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Developing strategies for medium volume production in directed energy deposition additive manufacturing

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Abstract: Additive Manufacturing (AM) processes enable the validation of design variants, and the manufacturing of low volume specialty components. Slow fabrication times are an issue for larger production volumes, but for the directed energy deposition (DED) and hybrid manufacturing (where additive and machining operations are interwoven), new process planning scenarios can be explored for both low and medium volume production levels, which aligns well with addressing on-demand service and out of production components. DED AM is a material deposition based process. Wire filament or powder is melted by a heat source, and multi-axis tool paths can be employed to deposit the material. Large freeform components can be fabricated without support material; however, production volume scalability is an issue. Prior to exploring multi-function or reconfigurable machines and dynamic layouts, a framework for defining nomenclature for DED AM precedence diagrams and value stream maps, and insights for systematically decomposing components for macro and micro level process planning needs to be developed. The goal of this research is to provide a foundation for DED and hybrid manufacturing for low volume production (100 – 2000 pcs) for short planning horizons (1 week to 1 month) which would align to 'medium volume' production levels. This specific paper will present research performed to date on addressing these challenges.

Keywords: Directed energy deposition, process planning, framework, medium volume

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1. Introduction to additive manufacturing and directed energy deposition

Additive Manufacturing (AM) is a family of layered manufacturing processes [1]. There are seven AM process families defined by ASTM: vat polymerization, material extrusion, binder jetting, material jetting, powder bed fusion, layered object manufacturing, and directed energy deposition. Manifold or 'water tight' computer aided design models (CAD) are fabricated directly with minimal process planning for most AM processes. Design variants can be rapidly validated as specialty tooling and fixtures are not required to fabricate components or assemblies. If volumes are higher, and the geometry lends itself to molding, rapid tooling can be manufactured to facilitate the production [2, 3]. AM systems lend themselves to distributed manufacturing systems (DMS), which are among the emerging trends as these systems enable an efficient use of resources, and a production on-demand solution can be established close to a customer. Researchers have explored using AM processes for supply chain management and supplying spare parts [4, 5]. One unsurprising outcome is that AM processes are effective for small complex components with long lead times, but technical feasibility is a hurdle in several situations (small build envelopes, achievable surface finishes, anisotropic properties, etc.) as well as managing economies of scale. The process planning activities may be minimal, but AM processes have slow fabrication times compared to other traditional processes, which is problematic for higher volumes.

Metallic components can be fabricated by all the listed AM processes (Fig. 1), but directed energy deposition (DED) AM allows for non-planar, variable thickness layers as it is a material deposition based process. It allows users to repair components or fabricate features onto existing components in addition to fabricating new components.

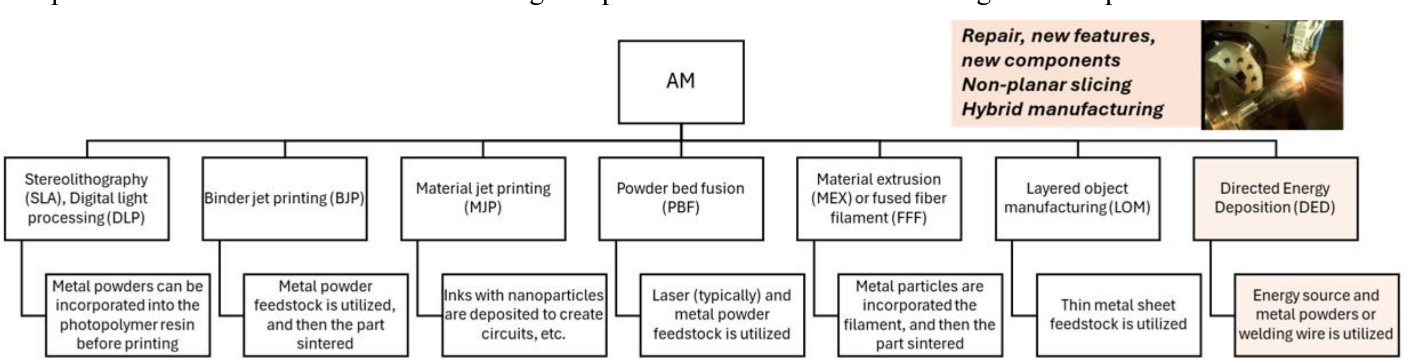


Figure 1. The 7 processes defined by ASTM, specialty component built by hybrid manufacturing, courtesy of Mazak.

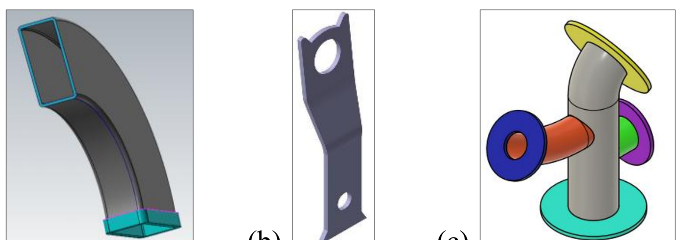
Wire filament or powder is melted by a heat source such as a laser or an electron beam, and multi-axis tool paths can be employed to deposit the material. This leads to the ability to fabricate large freeform components without support material; however, production volume scalability is an issue, as with the other AM process families. But, unlike other AM processes, DED AM allows for 'localized' manufacturing and the introduction of interwoven machining operations. It is proposed to introduce strategic component decomposition to break down the manufacturing process into manageable, repeatable operations across multiple stations / machines, where the components move sequentially or simultaneously through stations. The goal of this research is to provide a foundation for DED and hybrid manufacturing for low volume production (100 – 2000 pcs) for short planning horizons (1 week to 1 month) which would align to 'medium volume' production levels. DMS system principles are to be blended with cost and time efficiencies of traditional manufacturing.

2. Materials and methods

Two perspectives need to be considered when developing process plans: (i) micro levels and (ii) macro levels. At the micro level, the detailed information on the machine type, tools, operation parameters, and operation procedures are determined; whereas, at the macro level, the overall strategy and workflows are determined, such as the process sequences and workload balancing. Detailed multi-axis micro-level process plan case studies are utilized to provide a foundation for the macro-level process planning level (Fig. 2). It is assumed that that components are fabricated using 316L stainless steel. Mastercam APlus® is utilized to develop and virtually validate the base process plans. Multi-axis build strategies are utilized to eliminate support structures. Mastercam 2026 machine simulation is utilized for collision detection, and lead-lag or tilt angles are introduced as necessary. System costs are presented in Table 1. The target production volume is 1000 components for 1 week, and there are 80 available working hours: (2) 8 hr shifts, 5 day/week.

Table 1. Baseline assumptions (shaded cells represent estimated costs associated with a hybrid machine (HM)).

Element	Cost (1000's)
5 axis CNC machine	$250K
Deposition source (laser, feeding system, etc.)	$250K
Integration	$50K
Deposition system (3 axis)	$350K
Material handling - Transfer mechanism and integration per deposition system	$25K



(a) (b) (c)

Figure 2. (a) A bent tube (15x8x4 cm bounding box, 2 mm wall, (b) a strap (21x4 cm bounding box, 2 mm wall – base is 15 mm), (c) a family of parts bent tube with flanges (31x26x22 cm bounding box, 2 mm wall)

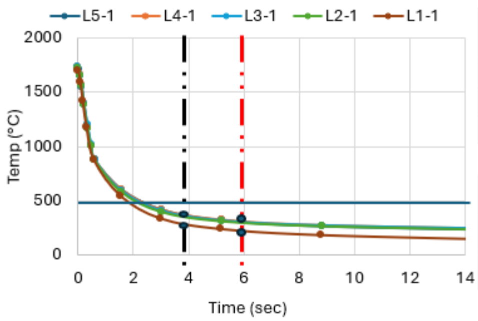
Heat management is a critical concern. In addition to the heat cycling issues, overheating introduces both geometric and grain growth issues, therefore interpass cooling or dwells can optimize heat distribution. For this research, a thin wall heuristic heat build up is considered to determine recommended dwell times. Representative multi-layer thin wall cooling curves, which were extracted from experimentally calibrated SYSWELD simulations [6, 7], are employed to estimate the time to temperature for a given threshold temperature (500 °C here). The Excel Solver is used to generate decaying exponential curves (Eq. 1) from the cooling curves. For a given travel speed and bead segment length, the deposition time is determined, and based on this information, the dwell time is calculated. For the travel speed 550 mm/min (black text), and 750 mm/min (red text), the time to travel select distances and the calculated temperature ranges are shown in Fig. 3. The temperature-time curve varies per layer. Note: closed loop tool paths are segmented into two sections (Fig. 2 (a) and (c)), and a one way tool path is used for the strap for the analyses, and temperatures are calculated at user defined critical points. This dwell time is leveraged for the decomposition and batch production strategies.

2.1. Flow diagrams

Precedence diagrams illustrate the planned sequence of activities complementing value stream maps (VSMs), which visualize and analyze the flow of materials and information. Precedence diagrams focus on the task dependencies; whereas VSMs focus on process improvement and waste reduction (i.e. non-value added time) and can be utilized to visualize component orientation and material handling set ups. With DED and hybrid AM, there are unique scenarios for the process dependencies. Layer merging allows for layers to be built sequentially between parts or various features in a part, where there are unique materials or process settings.

$$T(t) = a_0 \cdot e^{\wedge}(-a_1 \cdot t) + a_2$$

L1-1 curve: $a_0 = 1499.68$, $a_{1=1.066}$, $a_{2=161.04}$; L5-1 curve: $a_0 = 1496.9$, $a_{1=0.417}$, $a_{2=230}$



Travel (mm)	t (s)	Temp. range (°C)	t (s)	Temp. range (°C)
15	1.64	422 - 726	1.20	578 - 814
35	3.82*	187-445	2.80	237-549
75	8.18	161-284	6.00*	161-328

**values are indicated on the graph

Target Temp. (°C)	L1-1 Time (t)	L5-1 Time (t)
400°C	≈ 1.7 (s)	≈ 5.2 (s)
500°C	≈ 1.4 (s)	≈ 4.1 (s)

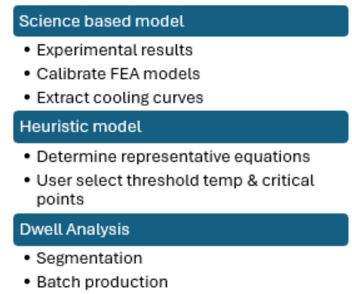


Figure 3. Cooling curves for a point on a multi-layer multi-junction component, the temperature ranges for select travel distances and time to achieve a temp., process flow chart.

For a precedence diagram, these merged operations are identified in a columnar table, with a thick outer boundary box (Fig. 4 (a)).Variable process settings allow for non-planar layers to be built. A variable symbol identifies this case (Fig. 4 (b)). Heat accumulation will occur, but the rate will be higher for short travel paths; therefore, this needs to be identified where it is occurring such as the beginning or end of a tool path (symbol shown in Fig. 4 (c)), and strategic dwells need to be introduced.

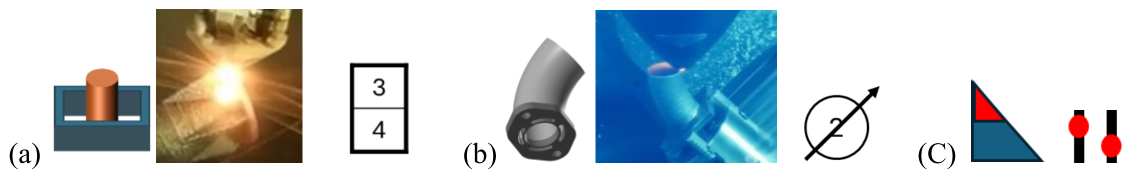


Figure 4. DED AM precedence diagram representations: (a) layer merge, (b) variable slice, (c) heat build up (final or initial part of the AM tool path).

2.2. Process summary tables and decomposition strategies

Tables that summarize the setups and tooling data, levels of compatibility, fixture and machine types and so forth use the feature geometry as a foundation for the required machine configurations, tool types, and other process information. The axis type (rotary, translational), kinematic structure, spindle speed and feed capabilities and related information is captured in a structured manner. However, for DED AM the heat related characteristics need to be captured as shrinkage, distortion, and induced residual stresses are influenced by both the geometry and the tool path. It is proposed to introduce a feature 'contact area', and surface area to volume ratio, and a qualitative heat accumulation measure with dwell time heuristics for downstream optimization and planning alternative build strategies.

There are two stages for the decomposition strategy, with the first stage being (i) determine the hourly rate for a given overall equipment efficiency (OEE) / production volume, and the related production time per component, then (ii) develop the process plan and supporting data sets, which include the: operation list (s), precedence diagram(s), VSMs, and process plan summary tables at the component and feature levels. With this information, the number of hybrid systems can be established for a baseline machine cost, floor layout estimates, etc. Based on the initial single component production solutions and recommended dwell times, segmentation and batch fabrication strategies can be introduced. From this information, machine selection sets, fixturing strategies, layouts, etc. can be determined.

3. Results and discussion

The bent tube in Fig. 2 (a) takes approximately 3.5 hours (dwell analysis occurs at every 5 layers) to complete once the final machining around the base (component removal and facing) is completed. This correlates to **0.29 parts/hr.** Planar slicing occurs at the blue base, which is machined, and a spine slice strategy is employed to build the neck. Stock is added to the front face for machining. For a 100% OEE, the hourly rate is 12.5 pcs/hr. Therefore 44 machines would be required, which represents at $24,200K investment as well as significant floor space and manpower. A more realistic OEE of 80% increases this value by 20%. However, when analysing the toolpaths, it can be determined that there is a 10:1 ratio of additive deposition time compared to the machining time. The travel speed for the machining tool paths is 7-7.5 times faster than the additive tool paths. There is significant idle time associated with the machining aspects, and segmentation can occur at select dwell locations. Segmenting the component into four sections, introducing stock to be machined to establish flat, good quality build planes, and staggering the additive segments for a machine with four additive systems and one machining centre would create a build sequence where the transfer and machining is completed in 15 minutes and the additive operations are completed in 45 minutes. It is assumed that the orientation is established during the transfer and that only 3 axis additive tool paths are required as a segment's rough top surface associated with planar slicing is machined. This production rate is **0.94** parts/hr. For the required volume and planning horizon, it is estimated 12 cells (4 AM machines, material handling, system, and (1) 5 axis CNC machine) are required. The estimated cost for the conceptual cell is $1,750K per system. With 12 systems, the costs are $21,000K (~13% less), but the productivity of the new configuration is 3 x greater than using a contemporary HM system as parallel processing occurs.

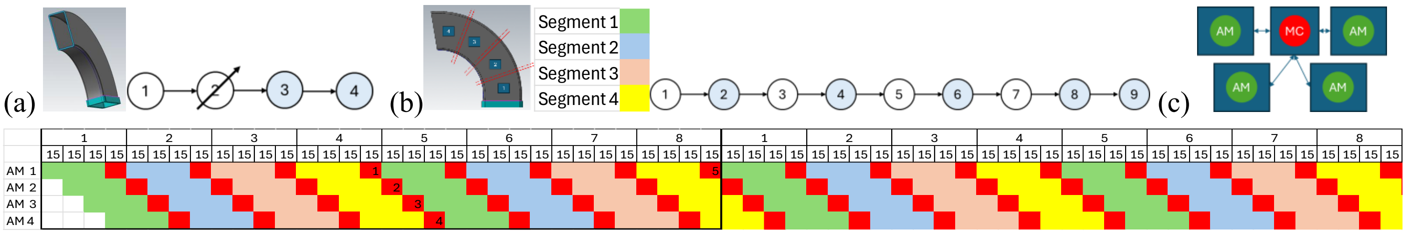


Figure 5: (a) Specialty component and precedence diagram (blue represents machining), (b) proposed segmentation and the additive / machining (red) sequence activities, (c) a (4) AM + (1) machining centre cell

The strap is built as a solid component using a spine slice strategy and multi-axis tool paths, and then the holes drilled. The cycle time is approximately 5 min.; however, the segments are short in length and unstable build conditions would occur. Introducing a dwell time per layer increased the cycle time to approx. 17 minutes (400 °C target). It is proposed to introduce batch production: build (4) components in one batch using a layer merge approach (one layer per part and index to the next layer), utilizing the dwell time information to inform the batch size. The effective production rate for the additive process is 12 parts/hr at 100% OEE, which indicates that one - two DED AM systems are required, and downstream machining can be performed on a drilling system. Note: the batch layout is refined when assessing potential collisions as multi-axis deposition is required to fabricate the component. Further analysis needs to be performed to determine if a robotic based system with a table-table stack or a 5 axis laser system is the most cost effective solution.

4. Conclusions and future work

With DED and hybrid AM, there are unique scenarios for the process dependencies. A framework for defining nomenclature for DED AM precedence diagrams, and insights for systematically decomposing components for macro and micro level process planning needs to be developed. Therefore, a high level and detailed level systems approach is taken for a balanced perspective. Establishing a framework for medium volume production allows us to maximize efficiencies and costs by distributing tasks as shown here. Multiple component types, build volumes and planning horizons need to be explored to determine effective cell structures and material transportation solutions. The flanged tube (Fig. 2 (c)) represents several thermostat housing and water outlet components and will be assessed to generate a general solution for this family of parts from a process planning and facilities layout / material transportation perspective. Components will be fabricated using a UMC-1000 system to emulate the process plans developed in this research.

5. Acknowledgements and conflicts of interest

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