Integrating with robotic manipulators, fabrication of intricate 3-D parts has become possible in the last five years.

CSAM ejects metal, ceramic and/or polymer powder particles at supersonic speeds to attain bonding to the substrate and other particles by impact. CSAM process parameters include particle spray angle, stand-off distance, and feed rate. CSAM's microstructural evolution occurs at the impact interface where heat generation, strain hardening, and mechanical diffusion realize bonding among particles. The impact induces mechanical interlocking, and the strength of the matrix depends on the impact velocity and ductility of the material. CSAM technology has some variations including vacuum, laser-assisted, and grit blasting as well as the most common two types called the high-pressure and low-pressure systems (Fig.2) (Ashokkumar et al., 2022; Balamurugan & Prabu, 2022).

Both the low- and high-pressure systems utilize several common components including a power feeder, heater, gas tank, de Laval nozzle, and a table or a chuck to hold and position the substrate. In the high-pressure set-up, the feeder releases the feedstock powder into the carrier gas (such as N_2) and the accelerating gas (He or N_2) supply unit feeds the compressed gas into the heating chamber in a controlled manner. These two gases are mixed in a temperature-controlled chamber before entering the converging-diverging nozzle which optimizes the propulsion velocity of the ejected particles like a jet engine. The substrate may be held by a rotational positioner, Cartesian table or a robot depending on the geometry. This way, a completely new part may be deposited as free-form fabrication or an existing part may be coated, cladded, or repaired by filling problematic cavities or cracks.

The low-pressure system is relatively simpler such that there is only the accelerating gas, and the feedstock powder is mixed into this gas at the throat of the de Laval nozzle by the relative vacuum generated at the highest velocity point. The powder mass flow rate is a function of the gas flow rate; however, this system cannot reach the high-impact velocities that the high-pressure systems can. Thermal assistance by a laser beam may be utilized to improve interlocking. The deposition cross-section is like a normal distribution curve (Fig.3, left) and a complete surface deposition is achieved by some overlap like spray painting (Assadi et al., 2003). The sprayed material is not homogeneous along the thickness direction as shown in Fig.3 (right) (Ashokkumar et al., 2022). The existence of voids and pores in the outer and surface layers is the main source of brittle mechanical behavior; therefore, an annealing heat treatment is recommended to improve ductility, sacrificing some of the strength (Fig.4) (Gärtner et al., 2006). A limitation of CSAM is that very complex shapes and interiors cannot be sprayed; and thus, near-net-shape parts are possible. The process requires expensive gases, specially designed post-processing, and a porosity of 1-2% is the best outcome attained so far.

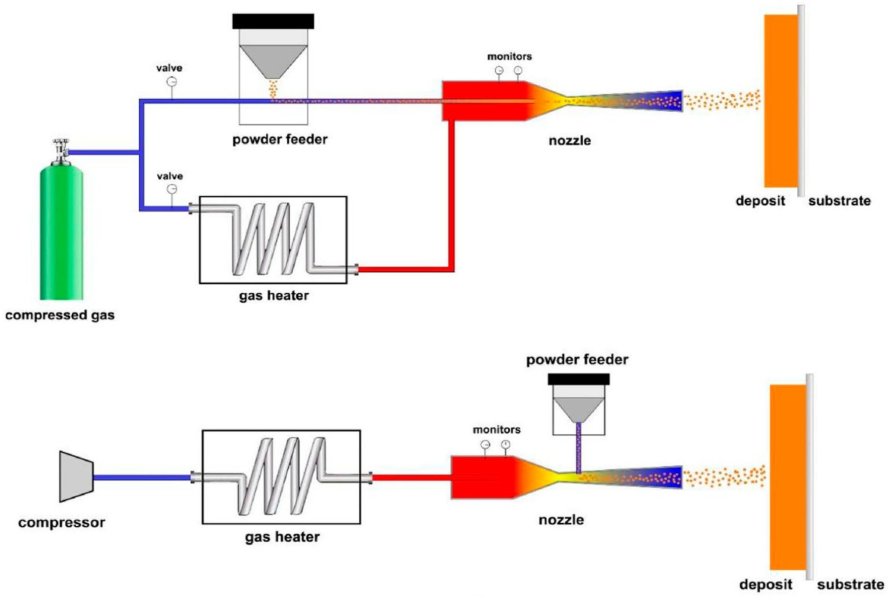

Fig. 2. High- (left) and low-pressure (right) CSAM systems (Balamurugan & Prabu, 2022).

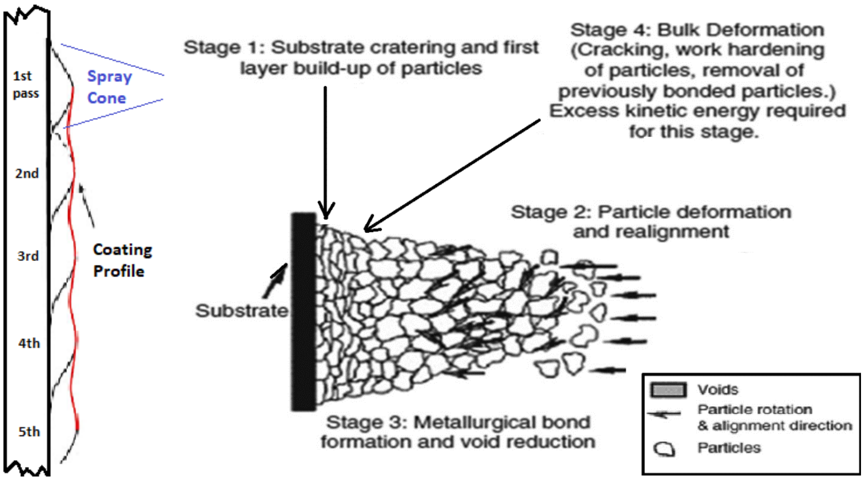

Fig. 3. Coating profile produced by subsequent deposits by CSAM (Left) (Cai et al., 2014) and stages of bonding particles at CSAM (Right) (Ashokkumar et al., 2022).

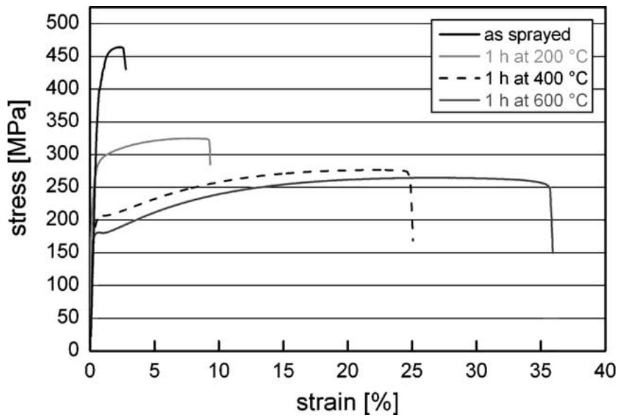

Fig. 4. Effect of heat treatment on tensile curves of high-P cold sprayed and heat-treated copper samples (Gärtner et al., 2006).

Additive Friction Stir Deposition

Additive Friction Stir Deposition (AFSD) is a newer and unique process mostly confused with friction stir additive manufacturing (FSAM) (Mishra et al., 2022). AFSD has advantages coming from solid state coalescence with almost no porosity, significantly smaller equiaxed homogeneous grains, and improved tensile strength and toughness that come with high productivity. Thanks to the severe plastic deformation that takes place during the friction stir deposition process. Additional advantages include being capable of making large parts from difficult-to-cast metal alloys in an open atmosphere as well as the flexibility of infeed material forms such as bars or chips. One drawback is that the yield strength is usually reduced, but strain hardenability is increased. Heat treatment options need to be considered especially in the precipitation-hardening metal alloys where the severe grain refinement does not allow precipitation. The part geometry produced by AFSD is near-net-shape; therefore, a sequence of machining and surface finish operations is needed. Being a relatively new technology, AFSD has many unknowns and a big potential for research until it becomes a more common method in the industry (Fig.5).

A schematic of the AFSD process is shown in Fig. 6. A hollow cylindrical tool is rotated pressing the substrate or the previously deposited layer. The feedstock in the form of a (9.525x9.525 mm) square rod is vertically fed towards the substrate and pushed from the back rotating with the tool under shape constraint. The bottom face of the feedstock starts to soften under frictional heat, and with the effect of the downward force, it spreads sideways. The feedstock becoming a thin disk gains a larger friction surface that increases the heat generated and thus the temperature rises. The rotation of the tool head applying pressure on the flattened feedstock causes a stirring effect on the material that has become visco-plastic, and four protrusions (knobs) located at the bottom of the tool head elevate the stirring effect. When the plasticized feedstock exceeds the tool diameter, the tool starts to move horizontally in the traverse direction, depositing the feedstock on the trailing side of the motion. Once the pass length is complete, the tool is shifted sideways or upwards to deposit the next layer. An overlap may or may not be employed in subsequent deposits on the same vertical level. The metal remains in a solid-state during the process over the recrystallization temperature, however, the deposited parts on the trailing side of the tool cool down in still air. When the tool passes over the deposit for the next one, the previously deposited layers are heated again to a temperature close to but lower than the material being stirred and deposited. Hence, when several layers (1-2 mm thick) are deposited on top of each other, the layers at the bottom of the built part are subjected to numerous heating-cooling cycles, but the top layers are subjected to fewer cycles. This causes a variation in grain size from bottom to top.

Fig. 5. Meld L3 machine tool installed in the University of Kentucky

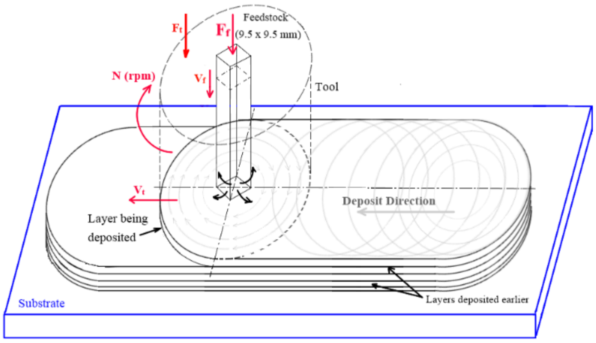

Fig. 6. A schematic of AFSD

AFSD has been commercialized since 2018 (Griffiths et al., 2019), and it is academically and industrially tested in metals such as Aluminum alloys AA 2020, 2219, 2050, 5083, 5B70, 6061, 6063, 7050, 7075, Mg alloys AZ31B and WE43, Steel alloys including 1018, 1060 and SS 316L as well as titanium alloy Ti6Al4V. The outcome of the AFSD process is dependent on the feedstock metal type and properties as well as the process parameters including tool head rotational speed and traverse speed, axial force, feedstock rod diameter and offset layer thickness.

Yu and Mishra (Yu & Mishra, 2021) published a comprehensive review elaborating on the micro-, meso- and macro-scale issues, advantages, and potential of AFSD. Accordingly, AFSD has the advantage of producing a fine equiaxed grain structure without any porosity. AFSD has a higher TRL on metal alloys with low melting temperatures and relatively high ductility, but it is anticipated that it has potential on higher-strength metal alloys too. The severe plastic deformation in AFSD takes place around 0.6-0.9T_m. The process builds a material with reduced yield strength, fatigue strength, hardness, and rupture strain (maximum elongation and increased ultimate tensile strength and strain hardenability. Residual stresses on the as-built work parts have not been elaborated yet.

Rivera et al. (Rivera et al., 2018) processed AA 2219-T851 at a deposition rate of 1000 cm^3/h and elaborated on the relationships among texture, grain refinement and the mechanical properties of the deposited material or semi-product paying attention to layers. Anderson-Wedge et al. (Anderson-Wedge et al., 2021) worked on the fatigue behavior of the same alloy. Babaniaris et al. (Babaniaris et al., 2022) processed rods made from compressed recyclable swarf AA 6063 and tested the outcomes after T4, T5 and T6 heat treatments. Jordon et al. (Jordon et al., 2020) is a summary of experiments on AFSD of screw-fed AA 5083 machining chips. In the same team's follow-up paper, (Beck et al., 2023) AFSD test results of AA 5083-H131 bar feedstock and recycling chips were compared. Perry et al. (Perry et al., 2020) investigated the interface formed in a dissimilar Aluminum alloy system, AA 2024 deposition onto AA

6061 substrate. Mukhopadhyay and Saha (Mukhopadhyay & Saha, 2020) proposed a variation to the process such that the low-strength AA 1060-H12 chips are used as the feedstock and the chips are fed to the front of the rotating tool head. Tang et al. (Tang et al., 2023) introduced a modified version, called friction extrusion additive manufacturing (FEAM). The main idea of the friction stir mechanism is the same, the force-controlled process stresses the extrusion stage more strongly and a tool pre-set thickness of 4 mm is produced instead of a thinner (1-2 mm) one. Griffith et al. (Griffiths et al., 2021) experimentally compared AFSD of AA 6061-T6 and Cu 110-H02 (half-hard) as feedstock in terms of microstructure evolution and its dependence on process variables. Ghadimi et al. (Ghadimi et al., 2023) and Phillips et al. (Phillips et al., 2021) tested AFSD of AA 2050 and AA 5083, respectively. They reported that the lubrication of AFSD needs to be matured, and some kind of non-contaminating lubricant should replace the graphite-based dry lubricant currently employed.

Yoder et al. (Yoder et al., 2021), compared the properties of as-built AA 7075 with the as-wrought feedstock. Joshi et al. (Joshi et al., 2022) investigated AFSD of AZ31B and Williams et al. (Williams et al., 2021) tested WE43 Mg alloy and obtained a refined, homogenous equiaxed microstructure when compared to the feedstock resulting in a reduction in average grain size from 45 to 2.7 µm on the top layer and 4.5 µm on the bottom one. Griffith et al. (Griffiths et al., 2022) tested the feasibility of AFSD of stainless steel 304 under water and showed good deposition quality and remarkable microstructure differences from conventional deposition. Martin et al. (Martin et al., 2022) applied AFSD on stainless steel 316L for surface repair to compensate for material loss on AISI 4340 substrate as groove filling and surface cladding. Farabi et al. (Farabi et al., 2022) tested AFSD of Ti6Al4V to analyze the microstructural and mechanical effects on the outcome.

The work published so far is heavily experimental and focused on nano, micro and macro behaviors of the tested alloys. How the semi-finished deposit will be commercialized has not been elaborated. Mechanical components that may be made using AFSD will be specified for their performances under load, but their surface features are also critical. Since the material produced by AFSD is remarkably different from the as-cast, wrought, and other additive alternatives, the effect of the machining and surface finishing processes will also be different.

The material properties produced by AFSD are sometimes superior to the conventional alternatives due to the unique grain structure. AFSD metals do not have homogeneous material properties along the build direction. The top layer shows a more textured and harder/stronger behavior while the texture fades away towards the bottom layer and the grains get somewhat larger. Heat treatment, for example, T6 or T651 in AA 6061 or AA 7075 can attain homogenization of the micro and macro properties; however, the resultant metal shows somewhat inferior mechanical properties as compared to the wrought one with the same temper. The single advantageous property that has been experimentally shown is high-cycle fatigue.

Fig. 7. *Examples of an experimental (Phillips et al., 2021) and two industrial AFSD parts (Cole, J., 2020; Stevenson, K., 2018).*

Other Technologies

Binder Jet (BJ) technology is an indirect fabrication method with the initial binding of the metal powder achieved by a thermoset polymeric binder and further sintering in an industrial furnace is a must. The sintering temperature is usually just below the melting temperature; therefore, it is regarded as a solid-state AM technology (Tuncer & Bose, 2020). There is no mechanical deformation involved as in CSAM and AFSD, and the final microstructure is also different (Li et al., 2020). BJ produces a porous structure with 95% density and some shrinkage during the sintering phase occurs. The parts have a lower surface roughness (as low as R_a 3 µm if a bead-blasting step is employed) compared to DMLS/SLM (R_a 12-16 µm). Such low surface roughness is beneficial for parts with internal channels and geometries that can be difficult to post-process. parts tend to have only moderate mechanical properties and high porosity, meaning that they may not be suitable for all requirements. Combining economy in equipment cost with geometric precision, BJ is commercialized by many companies.

Friction Stir Additive Manufacturing (FSAM) is an extension of the friction stir welding process (Mishra et al., 2022). The main difference between the two is that thin metal sheets are piled layer by layer and they are joined on the face by the heat and pressure produced by friction stirring in FSAM. In this sense, FSAM is like laminated object manufacturing (LOM) in which sheets are pasted to each other using some organic adhesive and pressure. In the FSAM process, a solid-state face welding process takes place where the heat is produced by the friction of a rotating carbide tool which simultaneously applies the needed pressure to eliminate any porosities.

Ultrasound Additive Manufacturing (UAM) works like FSAM; however, instead of frictional heat produced under high-pressure ultrasonic vibrations remove the oxide layer on the surfaces of the sheets, allowing them to fuse in solid state at a relatively low temperature (Arnold, 2023). This process perfectly fits the electronics and sensor production allowing the joining of dissimilar metals in sheet form as well as powder sandwiched between thin sheets. The main weakness so far is the anisotropy of the as-built part.

DISCUSSIONS

When the term M-AM is used, L-PBF (or SLM) is the main technology recalled. L-PBF has a significant advantage over other technologies by holding the highest TRL rating with the capability of building net-shape parts with minimal porosity and acceptable surface finish. However, the high cost of metal powders, inferior mechanical properties due to columnar microstructure coupled with tensile residual stresses on part surfaces and the low production rate opened the way for alternative technology development. Besides, the application of L-PBF is limited to specific and rather valuable alloys, and it is not widespread to ordinary and low-cost metal alloys such as carbon steels.

DED technologies eliminate the limitations of L-PBF on size and fabrication rate; however, they still employ the fusion-based boding method which does not bring improved mechanical and microstructural properties. Mechanical deformation-based solid-state M-AM technologies yield improved mechanical properties without tensile surface residual stresses, sacrificing geometric precision. CSAM may generate net-shape components, but AFSD (as well as FSAM and USAM) is a semi-product building process.

Gamon et al. (Gamon et al., 2021) and Tuncer and Bose (Tuncer & Bose, 2020) compared various M-AM processes including L-PBF, EB-PBF, L-powder DED, L-wire DED, CSAM, EB-DED, WAAM, laser hot wire, BJ, and CSAM in terms of as-built microstructure and associated micro-indentation hardness (HV) for alloy 625. Regardless of technical differences, all the tested processes produced irregular grain structures containing varying columnar arrays of micro-dendrites, cellular dendrite structures and varying arrays of precipitates as well as fine equiaxed ones. The hardness measurements were in a wide range (180–590 HV) BJ giving the lowest and CSAM the hardest.

Consequently, all M-AM-built parts require some sort of post-processing. Processes using powder feedstock need de-powdering. All processes need some de-burring operation. HIP is suggested and proven useful to reduce voids and porosities, but it is not a practical and economically feasible method. Heat treatment including some type of annealing is recommended in most cases, but recrystallization would release the residual stresses and thus geometric distortions would occur. Next, comes machining processes such as ball-end milling and turning. These subtractive operations achieve geometric precision along with improved surface roughness, but under most process conditions they produce tensile residual stresses (to a lesser extent). A finishing operation including abrasive, chemical or electro-chemical polishing or a deformation-based method such as burnishing, may follow the machining step to obtain improved surface integrity. To summarize, except in rare cases, none of the M-AM processes can manufacture a ready-to-use finished product. However, solid-state M-AM processes usually produce an outcome farther from the final product, while fusion-based processes and BJ may yield a geometry closer to the target with inferior mechanical properties.

CONCLUDING REMARKS

This paper provides a comparison of the more common and established fusion-based M-AM processes and two solid-state processes CSAM and AFSD. Powder bed fusion, directed energy deposition and binder jetting techniques produce parts with better geometric precision; however, surface integrity and mechanical properties are significantly inferior compared to as-wrought and as-cast material. Solid-state additive processes including cold spray and friction stir deposition are still in the development phase with lower TRL and MRL, but they offer superior mechanical performance sacrificing geometric precision. Most of the published research on solid-state M-AM processes is experimental. To develop a better understanding of the governing mechanisms in these processes novel analytical and numerical models need to be developed.

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