Hybrid Additive and Subtractive Manufacturing Framework for High-Precision Mechanical Component Production

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Abstract

Hybrid additive and subtractive manufacturing is increasingly being used to produce high-value metal components that require both geometric complexity and functional precision. Additive routes such as directed energy deposition and wire-arc additive manufacturing can create near-net-shape structures, internal passages, and material-efficient preforms, whereas subtractive machining remains necessary for datum recovery, tolerance closure, sealing surfaces, bores, and final roughness control. This manuscript revises and extends a hybrid manufacturing framework for high-precision mechanical component production by treating geometry partitioning, allowance allocation, deposition, in-situ metrology, semi-finish machining, finish machining, and final inspection as one coordinated process chain. The proposed method includes analytical expressions for part zoning, machining allowance, deposition time, material removal time, total route duration, dimensional error propagation, surface-finish improvement, material utilization, and multi-objective route selection. An illustrative Ti-6Al-4V precision housing case is used to demonstrate how staged hybrid processing can reduce dimensional deviation from 0.42 mm in the as-deposited state to approximately 0.025 mm after finishing, while improving roughness from Ra = 14.2 µm to Ra = 1.4 µm and maintaining a much lower buy-to-fly ratio than a billet-based subtractive route. The revised framework is positioned for aerospace, tooling, energy, repair, and high-performance mechanical applications where process planning, metrology feedback, and finish-machining strategy must be considered together rather than as isolated post-processing decisions.

Keywords: hybrid manufacturing, additive-subtractive manufacturing, directed energy deposition, wire-arc additive manufacturing, CNC machining, precision engineering, process planning, metrology, surface finish, dimensional accuracy

1. Introduction

Metal additive manufacturing has created new possibilities for producing mechanical components that are difficult to manufacture using conventional methods alone. Its ability to build complex shapes layer by layer allows engineers to design lightweight structures, internal channels, lattice features, repaired surfaces, topology-optimized parts, and near-net-shape metallic components with much greater freedom. These advantages are especially valuable in aerospace, energy systems, tooling, biomedical devices, and advanced mechanical industries, where performance, weight reduction, customization, and material efficiency are important. However, in practical engineering applications, the ability to print a complex geometry is only the first step. A printed part must still meet the dimensional accuracy, surface quality, mechanical strength, fatigue resistance, and inspection standards required for real service conditions. This remains a major challenge because metal additive manufacturing often produces parts with surface roughness, residual stress, thermal distortion, porosity, lack-of-fusion defects, anisotropic behavior, and dimensional variation caused by repeated heating and cooling during layer-by-layer deposition (Lewandowski & Seifi, 2016; Sames *et al*., 2016).These limitations become more serious when additive manufacturing is used for high-performance materials such as titanium alloys, nickel-based alloys, stainless steels, and functionally graded metallic structures.

In critical mechanical systems, even a small surface defect, inaccurate bore, rough sealing face, or distorted datum surface can affect assembly, leakage control, fatigue life, or structural safety. A component may look successful after printing, but it may still require accurate holes, threaded regions, bearing seats, mating surfaces, sealing lands, and low-roughness functional areas before it can be accepted as a finished engineering part. For this reason, metal additive manufacturing should not be treated as a complete replacement for precision machining. A more realistic and industrially useful approach is to combine the design freedom of additive manufacturing with the accuracy and surface control of subtractive manufacturing (Hossain, Barman, Pi, & Islam, 2022). Subtractive manufacturing, particularly CNC machining, remains one of the most dependable methods for producing tight tolerances and high-quality surface finishes. Machining can create accurate datums, correct dimensional errors, improve surface roughness, and produce functional features that are difficult to obtain directly from the as-built additive condition. At the same time, producing a complex component entirely from billet material can be inefficient. It may require long roughing operations, high material removal, increased tool wear, and higher production cost, especially when the part includes internal features or complex freeform geometry. Hybrid additive and subtractive manufacturing addresses this issue by allowing additive manufacturing to produce the near-net shape and subtractive machining to finish the areas that require precision. In this way, each process is used where it performs best: additive manufacturing provides geometric flexibility and material efficiency, while machining provides final dimensional and surface-quality control (Hossain, Barman, Pi, & Islam, 2022). The value of hybrid manufacturing is not simply in placing additive and subtractive processes next to each other. Its real strength comes from planning both processes as one connected manufacturing route. In a well-designed hybrid process, machining is not treated as a last-minute correction after printing. Instead, machining allowance, datum recovery, tool access, inspection points, surface finish requirements, and tolerance-critical features are considered before deposition begins. Certain regions may be intentionally overbuilt so that machining can remove excess material and achieve the required final dimensions. In other cases, machining may be introduced between additive steps to restore surfaces, recover datums, control distortion, or prepare a stable base for the next deposition stage. This makes hybrid additive-subtractive manufacturing a practical process-planning strategy rather than only a post-processing method. This integrated view is important because metal additive manufacturing still faces several quality barriers. During deposition, localized melting and solidification create complex thermal histories inside the part. These thermal cycles may lead to residual stress, warping, microstructural variation, and local defects. Surface roughness is also a major concern, especially for components that must function under sealing, sliding, fatigue, or assembly-contact conditions. In high-precision mechanical production, even small errors in flatness, circularity, perpendicularity, hole location, or surface finish can reduce part performance. Therefore, additive manufacturing needs to be supported by machining, metrology, and feedback-based correction if it is to be used reliably for critical mechanical components (Lewandowski & Seifi, 2016; Tapia & Elwany, 2014).

The need for hybrid manufacturing also fits well with the broader movement toward smart manufacturing. Modern production systems are increasingly expected to monitor process conditions, detect quality issues early, reduce downtime, and use data to support better decision-making. In this context, hybrid additive-subtractive manufacturing provides a strong foundation for intelligent production because both additive deposition and machining generate valuable process information. Thermal signals, machine logs, toolpath data, dimensional measurements, cutting behavior, surface inspection results, and sensor feedback can all help determine whether the process should continue, pause, adjust parameters, or perform intermediate machining. This type of real-time monitoring and quality-focused decision-making is central to advanced manufacturing systems (Hossain, Pi, Islam, & Lide, 2021). Artificial intelligence can further improve the reliability of hybrid manufacturing by helping engineers interpret process data more effectively. Many defects in metal additive manufacturing begin during the build process and may not be easy to correct after the component is completed. AI-supported monitoring can help identify abnormal thermal behavior, process instability, parameter deviation, and defect-prone regions while the part is still being manufactured. When this capability is linked with a hybrid production route, the process can become more responsive. For example, the system may detect distortion, pause deposition, machine a critical surface, recover a datum, or adjust process parameters before additional material is added. This creates a stronger connection between sensing, analysis, and physical correction during manufacturing (Hossain, Bhuiyan, Rahman, & Hasan, 2024).

Hybrid manufacturing is also important for multi-material and functionally graded components. These components are designed with gradual changes in material composition or properties, which can improve thermal resistance, wear behavior, lightweight performance, and structural strength. However, they also create new challenges for machining and inspection because different material regions may respond differently to cutting forces, heat generation, tool wear, and surface-finishing operations. For this reason, a hybrid framework for high-precision production must consider not only the external geometry of the component, but also the material distribution, machinability, and final performance requirements. This is especially important for next-generation mechanical and thermal engineering components, where advanced geometry and advanced material behavior are often combined in the same part (Hossain, Badugu, & Seelu, 2023). Thermal engineering components provide a clear example of why additive and subtractive processes must work together. Additively manufactured compact heat exchangers can include internal channels, thin walls, compact flow paths, and enhanced heat-transfer surfaces that are difficult to produce through conventional machining alone. These features can improve thermal performance and support more efficient industrial energy systems. However, the same components still require accurate mounting faces, flat sealing surfaces, reliable interfaces, and tight dimensional control for assembly and operation. In this case, additive manufacturing creates the performance-enhancing geometry, while subtractive machining helps make the component usable, sealable, and reliable in a real engineering system (Hossain, Dangol, Hasan, & Badugu, 2023).

Mechanical characterization is another essential part of hybrid manufacturing because the final component must be evaluated by both its geometry and its performance. A part may meet the required shape but still fail to satisfy strength, hardness, fatigue resistance, wear behavior, thermal stability, or structural reliability requirements. This issue becomes even more important for functionally graded metallic components, where material transitions may influence local mechanical behavior and failure response. Therefore, a practical hybrid additive-subtractive manufacturing framework should connect process planning, machining, metrology, and performance evaluation into one continuous route from design to final validation (Hossain, Dangol, Matheswaran, & Venkat, 2024). Based on these needs, the present study develops a practical framework for hybrid additive and subtractive manufacturing of high-precision mechanical components. The proposed framework begins by identifying tolerance-critical surfaces, additive-friendly zones, machining-access regions, inspection points, and functional features. These early decisions are then connected to machining allowance, deposition planning, intermediate metrology, semi-finish machining, finish machining, and final inspection. This approach places the actual function of the component at the center of the manufacturing plan. Instead of asking only what can be printed, the framework asks what must be accurate, what must be smooth, what must be inspected, and what must perform reliably after production.

The main contribution of this manuscript is to present hybrid additive-subtractive manufacturing as an engineer-focused process-planning framework for producing high-precision mechanical components. Unlike studies that focus mainly on machine architecture, topology optimization, or cost comparison, this work emphasizes the practical decisions required to move from printable geometry to functional mechanical hardware. It argues that additive deposition and subtractive machining should be planned together from the beginning rather than treated as separate operations. By combining geometry zoning, machining allowance, metrology feedback, AI-supported monitoring, semi-finish machining, finish machining, and final inspection, the proposed framework offers a realistic pathway for producing complex mechanical components with reliable dimensional accuracy, surface quality, and performance readiness. This direction is especially relevant to modern manufacturing research because hybrid processing, smart monitoring, AI-based control, and advanced material systems are becoming central to the future of precision mechanical production (Hossain, Pi, Islam, & Lide, 2021; Hossain, Barman, Pi, & Islam, 2022; Hossain, Bhuiyan, Rahman, & Hasan, 2024).

2. Literature Review

2.1. Development of Hybrid Additive and Subtractive Manufacturing

Hybrid additive and subtractive manufacturing has gradually moved from being a post-processing strategy to becoming a more integrated manufacturing approach for producing high-precision mechanical components. In the earlier stage of metal additive manufacturing, printed parts were often treated as near-net-shape products that required machining only after the build was completed. This approach helped improve surface finish and dimensional accuracy, but it did not fully address problems such as tool accessibility, datum recovery, inspection planning, machining allowance, and thermal distortion. As hybrid manufacturing research developed, it became clearer that additive and subtractive operations should be planned together from the beginning rather than treated as separate stages after the design is finalized (Kerbrat *et al.*, 2011; Newman *et al.*, 2015; Zhu *et al.*, 2013).

This shift is important because the success of a hybrid route depends on more than the ability to deposit and machine material. It also depends on how the part geometry is divided, where machining stock is preserved, when intermediate inspection is performed, and how the final tolerance-critical surfaces are produced. The integration of directed energy deposition, wire arc additive manufacturing, CNC machining, and inspection systems has made it possible to build, measure, correct, and finish a component within the same manufacturing environment. Such systems can reduce setup changes, minimize registration errors, improve geometric consistency, and support more flexible repair and production strategies (D'Avila *et al.*, 2020; Flynn *et al.*, 2016; Rabalo *et al.*, 2023; Smith *et al.*, 2024).

For high-precision mechanical component production, this integrated direction is especially valuable. Many engineering parts require complex internal or external geometries, but they also require accurate datums, precision bores, smooth sealing faces, threaded features, and reliable mating surfaces. Additive manufacturing alone often cannot satisfy all of these requirements in the as-built condition. At the same time, machining the entire component from billet can waste material and limit design freedom. Hybrid manufacturing addresses this practical gap by using additive manufacturing for near-net-shape material placement and subtractive machining for final dimensional and surface-quality control (Hossain, Barman, Pi, & Islam, 2022).

2.2. Process Planning and Manufacturability Considerations

Process planning is one of the central issues in hybrid additive-subtractive manufacturing. A single component can often be produced through several possible routes, including full machining, full additive manufacturing followed by machining, or an interleaved sequence of deposition, inspection, semi-finishing, and final machining. Choosing the best route requires careful consideration of part geometry, machining accessibility, deposition direction, fixture strategy, surface requirements, and final inspection needs. Automated and decision-based planning methods have therefore become important because they help connect CAD geometry with realistic manufacturing execution (Behandish *et al.*, 2018; Fuchs *et al.*, 2021; He *et al.*, 2023; Kwon & Oh, 2023).

A major challenge in this area is that a geometry that is easy to print may not be easy to finish. Thin walls, deep pockets, internal channels, overhangs, and freeform surfaces may be suitable for additive manufacturing, but they can create difficulties for machining and inspection. If machining access is not considered early, the final part may contain surfaces that cannot be reached by the cutting tool or cannot be measured accurately. Similarly, if machining allowance is not assigned properly, the finishing operation may either fail to remove as-built surface irregularities or remove too much material and reduce the benefit of additive manufacturing. These problems show why hybrid manufacturing requires early manufacturability analysis rather than late-stage correction (Kerbrat *et al.*, 2011; Liu *et al.*, 2023; Zhu *et al.*, 2013).

Topology optimization has made this issue even more important. Additive manufacturing allows engineers to design lightweight and performance-driven structures, but optimized shapes may include complex surfaces that are difficult to machine after printing. Therefore, topology optimization for hybrid manufacturing must consider not only strength and weight reduction, but also machining access, support removal, residual deformation, dimensional correction, and inspection feasibility. Recent work has shown that process planning should be included directly in the design and optimization stage so that the final component is not only printable, but also finishable and inspectable (Liu *et al*., 2023; Xu *et al*., 2024).

2.3. DED and WAAM as Hybrid Manufacturing Routes

Directed energy deposition and wire arc additive manufacturing are widely used in hybrid manufacturing because they are suitable for metallic near-net-shape production, repair, and feature addition. DED offers flexibility in depositing material onto existing surfaces and can be integrated with multi-axis machine tools. This makes it useful for repair applications, graded materials, and localized feature building. WAAM is attractive for larger metallic components because it offers high deposition rates, efficient material use, and the ability to produce medium-to-large structures from engineering alloys such as titanium, aluminum, steel, and nickel-based materials (Ahn, 2021; Dezaki *et al*., 2022; Ding *et al*., 2015; Williams *et al*., 2016).

Despite these advantages, DED and WAAM also introduce quality challenges that make subtractive finishing necessary. Deposited beads may produce uneven surfaces, waviness, local height variation, and geometric deviation. Repeated thermal cycles may also cause residual stress, distortion, and microstructural variation. These effects can reduce the dimensional accuracy and surface quality of the as-built component. Therefore, machining allowance must be included in the process plan so that enough material remains for semi-finishing and final machining. Without proper allowance, the process may not achieve the required precision; with excessive allowance, the material and time-saving benefits of additive manufacturing may be reduced (Feldhausen *et al*., 2022; Haley *et al*., 2024).

A practical hybrid route must therefore balance deposition efficiency with finishing requirements. The additive stage should not be planned only to create the approximate shape of the part. It should also create a shape that can be measured, corrected, and machined into the final component. This is particularly important for tolerance-critical regions such as datum surfaces, holes, sealing lands, and assembly interfaces. In this context, DED and WAAM are not simply deposition technologies; they are part of a broader process chain that requires machining, metrology, and feedback-based correction to achieve high-precision outcomes (Hossain, Barman, Pi, & Islam, 2022).

2.4. Monitoring, Metrology, and Feedback-Based Correction

Metrology plays a critical role in hybrid additive-subtractive manufacturing because errors can accumulate during deposition if they are not detected early. In conventional machining, inspection may occur mainly after the finishing stage. In hybrid manufacturing, however, measurement becomes more useful when it is performed during the process. In-situ probing, surface scanning, height mapping, thermal monitoring, acoustic sensing, melt-pool observation, and machine-log analysis can provide useful information about bead geometry, thermal behavior, dimensional deviation, and defect formation (Everton *et al*., 2016; Grasso & Colosimo, 2017; Tapia & Elwany, 2014).

The value of in-situ metrology increases when additive deposition and machining are performed within the same setup. Measurement data can help determine whether the process should continue, whether an intermediate machining operation is needed, or whether a datum must be recovered before additional material is deposited. For example, probing may identify registration error, surface scanning may reveal excess material or insufficient build height, and thermal data may indicate distortion risk. These measurements can then be used to update the toolpath, adjust machining allowance, or introduce corrective machining before the error becomes more difficult to remove (Feldhausen *et al*., 2022; Haley *et al*., 2024).

This feedback-based approach is especially important for high-precision mechanical components because final inspection alone may not be enough to guarantee process reliability. If dimensional error is discovered only at the end of production, the part may require costly rework or may become unusable. By contrast, intermediate metrology allows the process to be corrected while there is still enough material and access to recover the geometry. Therefore, in the present framework, metrology is not treated as a separate inspection activity. It is treated as a decision point that connects deposition, semi-finish machining, final machining, and final inspection.

2.5. Smart Manufacturing and AI-Based Process Control

The development of smart manufacturing has strengthened the role of data-driven monitoring and control in advanced production systems. Modern manufacturing is increasingly moving away from purely experience-based decision-making and toward systems that can collect process data, identify quality risks, predict maintenance needs, and support real-time correction. This direction is highly relevant to hybrid additive-subtractive manufacturing because both additive and subtractive processes generate valuable data during production. Thermal signals, machine parameters, toolpath records, cutting behavior, vibration, surface measurements, and inspection results can all support better process decisions (Hossain, Pi, Islam, & Lide, 2021).

Artificial intelligence has become particularly important in metal additive manufacturing because many defects begin during the build process. Defects such as porosity, lack of fusion, unstable bead formation, and thermal distortion may develop gradually and may not be easy to correct after the component is completed. AI-supported monitoring can help identify abnormal process behavior, parameter deviation, defect-prone zones, and unstable thermal conditions earlier in the production cycle. When this capability is linked with a hybrid manufacturing route, the process can become more responsive because detected errors can be corrected through machining, parameter adjustment, or additional inspection before final finishing (Hossain, Bhuiyan, Rahman, & Hasan, 2024).

In practical terms, AI does not remove the need for engineering judgment. Instead, it improves the quality of that judgment by helping engineers interpret complex process information more quickly and consistently. For hybrid manufacturing, the most useful role of AI is to support decisions such as when to interrupt deposition, when to machine a surface, how much cleanup allowance is needed, and whether a part is ready for final finishing. This makes AI-based process control a natural extension of the hybrid manufacturing framework rather than a separate technology.

2.6. Advanced Materials, Functional Components, and Performance Requirements

Hybrid manufacturing is increasingly important for advanced materials and functional components. Multi-material and functionally graded additive manufacturing allow engineers to design components with gradual changes in material composition, thermal behavior, wear resistance, or mechanical properties. These structures can be useful in thermal systems, tooling, aerospace components, and other demanding mechanical applications. However, they also introduce new challenges for machining and inspection because different material regions may respond differently to cutting forces, heat generation, tool wear, and surface finishing conditions (Hossain, Badugu, & Seelu, 2023).

Thermal engineering components provide a clear example of this need for hybrid processing. Additively manufactured compact heat exchangers can contain internal flow channels, thin walls, and complex heat-transfer surfaces that would be difficult to manufacture using conventional machining alone. These features can improve compactness and thermal performance, but the same components still require accurate mounting faces, sealing surfaces, and dimensional control for assembly and operation. This means that additive manufacturing may create the performance-enhancing geometry, while subtractive machining ensures that the component can be assembled, sealed, and used reliably in service (Hossain, Dangol, Hasan, & Badugu, 2023).

Mechanical performance evaluation is also essential because a hybrid-manufactured part must be judged by both geometry and function. A component may meet dimensional requirements but still need to demonstrate adequate strength, hardness, fatigue resistance, wear behavior, thermal stability, and structural reliability. This is especially important for functionally graded metallic components, where material transitions may influence local stress distribution and failure behavior. For this reason, hybrid manufacturing research should connect process planning with mechanical characterization and performance validation rather than treating them as separate stages (Hossain, Dangol, Matheswaran, & Venkat, 2024).

2.7. Sustainability and Industrial Significance

Sustainability is another important motivation for hybrid additive-subtractive manufacturing. Additive manufacturing can reduce material waste by depositing material closer to the final geometry, while machining can provide the precision required for functional use. For suitable part families, WAAM- and DED-based hybrid manufacturing may reduce material removal, improve buy-to-fly ratio, and shorten roughing operations compared with machining from solid billet. However, the environmental and economic advantages of hybrid manufacturing are not automatic. They depend on the amount of deposited material, energy consumption, shielding gas use, machining demand, scrap rate, and the conventional process used for comparison (Priarone *et al.*, 2019).

A meaningful sustainability assessment should therefore consider the complete manufacturing route rather than only the additive stage. If too much material is deposited and later removed, the process may lose part of its material-efficiency advantage. On the other hand, if in-situ metrology and intermediate machining reduce scrap, rework, and failed builds, the hybrid route can offer stronger industrial value. Broader environmental research also shows that manufacturing development should be considered within the larger context of energy use, ecological impact, and sustainable industrial transition (Chinchwade, Barman, Hossain, & Karmakar, 2024).

From an industrial perspective, hybrid additive-subtractive manufacturing is most valuable when it provides a reliable pathway from digital design to functional hardware. Industries do not need printed geometry alone; they need components that can be assembled, inspected, certified, and used under real operating conditions. This is why hybrid manufacturing is particularly relevant for aerospace, energy, tooling, repair, and advanced mechanical systems where material cost, part complexity, and precision requirements are all high.

2.8. Research Gap and Position of the Present Study

The reviewed literature shows that hybrid additive-subtractive manufacturing has made significant progress in machine-tool integration, process planning, topology-aware design, monitoring, AI-based control, advanced materials, and sustainability. However, much of the existing work focuses on individual parts of the problem. Some studies emphasize machine architecture, while others focus on topology optimization, monitoring methods, material behavior, or economic analysis. Fewer studies present a practical process framework that connects geometry partitioning, machining allowance, DED/WAAM deposition, in-situ metrology, semi-finish machining, finish machining, and final inspection as one continuous production route.

This gap is important because high-precision mechanical component production requires more than successful deposition. It requires a planned relationship between additive geometry, machining stock, datum control, metrology feedback, surface finishing, tolerance closure, and final performance validation. Without this connection, hybrid manufacturing may remain a collection of useful technologies rather than a reliable engineering route.

The present study addresses this gap by developing a structured hybrid additive and subtractive manufacturing framework for high-precision mechanical component production. The framework treats additive deposition and subtractive machining as interdependent operations rather than separate steps. It places metrology and feedback at the center of the route so that errors can be identified and corrected before they affect final machining. By linking geometry partitioning, allowance allocation, DED/WAAM deposition, in-situ measurement, semi-finish machining, finish machining, and final inspection, the proposed framework offers a practical pathway for producing complex mechanical components with reliable dimensional accuracy, surface quality, and performance readiness. This approach builds on prior work in hybrid manufacturing, smart production, AI-based monitoring, functionally graded materials, and mechanical performance evaluation while translating those ideas into an engineer-focused process route for industrial application (Hossain, Pi, Islam, & Lide, 2021; Hossain, Barman, Pi, & Islam, 2022; Hossain, Bhuiyan, Rahman, & Hasan, 2024).

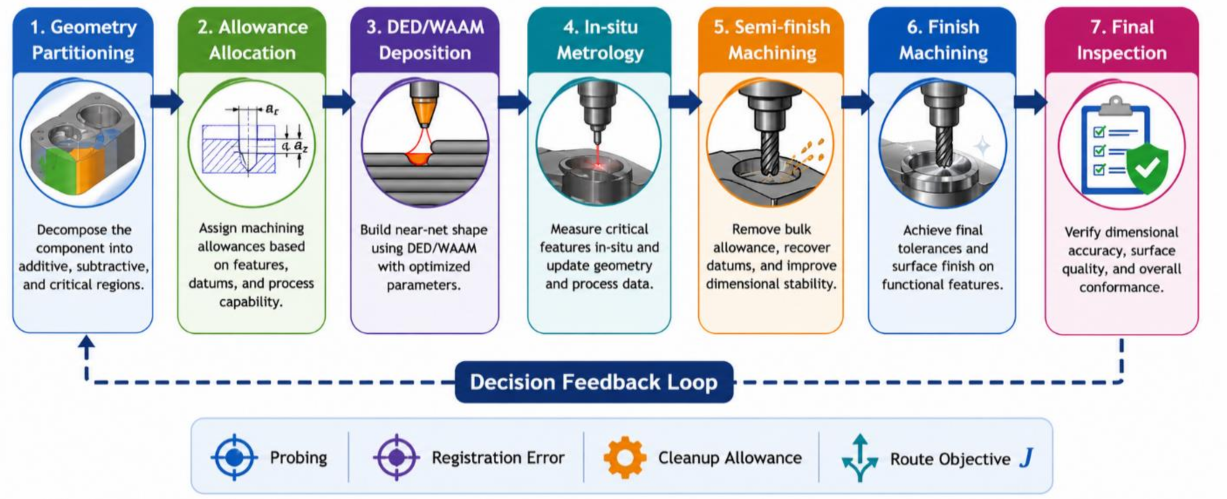
Table 1: Representative themes from the revised hybrid manufacturing literature.

Theme	Key insight	Representative citations
Design for hybrid manufacturability	Manufacturability should be evaluated before process selection and toolpath generation.	Kerbrat *et al*. (2011); Thompson *et al*. (2016); Zhu *et al*. (2013)
Machine-tool integration	Single-platform hybrid systems reduce re-fixturing and enable coordinated deposition, machining, and inspection.	Flynn *et al*. (2016); Newman *et al*. (2015); Smith *et al*. (2024)
DED/WAAM materials and routes	Wire and DED processes support efficient material placement, repair, and large metallic features.	Ahn (2021); Ding *et al*. (2015); Williams *et al*. (2016)
Automated planning	Feature decomposition and accessibility constraints should guide additive/subtractive switching.	Behandish *et al*. (2018); He *et al*. (2023); Kwon and Oh (2023)
Monitoring and AI support	Sensor data and AI models can convert inspection from a passive check into a route-control mechanism.	Everton *et al*. (2016); Haley *et al*. (2024); Hossain *et al*. (2024)
Advanced components and sustainability	Thermal, graded, and high-value parts need quality closure as well as material-efficiency evaluation.	Chinchwade *et al*. (2024); Hossain *et al*. (2023); Priarone *et al*. (2019)

3. Methodology and Calculation

3.1. Framework logic

The proposed framework targets metal hybrid routes in which a near-net-shape preform is produced by DED or WAAM and then finished by multi-axis CNC machining. The framework begins by partitioning the component into additive-dominant volume, hybrid-critical transition volume, and machining-critical surfaces. Additive-dominant regions are those where material efficiency or geometric freedom makes deposition preferable. Machining-critical surfaces include bores, datums, sealing lands, bearing seats, threaded features, and mating faces. Hybrid-critical regions are the transition zones where the designer must reserve enough stock for cleanup without sacrificing the material-efficiency advantage of AM (D'Avila *et al*., 2020; Hossain, Barman, Pi, & Islam, 2022; Stavropoulos *et al*., 2020).



1. Geometry Partitioning
Decompose the component into additive, subtractive, and critical regions.

2. Allowance Allocation
Assign machining allowances based on features, datums, and process capability.

3. DED/WAAM Deposition
Build near-net shape using DED/WAAM with optimized parameters.

4. In-situ Metrology
Measure critical features in-situ and update geometry and process data.

5. Semi-finish Machining
Remove bulk allowance, recover datums, and improve dimensional stability.

6. Finish Machining
Achieve final tolerances and surface finish on functional features.

7. Final Inspection
Verify dimensional accuracy, surface quality, and overall conformance.

Fig 1: Proposed hybrid additive-subtractive framework for high-precision component production.

The process sequence follows the logic shown in Figure 1. First, the CAD model is divided into functional zones. Second, each machining-critical surface receives a quantified allowance based on expected additive deviation, process scatter, and registration uncertainty. Third, deposition produces a near-net-shape preform. Fourth, in-situ probing or scanning evaluates whether the preform contains enough stock and whether the datum strategy is still valid. Fifth, semi-finish machining recovers references and removes unstable geometry. Finally, finish machining and final inspection close the tolerance loop (Feldhausen *et al*., 2022; Haley *et al*., 2024; Smith *et al*., 2024).

3.2. Mathematical formulation

Let the component domain be represented by Ω. The first planning decision is to partition the part into additive-dominant, hybrid-critical, and machining-critical domains:

$$\Omega = \Omega_A \cup \Omega_H \cup \Omega_M \tag{1}$$

$$a_j = \max(a_{min}, |e_{A,j}| + \beta\sigma_{A,j} + \delta_{reg}) \tag{2}$$

$$t_{add,i} = V_{add,i} / (\eta_d r_d) \tag{3}$$

$$t_{sub,j} = V_{rm,j} / MRR_j \tag{4}$$

$$T_{total} = \Sigma t_{add,i} + \Sigma t_{sub,j} + n_{tc} t_{tc} + n_{met} t_{met} + t_{setup} \tag{5}$$

$$e_{f,j} = (e_{reg,j}^2 + e_{path,j}^2 + e_{tool,j}^2 + e_{therm,j}^2)^{0.5} \tag{6}$$

$$I_{Ra,j} = [(R_{a,A,j} - R_{a,f,j}) / R_{a,A,j}] \times 100 \tag{7}$$

$$U_m = V_{part} / (V_{add} + V_{stock\_extra}) \tag{8}$$

$$J = w1(T_{total}/T_{ref}) + w2(C_{total}/C_{ref}) + w3(e_f/e_{allow}) + w4(R_{a,f}/R_{a,allow}) \tag{9}$$

Equation (1) establishes the manufacturing intent. Ω_A

contains geometry where additive freedom is advantageous, Ω_M contains surfaces that must be machined for function, and Ω_H contains the interface where stock allowance protects the final machining operation. Equation (2) assigns machining allowance a_j to a critical surface j. The allowance must cover minimum machinable stock, expected additive deviation, process variability, and registration uncertainty.

Equations (3)-(5) estimate deposition time, machining time, and total route time, while Equation (6) represents final dimensional error as the root-sum-square of registration, path, tool, and thermal error components. Equations (7)-(9) then quantify roughness improvement, material utilization, and multi-objective route quality (He *et al.*, 2023; Kwon & Oh, 2023; Priarone *et al.*, 2019).

Table 2: Core variables and engineering interpretation used in the proposed framework.

Variable	Unit	Engineering meaning
Ω_A	-	Additive-dominant region where deposition offers geometric or material-efficiency value.
Ω_H	-	Hybrid-critical transition region where allowance must be preserved for cleanup.
Ω_M	-	Machining-critical surface set such as datum faces, bores, seals, and bearing seats.
a_j	mm	Machining allowance assigned to critical surface j.
η_d	-	Effective deposition efficiency after bead losses and process inefficiency.
r_d	mm³/h	Effective additive deposition rate for the selected DED or WAAM process window.
MRR_j	mm³/min	Material-removal rate for machining zone j.
$e_{f,j}$	mm	Final dimensional deviation after hybrid processing.
$R_{a,f,j}$	µm	Final roughness after the last finishing operation.
J	-	Weighted route objective combining time, cost, accuracy, and surface finish.

3.3. Illustrative Ti-6Al-4V calculation

The calculation uses an illustrative Ti-6Al-4V precision housing with a final part volume of 95,000 mm³. The hybrid route deposits a near-net-shape preform of 128,000 mm³ and reserves local stock around bores, mating faces, and sealing surfaces. The case values are not reported as new experimental measurements; they are engineering-scale values used to demonstrate how the proposed framework can be applied during planning. This approach is consistent with process-planning studies that use representative geometry and route variables to compare hybrid, additive, and subtractive alternatives (Behandish *et al.*, 2018; Hossain, Barman, Pi, & Islam, 2022; Newman *et al.*, 2015).

$$t_{add} = 128{,}000 / (0.88 \times 120{,}000) = 1.21\ \text{h} \tag{10}$$

$$a_j = \max(0.30,\ 0.18 + 2 \times 0.06 + 0.05) = 0.35\ \text{mm} \tag{11}$$

$$t_{rough} = 25{,}000 / 1{,}800 = 13.9\ \text{min} \tag{12}$$

$$t_{finish} = 8{,}000 / 220 = 36.4\ \text{min} \tag{13}$$

$$e_f = (0.010^2 + 0.014^2 + 0.008^2)^{0.5} = 0.019\ \text{mm} \tag{14}$$

$$I_{Ra} = [(14.2 - 1.4) / 14.2] \times 100 = 90.1\% \tag{15}$$

Equation (11) yields a machining allowance of 0.35 mm when the expected additive deviation is 0.18 mm, the local standard deviation term is 0.06 mm, $\beta = 2$, and the registration uncertainty is 0.05 mm. This allowance is sufficient to support finish cleanup while avoiding unnecessary overbuilding. The result also reflects the practical role of metrology: without measurement, the planner cannot know whether reserved stock is still present in the correct coordinate frame after deposition (Everton *et al.*, 2016; Haley *et al.*, 2024).

Table 3: Illustrative case-study values for a Ti-6Al-4V precision housing.

Quantity	Value	Comment
Final part volume	95,000 mm³	Nominal finished component volume.
Deposited preform volume	128,000 mm³	Includes reserved allowance on critical surfaces.
Deposition efficiency η_d	0.88	Accounts for process losses and bead inefficiency.
Effective deposition rate r_d	120,000 mm³/h	Representative high-productivity metal deposition assumption.
Machining allowance a_j	0.35 mm	Calculated for critical surfaces.
Rough stock removed	25,000 mm³	Semi-finish and datum-recovery operations.
Finish stock removed	8,000 mm³	Bores, sealing lands, and mating faces.
Estimated full route time	2.39 h	Includes deposition, machining, probing, changeovers, and setup.
Final dimensional deviation e_f	0.019-0.025 mm	Root-sum-square calculation and conservative planning band.
Surface-finish improvement	90.1%	From Ra = 14.2 µm to Ra = 1.4 µm.

4. Results and Discussion

4.1. Stagewise improvement in dimensional accuracy and surface finish

The illustrative results show that the strongest quality gain occurs when machining is staged rather than delayed until the end of the build. The as-deposited condition is assumed to exhibit a mean dimensional deviation of 0.42 mm on critical surfaces and a roughness of Ra = 14.2 µm. Semi-finish machining reduces the deviation to 0.11 mm and roughness to Ra = 4.6 µm by recovering datum surfaces and removing unstable stock. Final machining then reduces the deviation to approximately 0.025 mm and roughness to Ra = 1.4 µm. This result is consistent with hybrid manufacturing literature showing that material placement and precision closure must be planned together (Flynn *et al.*, 2016; Hossain, Barman, Pi, & Islam, 2022; Smith *et al.*, 2024).

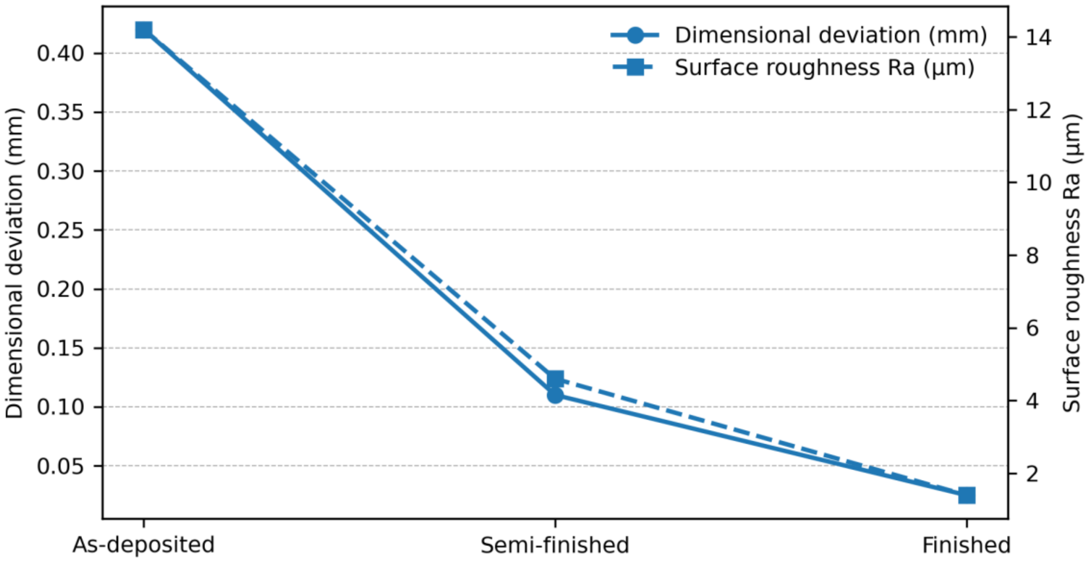


Fig 2: Illustrative progression of dimensional deviation and surface roughness through the hybrid route.

Figure 2 does not imply that any hybrid machine automatically guarantees precision. It shows a planning principle: the route becomes effective when allowance is reserved before deposition, datums are recovered before finish cuts, and measurement verifies that the stock model still agrees with the physical preform (Feldhausen *et al*., 2022; Grasso & Colosimo, 2017; Haley *et al*., 2024).

4.2. Route-level comparison

Table 4 compares a pure subtractive route, a pure additive route, and the proposed hybrid route. Pure subtractive production offers the tightest tolerance and smoothest surface but requires a high buy-to-fly ratio because much of the starting billet is removed. Pure additive production has the lowest buy-to-fly ratio and shorter gross forming time, but its as-built tolerance and roughness are insufficient for many mechanical assemblies. The hybrid route lands between these extremes: it preserves much of the material-efficiency advantage of deposition while approaching the functional surface quality and dimensional closure of machining (Priarone *et al*., 2019; Stavropoulos *et al*., 2020; Williams *et al*., 2016).

Table 4: Illustrative route comparison for three manufacturing strategies.

Route	Cycle time (h)	Buy-to-fly ratio	Final tolerance band (mm)	Final Ra (µm)	Overall interpretation
Pure subtractive	3.8	5.40	0.020	1.2	Highest precision, highest material waste.
Pure additive	1.6	1.25	0.180	12.5	Fast and efficient, but insufficient finish for critical interfaces.
Hybrid AM/SM	2.4	1.55	0.025	1.4	Balanced route for complex precision parts.

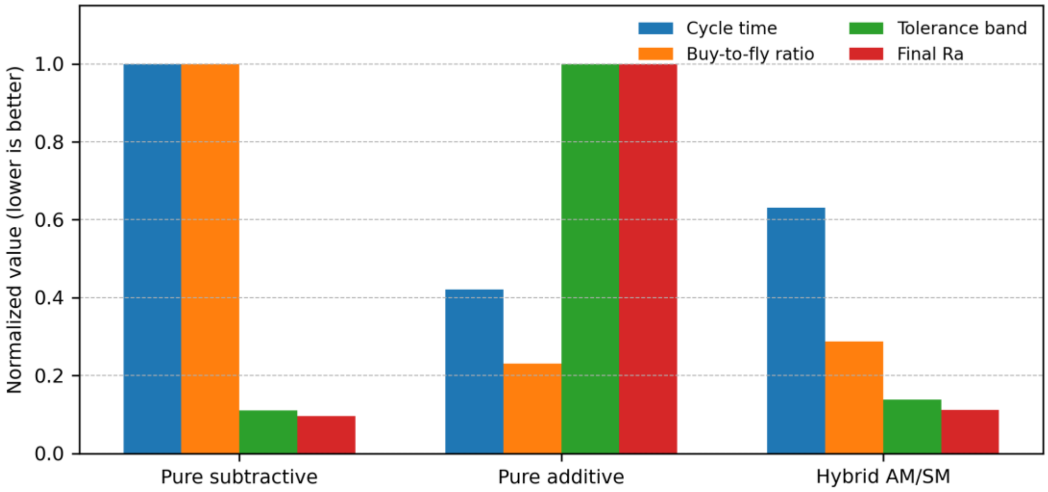


Fig 3: Normalized comparison of pure subtractive, pure additive, and hybrid routes. Lower values indicate better performance for each metric.

4.3. Process interpretation and sensitivity

The route objective J is useful because no single metric defines the best hybrid plan. A repair application may prioritize time and minimum heat input, while a sealing component may place greater weight on final tolerance and surface roughness. A thermal component may require both internal-channel complexity and verified external interfaces, making the framework relevant to additively manufactured heat exchangers and compact energy-system hardware (Hossain, Dangol, Hasan, & Badugu, 2023; Thompson *et al*., 2016). A functionally graded or multi-material component may require additional attention to interfacial quality, machining response, and local property variation (Hossain, Badugu, & Seelu, 2023; Hossain, Dangol, Matheswaran, & Venkat, 2024; Bourell *et al*., 2017).

The sensitivity of the framework is strongest in three variables: allowance a_j, registration uncertainty δ_reg, and final removal rate MRR_j. If a_j is too small, finish machining may fail to clean up the surface. If it is too large, the process loses the material-efficiency advantage of AM. If δ_reg is not controlled, the machining coordinate frame may not correspond to the deposited geometry. Finally, MRR_j affects cycle time but cannot be increased indefinitely because tool deflection, heat generation, and final roughness place limits on finishing cuts. These tradeoffs are consistent with the broader AM materials and processing literature, which shows that processing conditions, microstructure, surface state, and mechanical performance remain coupled (DebRoy *et al*., 2018; Herzog *et al*., 2016; Oliveira *et al*., 2020; Sames *et al*., 2016).

4.4. Sustainability and industrial transferability

The hybrid route may reduce material waste for expensive alloys because it avoids cutting the entire component from billet. However, a responsible interpretation must also consider deposition energy, shielding gas, consumable wire or powder, machining time, inspection resources, and scrap risk. This is why process-level comparisons should be geometry-specific rather than universal. Priarone *et al*. (2019) showed that the economic and environmental value of WAAM-based integrated manufacturing depends on geometry class and machining demand. More broadly, ecological-footprint modeling underscores that manufacturing improvement should be evaluated in relation to energy transition, resource use, and environmental consequences rather than through material utilization alone (Chinchwade, Barman, Hossain, & Karmakar, 2024).

From an implementation standpoint, the framework is most transferable when the manufacturer has access to machine-specific deposition-rate libraries, machining parameter databases, metrology routines, and historical deviation data. It can therefore be embedded into CAD/CAM workflows, digital manufacturing dashboards, or smart production systems that combine monitoring, predictive maintenance, and quality control (Feldhausen *et al*., 2022; Hossain, Pi, Islam, & Lide, 2021; Smith *et al*., 2024).

5. Industrial Implications

For aerospace, tooling, energy, and repair applications, the framework provides a practical way to convert hybrid manufacturing from a general technology concept into an engineering decision process. Geometry partitioning can be performed during CAD review. Allowance allocation can be calibrated from previous build data. Probing can verify whether the preform contains adequate stock. Semi-finish machining can recover datums before final cuts, and final inspection can close the route with measurable evidence. This staged approach is particularly useful for high-value components where a single lost part can erase the economic benefit of material-efficient deposition (D'Avila *et al*., 2020; Flynn *et al*., 2016; Seifi *et al*., 2017).

The framework also supports remanufacturing and repair. Many high-value parts do not require full-volume AM; they require material restoration on worn or damaged regions followed by precision machining of references and functional surfaces. In such cases, the same planning logic applies: deposited volume must be localized, stock must be protected, and probing must verify the relationship between the original part and the rebuilt material. This repair-oriented interpretation is consistent with the broader hybrid process literature and with DED's suitability for restoration and graded material placement (Ahn, 2021; Dezaki *et al*., 2022; Guo & Leu, 2013).

6. Limitations and Future Work

The present study is a framework and illustrative calculation rather than a full experimental validation. The Ti-6Al-4V values are intended to demonstrate route logic, not to define universal process capability. Actual performance will vary with machine stiffness, deposition head, feedstock quality, shielding conditions, heat accumulation, scanning or toolpath strategy, fixture design, tool wear, probing accuracy, and post-processing requirements. Future work should validate the framework using physical builds, repeated measurement data, and uncertainty analysis across different alloys and geometry classes (Everton *et al*., 2016; Lewandowski & Seifi, 2016; Seifi *et al*., 2017).

A second limitation is that the current objective function uses weighted normalization rather than a full techno-economic or life-cycle model. Future research should integrate energy consumption, feedstock waste, tool wear, inspection cost, rework probability, and carbon-intensity assumptions. A third future direction is the integration of AI and digital twin methods so that the allowance model and switching logic can be updated from real-time sensor data. This would align hybrid manufacturing with the smart manufacturing and AI-based AM control directions identified by Hossain, Bhuiyan, Rahman, and Hasan (2024), Hossain, Pi, Islam, and Lide (2021), and Haley *et al*. (2024).

7. Conclusion

This study presented a practical framework for hybrid additive and subtractive manufacturing of high-precision mechanical components. The main idea is that hybrid manufacturing should not be treated as a simple process where a part is printed first and then corrected later by machining. Instead, it should be planned as one connected manufacturing route, where geometry partitioning, allowance allocation, DED/WAAM deposition, in-situ metrology, semi-finish machining, finish machining, and final inspection support each other from the beginning. This type of planning is important because high-precision components require both the design freedom of additive manufacturing and the accuracy of subtractive machining (Newman *et al*., 2015; Smith *et al*., 2024; Zhu *et al*., 2013). The illustrative Ti-6Al-4V case shows that a staged hybrid route can improve dimensional accuracy and surface finish while reducing material waste compared with a fully subtractive approach.

However, the main lesson is not that hybrid manufacturing is always better than single-process manufacturing. Its real strength comes from using each process for the task it performs best. Additive manufacturing is useful for near-net-shape deposition, complex geometry, internal features, and material-efficient production. Machining is still necessary for datum surfaces, precision bores, sealing faces, threaded regions, mating surfaces, and final tolerance control. Metrology acts as the connection between these stages by detecting errors early and guiding correction before final finishing (Haley *et al*., 2024; Hossain, Barman, Pi, & Islam, 2022; Priarone *et al*., 2019).

The study also highlights that the future of hybrid manufacturing will depend on more than simply placing additive and subtractive tools on the same machine platform. A reliable hybrid system must combine process knowledge, measurement feedback, AI-supported monitoring, material behavior, and sustainability-aware decision-making. Recent work on smart manufacturing, AI-based metal AM control, functionally graded metallic components, thermal AM applications, and ecological-footprint awareness shows that advanced manufacturing must focus not only on producing complex shapes, but also on producing reliable, inspectable, and usable engineering components (Chinchwade, Barman, Hossain, & Karmakar, 2024; Hossain, Bhuiyan, Rahman, & Hasan, 2024; Hossain, Dangol, Matheswaran, & Venkat, 2024).

Overall, the proposed framework offers an engineer-focused pathway for moving from printable geometry to functional mechanical hardware. It shows how machining allowance should be planned before deposition, how metrology can be used as a decision point, and how semi-finish and finish machining can be used to control accumulated error. This approach can help reduce trial-and-error production, improve dimensional and surface quality, and make better use of high-value metallic materials. Future research should validate the framework through experimental studies involving different alloys, part sizes, machine configurations, and inspection methods. Further work may also include digital twin modeling, AI-based toolpath correction, fatigue testing, and life-cycle assessment to make the framework stronger for aerospace, energy, tooling, repair, and other precision mechanical applications.

References

1. Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S., & Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. Computer-Aided Design, 69, 65-89. https://doi.org/10.1016/j.cad.2015.04.001
2. DebRoy, T., Wei, H. L., Zuback, J. S., Mukherjee, T., Elmer, J. W., Milewski, J. O., Beese, A. M., Wilson-Heid, A., De, A., & Zhang, W. (2018). Additive manufacturing of metallic components - Process, structure and properties. Progress in Materials Science, 92, 112-224. https://doi.org/10.1016/j.pmatsci.2017.10.001
3. Hossain, M. A., Dangol, S., Hasan, D. W., & Badugu, D. (2023). Thermal performance study of additively manufactured compact heat exchangers for industrial energy systems. Journal of Mechanical, Civil and Industrial Engineering, 4(4), 86-103. https://doi.org/10.32996/jmcie.2023.4.4.9
4. Kerbrat, O., Mognol, P., & Hascoet, J.-Y. (2011). A new DFM approach to combine machining and additive manufacturing. Computers in Industry, 62(7), 684-692. https://doi.org/10.1016/j.compind.2011.04.003
5. Newman, S. T., Zhu, Z., Dhokia, V., & Shokrani, A. (2015). Process planning for additive and subtractive manufacturing technologies. CIRP Annals - Manufacturing Technology, 64(1), 467-470. https://doi.org/10.1016/j.cirp.2015.04.109
6. Flynn, J. M., Shokrani, A., Newman, S. T., & Dhokia, V. (2016). Hybrid additive and subtractive machine tools - Research and industrial developments. International Journal of Machine Tools and Manufacture, 101, 79-101. https://doi.org/10.1016/j.ijmachtools.2015.11.007
7. Smith, S., Schmitz, T., Feldhausen, T., & Sealy, M. (2024). Hybrid metal additive/subtractive machine tools and applications. CIRP Annals - Manufacturing Technology, 73(2), 615-638. https://doi.org/10.1016/j.cirp.2024.05.002
8. Priarone, P. C., Campatelli, G., Montevecchi, F., Venturini, G., & Settineri, L. (2019). A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining. CIRP Annals - Manufacturing Technology, 68(1), 37-40. https://doi.org/10.1016/j.cirp.2019.04.005
9. D'Avila, J. L., Inforcatti Neto, P., Noritomi, P. Y., Coelho, R. T., & da Silva, J. V. L. (2020). Hybrid manufacturing: A review of the synergy between directed energy deposition and subtractive processes. The International Journal of Advanced Manufacturing Technology, 110, 3377-3390. https://doi.org/10.1007/s00170-020-06062-7
10. Hossain, M. A., Bhuiyan, M. A. A., Rahman, A., & Hasan, D. W. (2024). Integration of artificial intelligence for real-time monitoring and process control in metal additive manufacturing systems. Journal of Mechanical, Civil and Industrial Engineering, 5(3), 8-28. https://doi.org/10.32996/jmcie.2024.5.3.2
11. Stavropoulos, P., Bikas, H., Avram, O., Valente, A., & Chryssolouris, G. (2020). Hybrid subtractive-additive manufacturing processes for high value-added metal components. The International Journal of Advanced Manufacturing Technology, 111, 645-655. https://doi.org/10.1007/s00170-020-06099-8
12. Behandish, M., Nelaturi, S., & de Kleer, J. (2018). Automated process planning for hybrid manufacturing. Computer-Aided Design, 102, 115-127. https://doi.org/10.1016/j.cad.2018.04.022
13. Fuchs, C., Semm, T., & Zaeh, M. F. (2021). Decision-based process planning for wire and arc additively manufactured and machined parts. Journal of Manufacturing Systems, 59, 180-189. https://doi.org/10.1016/j.jmsy.2021.01.016
14. He, Y., Wei, J., He, Y., Rong, X., Guo, W., Wang, F., Wang, Y., & Liu, J. (2023). A process strategy planning of additive-subtractive hybrid manufacturing based multi-dimensional manufacturability evaluation of geometry feature. Journal of Manufacturing Systems, 67, 296-314. https://doi.org/10.1016/j.jmsy.2023.02.003
15. Kwon, S., & Oh, Y. (2023). Optimal process planning for hybrid additive-subtractive manufacturing using recursive volume decomposition with decision criteria. Journal of Manufacturing Systems, 71, 360-376.

https://doi.org/10.1016/j.jmsy.2023.09.018

16. Feldhausen, T., Heinrich, L., Saleeby, K., Burl, A., Post, B., MacDonald, E., Saldana, C., & Love, L. (2022). Review of Computer-Aided Manufacturing (CAM) strategies for hybrid directed energy deposition. Additive Manufacturing, 56, 102900. https://doi.org/10.1016/j.addma.2022.102900
17. Haley, J., Karandikar, J., Herberger, C., MacDonald, E., Feldhausen, T., & Lee, Y. (2024). Review of in situ process monitoring for metal hybrid directed energy deposition. Journal of Manufacturing Processes, 109, 128-139. https://doi.org/10.1016/j.jmapro.2023.12.004
18. Hossain, M. A., Barman, S. C., Pi, W., & Islam, S. M. T. (2022). A study on hybrid manufacturing systems integrating additive manufacturing and CNC machining for high-precision industrial component production. Journal of Mechanical, Civil and Industrial Engineering, 3(2), 24-41. https://doi.org/10.32996/jmcie.2022.3.2.4
19. Rabalo, M. A., Rubio, E. M., Agustina, B., & Camacho, A. M. (2023). Hybrid additive and subtractive manufacturing: Evolution of the concept and last trends in research and industry. Procedia CIRP, 118, 741-746. https://doi.org/10.1016/j.procir.2023.06.127
20. Xu, S., Liu, J., Yaji, K., & Lu, L. (2024). Topology optimization for hybrid additive-subtractive manufacturing incorporating dynamic process planning. Computer Methods in Applied Mechanics and Engineering, 431, 117270. https://doi.org/10.1016/j.cma.2024.117270
21. Liu, J., Huang, J., Zheng, Y., Hou, S., Xu, S., Ma, Y., Huang, C., Zou, B., & Li, L. (2023). Challenges in topology optimization for hybrid additive-subtractive manufacturing: A review. Computer-Aided Design, 161, 103531. https://doi.org/10.1016/j.cad.2023.103531
22. Dezaki, M. L., Serjouei, A., Zolfagharian, A., Fotouhi, M., Moradi, M., Ariffin, M. K. A., & Bodaghi, M. (2022). A review on additive/subtractive hybrid manufacturing of directed energy deposition (DED) process. Advanced Powder Materials, 1(4), 100054. https://doi.org/10.1016/j.apmate.2022.100054
23. Zhu, Z., Dhokia, V., & Newman, S. T. (2013). The development of a novel process planning algorithm for an unconstrained hybrid manufacturing process. Journal of Manufacturing Processes, 15(4), 404-413. https://doi.org/10.1016/j.jmapro.2013.06.006
24. Lauwers, B., Klocke, F., Klink, A., Tekkaya, A. E., Neugebauer, R., & McIntosh, D. (2014). Hybrid processes in manufacturing. CIRP Annals - Manufacturing Technology, 63(2), 561-583. https://doi.org/10.1016/j.cirp.2014.05.003
25. Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., & Colegrove, P. (2016). Wire + arc additive manufacturing. Materials Science and Technology, 32(7), 641-647. https://doi.org/10.1179/1743284715Y.0000000073
26. Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). Wire-feed additive manufacturing of metal components: Technologies, developments and future interests. The International Journal of Advanced Manufacturing Technology, 81, 465-481. https://doi.org/10.1007/s00170-015-7077-3
27. Hossain, M. A., Pi, W., Islam, S. M. T., & Lide, M. I. (2021). Smart manufacturing framework for real-time process monitoring, predictive maintenance, and quality control in advanced mechanical production systems. Journal of Mechanical, Civil and Industrial Engineering, 2(1), 11-24. https://doi.org/10.32996/jmcie.2021.2.1.3
28. Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., & Martina, F. (2016). Design for additive manufacturing: Trends, opportunities, considerations, and constraints. CIRP Annals - Manufacturing Technology, 65(2), 737-760. https://doi.org/10.1016/j.cirp.2016.05.004
29. Herzog, D., Seyda, V., Wycisk, E., & Emmelmann, C. (2016). Additive manufacturing of metals. Acta Materialia, 117, 371-392. https://doi.org/10.1016/j.actamat.2016.07.019
30. Frazier, W. E. (2014). Metal additive manufacturing: A review. Journal of Materials Engineering and Performance, 23, 1917-1928. https://doi.org/10.1007/s11665-014-0958-z
31. Everton, S. K., Hirsch, M., Stravroulakis, P., Leach, R. K., & Clare, A. T. (2016). Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing. Materials & Design, 95, 431-445. https://doi.org/10.1016/j.matdes.2016.01.099
32. Grasso, M., & Colosimo, B. M. (2017). Process defects and in situ monitoring methods in metal powder bed fusion: A review. Measurement Science and Technology, 28(4), 044005. https://doi.org/10.1088/1361-6501/aa5c4f
33. Hossain, M. A., Badugu, D., & Seelu, B. (2023). Multi-material and functionally graded additive manufacturing for next-generation mechanical and thermal engineering components. British Journal of Multidisciplinary Studies, 1(2), 11-26. https://doi.org/10.32996/bjmss.2023.2.2.2
34. Ahn, D.-G. (2021). Directed energy deposition (DED) process: State of the art. International Journal of Precision Engineering and Manufacturing-Green Technology, 8, 703-742. https://doi.org/10.1007/s40684-020-00302-7
35. Lewandowski, J. J., & Seifi, M. (2016). Metal additive manufacturing: A review of mechanical properties. Annual Review of Materials Research, 46, 151-186. https://doi.org/10.1146/annurev-matsci-070115-032024
36. Seifi, M., Gorelik, M., Waller, J., Hrabe, N., Shamsaei, N., Daniewicz, S., & Lewandowski, J. J. (2017). Progress towards metal additive manufacturing standardization to support qualification and certification. JOM, 69, 439-455. https://doi.org/10.1007/s11837-017-2265-2
37. Chinchwade, N., Barman, S. C., Hossain, M. A., & Karmakar, M. (2024). Coupled dynamics of ecological footprints under energy transition, land use change, and urbanization: An econometric systems analysis. International Journal on Economics, Finance and Sustainable Development, 6(3), 592-602. https://doi.org/10.31149/ijefsd.v8i1.5613
38. Tapia, G., & Elwany, A. (2014). A review on process monitoring and control in metal-based additive manufacturing. Journal of Manufacturing Science and Engineering, 136(6), 060801. https://doi.org/10.1115/1.4028540
39. Hossain, M. A., Dangol, S., Matheswaran, K., & Venkat, N. S. G. (2024). Mechanical characterization and performance evaluation of functionally graded metallic

components for advanced engineering applications. International Journal of Future Engineering Innovations, 1(3), 59-68. https://doi.org/10.54660/IJFEI.2024.1.3.59-68

40. Oliveira, J. P., Santos, T. G., & Miranda, R. M. (2020). Revisiting fundamental welding concepts to improve additive manufacturing: From theory to practice. Progress in Materials Science, 107, 100590. https://doi.org/10.1016/j.pmatsci.2019.100590
41. Bourell, D., Kruth, J.-P., Leu, M., Levy, G., Rosen, D., Beese, A. M., & Clare, A. (2017). Materials for additive manufacturing. CIRP Annals - Manufacturing Technology, 66(2), 659-681. https://doi.org/10.1016/j.cirp.2017.05.009
42. Guo, N., & Leu, M. C. (2013). Additive manufacturing: Technology, applications and research needs. Frontiers of Mechanical Engineering, 8, 215-243. https://doi.org/10.1007/s11465-013-0248-8
43. Sames, W. J., List, F. A., Pannala, S., Dehoff, R. R., & Babu, S. S. (2016). The metallurgy and processing science of metal additive manufacturing. International Materials Reviews, 61(5), 315-360. https://doi.org/10.1080/09506608.2015.1116649