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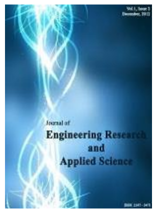

Hybrid Manufacturing: The Integration of Subtractive and Additive Processes

Udu Chukwudi Emeka, Aguh Patrick Sunday, Okpala Charles Chikwendu

Industrial/Production Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria

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Abstract
Hybrid Manufacturing (HM), which integrates Additive Manufacturing (AM) and Subtractive Manufacturing (SM) within a unified platform, has emerged as a pivotal advancement in contemporary production technologies. The resulting synergy enhances manufacturing flexibility, supports mass customization, and improves material utilization, while also reducing lead times and tooling requirements. This article presents a comprehensive review of HM systems, highlighting their operational principles, enabling technologies, and implementation strategies. Key system architectures such as the integration of Directed Energy Deposition (DED) or Laser Metal Deposition (LMD) with Computer Numerical Control (CNC) machining are discussed in detail. Case studies from aerospace, medical, and automotive industries were examined to demonstrate practical applications and performance outcomes. Additionally, the article explored critical challenges including thermal management, toolpath integration, interfacial bonding, and process monitoring. Emphasis was placed on the role of advanced simulation tools, in-situ sensing, and AI-driven optimization in overcoming these challenges and advancing HM capabilities. The paper concluded with a discussion of emerging trends and future research directions, underscoring HM's role as a cornerstone in the evolution toward intelligent, sustainable, and digitally integrated production systems.

Keywords: *Hybrid manufacturing, additive manufacturing, subtractive manufacturing, directed energy deposition, computer numerical, advanced manufacturing, industry 4.0, digital twin*

1. Introduction

The continuous evolution of manufacturing technologies reflects the growing demands for enhanced efficiency, precision, customization, and sustainability in modern industry. Historically, manufacturing has been dominated by subtractive processes such as milling, turning, and drilling, where material is removed from a workpiece to achieve the desired geometry. These Subtractive Manufacturing (SM) methods are capable of producing high-precision parts with excellent surface finishes and dimensional accuracy. However, they often suffer from limitations related to geometric complexity, material waste, and design constraints. In contrast, Additive Manufacturing (AM), has emerged as a transformative approach that enables layer-by-layer fabrication of intricate parts directly from digital models.

Commonly referred to as 3D printing, AM is revolutionizing production systems, as it leads to improved customization and the production of on-demand components, hence optimizing lead times and reducing the need for large inventories [26, 29, 37]. Technologies such as Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) have introduced new design possibilities, particularly in the production of lightweight, customized, and functionally optimized components. Despite its advantages, AM still faces critical challenges that hinder its broader industrial adoption. Issues such as poor surface finish, dimensional inaccuracies, and microstructural anisotropy can negatively impact the mechanical integrity and performance of printed parts.

For instance, Diaz et al. [11], highlighted that AM components are susceptible to surface porosity and roughness, which reduce fatigue life and corrosion resistance. Lee et al. [19], noted that AM struggles to meet stringent tolerances required in precision-critical sectors, while Babu et al. [4], emphasized that the presence of anisotropic mechanical properties is due to heterogeneous thermal histories during fabrication. Also, Altiparmak [3], underscored the relatively slower build rates of AM processes when compared to conventional techniques, as it limits scalability for high-volume production. These limitations underscore the need for a more integrated approach that combines

*Corresponding author: chydoskemy@yahoo.com, ps.aguh@unizik.edu.ng, cc.okpala@unizik.edu.ng

the benefits of both additive and subtractive manufacturing methods.

HM emerged as a strategic solution that unites AM and SM processes within a single system or workflow. By leveraging the geometric freedom and material efficiency of AM with the accuracy and surface quality of SM, hybrid systems are capable of producing complex, high-performance components in a more efficient and cost-effective manner. Applications in aerospace, biomedical, and tooling industries have already demonstrated HM's potential in reducing lead times, improving part quality, and enabling innovative design strategies [20, 21]. The motivation for HM aligns closely with the principles of Industry 4.0 digital integration, smart production, and sustainability.

Characterized by the fusion of digital technologies with traditional industrial processes, Industry 4.0 which represents a new era in manufacturing, deals with the applications of intelligent products and production process, and results in significant changes in the role of workers, thereby leading to an evolution in human-machine interaction [16, 17]. HM systems support advanced functionalities such as in-situ repair, multi-material printing, and waste minimization, thus positioning them as key enablers of circular manufacturing. This paper aims to provide a comprehensive review of HM systems, exploring their principles, architectures, integration strategies, industrial applications, enabling technologies, and future research opportunities.

2. Additive and Subtractive Manufacturing: Fundamentals and Integration

Additive and subtractive manufacturing represent two distinct yet complementary paradigms in the production of components. AM is defined by ASTM International (F2792) as the process of joining materials to build objects from 3D model data, typically layer by layer. AM is fundamentally digital and enables unprecedented design freedom, mass customization, and the fabrication of complex geometries, including internal cavities and lattice structures that are challenging to produce using conventional methods [4]. In contrast, SM operates by removing material from a solid block through machining processes such as milling, turning, drilling, and grinding. These processes are commonly executed using Computer Numerical Control (CNC) machines, known for delivering high precision, tight dimensional tolerances, and excellent surface finishes. The maturity and reliability of SM make it indispensable in the sectors that require strict compliance with performance and safety standards.

The integration of AM and SM within HM systems unlocks new opportunities for combining the best attributes of both approaches. HM allows for the sequential or simultaneous execution of additive and subtractive operations, leading to the production of complex parts in a single setup, thereby significantly reducing setup times and inter-machine transfers [14, 40]. This integration is especially effective in addressing limitations commonly associated with AM such as poor surface finish, weak interlayer bonding, and dimensional inaccuracies. For example, combining Directed Energy Deposition (DED) with post-deposition CNC machining enhance both part integrity and surface quality [10]. DED, which deposits material in wire or powder form while simultaneously melting it with a focused energy source, is suited for large-scale components and repairs, offering high deposition rates but lower resolution.

Conversely, Powder Bed Fusion (PBF) techniques like Selective Laser Melting (SLM) and Electron Beam Melting (EBM) achieve finer details and higher resolution but at slower build speeds and with greater post-processing demands. On the subtractive side, traditional methods such as milling, turning, and grinding remain essential. Milling allows for shaping of both flat and contoured surfaces using rotary cutters, while turning is ideal for cylindrical features, and grinding ensures superior surface finishes and tight tolerances. These subtractive techniques are well-established, supported by standardized tooling, robust process control systems, and broad industrial adoption making, thereby them ideal complements to AM in HM environments.

Comparative analysis of AM and SM processes

Additive and subtractive manufacturing differ significantly in accuracy, material efficiency, cost, and design flexibility. While AM excels in complex geometries and minimal waste, SM offers superior precision and surface finish. This comparative analysis evaluates these factors to highlight the strengths and limitations of each process in modern manufacturing. Table 1 provides a comparative overview of AM and SM across critical performance metrics such as precision, material efficiency, production cost, and design complexity. This analysis underscores their distinct capabilities, and supports the integration of both processes within HM systems for optimized production outcomes.

Table 1: Comparative analysis of AM and SM manufacturing processes

Parameter	Additive Manufacturing (AM)	Subtractive Manufacturing (SM)
Process Principle	Builds parts layer by layer by adding material	Removes material from a solid block to form the part
Design Flexibility	High — allows complex geometries and internal structures	Limited — complex geometries require specialized tooling
Material Utilization	High — minimal waste, near-net shape	Low — significant material removal and waste
Surface Finish	Moderate — often requires post-processing	Excellent — fine finish achievable with precision tooling
Dimensional Accuracy	Moderate — affected by thermal distortion and layer resolution	High — capable of tight tolerances and precision machining
Tooling Requirement	Minimal — often tool-less production	Extensive — requires cutting tools, jigs, and fixtures
Production Speed	Slower — especially for large or dense parts	Faster — especially for simple or high-volume parts
Material Range	Limited — mostly metals, polymers, and composites in specific forms	Broad — includes metals, plastics, ceramics, and alloys
Cost Efficiency	Cost-effective for low-volume, customized parts	Cost-effective for high-volume, standardized production
Sustainability	High — due to reduced material waste and energy use	Lower — due to material wastage and energy-intensive processes

The table highlights the fundamental differences between AM and SM across key parameters. AM offers greater design freedom, enabling the creation of complex geometries and internal features with minimal material waste. However, it often requires post-processing for improved surface finish and accuracy. In contrast, SM delivers superior dimensional precision and surface quality, but results in higher material waste and limited geometric flexibility. While AM is ideal for customized, low-volume production, SM excels in high-volume, standardized parts. This comparative analysis underscores why integrating both methods in hybrid systems leverages their respective strengths for optimized manufacturing outcomes.

3. Integrating Additive and Subtractive Processes for Advanced Production

HM refers to the seamless integration of AM and SM within a unified machine platform or a highly coordinated workflow. This fusion capitalizes on the geometric complexity and material efficiency of AM, along with the precision, surface quality, and tolerance control inherent to SM. The goal is to produce components that are not only structurally intricate but also dimensionally accurate and functionally optimized. In hybrid systems, processes may be coordinated spatially on the same machine tool or temporally through sequenced operations, offering improved process flexibility, reduced lead times, and enhanced part performance. Alfattani [2], highlighted that hybrid systems can reduce production time by up to 50%, improve surface finish by 70%, and maintain dimensional accuracy within ±0.5 µm. The integration of both processes enables efficient fabrication of geometries and finishes that would be challenging or impossible with stand-alone AM or SM methods. As a result, HM is increasingly recognized as a core enabler of Industry 4.0, where intelligent, multi-capability production systems are critical.

From a system architecture perspective, HM can be classified by process sequencing and integration level: sequential vs. concurrent execution, and integrated vs. modular configurations. In sequential systems, AM and SM operations occur one after another typically beginning with additive deposition, followed by subtractive finishing to refine accuracy and surface quality. This approach is relatively simple to implement, but may involve challenges with part repositioning and alignment. Concurrent systems, by contrast, perform additive and subtractive operations simultaneously or in rapid succession, requiring advanced coordination of toolpaths, thermal control, and real-time monitoring. Though more complex, concurrent systems offer productivity gains and are well-suited for internal cavities, overhangs, and other conformal features [12, 23, 28]. Integrated systems house both AM and SM functions within a single machine tool, often governed by a unified software platform. This integration reduces handling errors and space requirements while improving cycle efficiency. Modular systems, on the other hand, involve separate AM and SM equipment working in tandem. Though offering flexibility in machine configuration and upgrades, modular setups demand meticulous synchronization and fixturing to manage transfer-related inaccuracies.

Recent advancements in machine tool design have accelerated the development of hybrid platforms that merge CNC machining with DED technologies. These hybrid machines commonly feature interchangeable heads or multi-functional nozzles that enable both material deposition and machining in a single setup. One prominent configuration is the CNC + Laser DED system, which integrates laser cladding with precision CNC milling, which is ideal for repairing components or producing high-strength parts. Mill-turn-additive systems combine turning, milling, and deposition for cylindrical components with complex internal and external features. Additionally, robotic hybrid systems utilize multi-axis robotic arms equipped with both deposition and machining tools, thus offering greater orientation freedom for large, intricate geometries. Figure 1.0 presents a notable example of this integration.

Figure 1: DMG Mori LASERTEC 65 3D

DMG Mori LASERTEC 65 3D blends 5-axis CNC milling with laser metal deposition, allowing for complex part construction and precise finishing within a single machine environment [44]. These innovations underscore the transformative potential of HM in enabling efficient, versatile, and high-quality production across various industrial sectors.

Conceptual diagram of CNC with DED hybrid machine architecture

Figure 2 illustrates the conceptual architecture of a HM system that integrates CNC machining with DED. This setup combines precise subtractive capabilities with additive deposition, and enables seamless transition between processes. It demonstrates the coordinated toolpaths, shared workspace, and integrated control system that is essential for efficient hybrid operations.

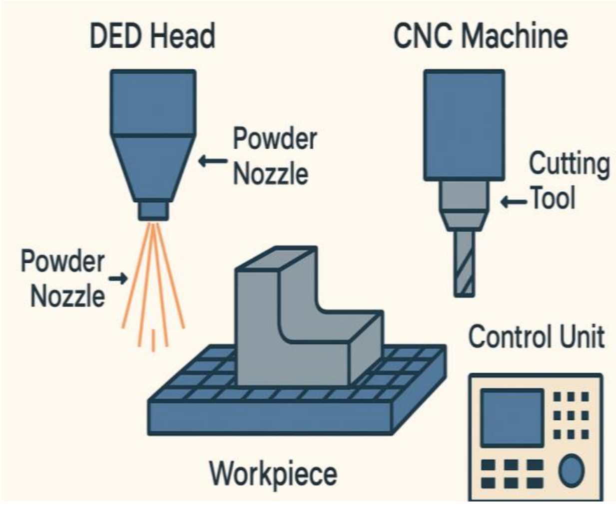

Figure 2: Conceptual diagram of CNC with DED hybrid machine architecture

The conceptual diagram of a CNC with DED hybrid machine architecture illustrates the integration of additive and subtractive manufacturing processes within a single platform. This hybrid setup combines the precision and accuracy of CNC machining with the flexibility and complexity of DED-based additive deposition. The architecture typically features a shared workspace where the part undergoes sequential or concurrent processing, allowing additive material buildup, followed by precision subtractive finishing without removing the workpiece from the machine. Central to this system is an integrated control unit that synchronizes toolpath planning and process parameters for both machining and deposition, ensuring seamless transition and minimizing errors. The machine incorporates multi-axis CNC tool heads alongside a DED laser or electron beam source, which enables complex geometries with high surface quality and dimensional accuracy. Real-time sensors monitor key variables such as temperature and deposition quality, and thereby allows adaptive adjustments. This conceptual framework exemplifies how HM enhances efficiency, reduces lead time, and expands design possibilities in modern production environments.

4. Comparison of hybrid system architectures

Table 2 illustrates the comparison of hybrid system architectures, it highlights key differences between sequential, concurrent, integrated, and modular setups. This comparison emphasizes how architecture influences process coordination, machine design, and operational efficiency, thereby providing insight into the strategic selection of hybrid configurations for specific manufacturing applications and performance goals.

As shown in the table, sequential systems execute additive and subtractive processes one after the other, and offers moderate integration and cost efficiency. Concurrent systems allow processes to operate simultaneously; it enables high process integration and flexibility but at higher costs. Integrated (monolithic) systems feature a unified machine with centralized control, and is ideal for precision-critical industries. Modular architectures use separate but connected machines and provides operational flexibility and adaptability. This comparison helps manufacturers to select the most suitable hybrid architecture for specific production needs.

5. Process Integration and Workflow

HM systems unify the complementary strengths of AM and SM through sophisticated coordination of tools, software platforms, and materials. Achieving seamless integration between these two fundamentally distinct processes necessitates a high degree of orchestration in toolpath generation, real-time process control, and interfacial material management. This section focuses on three critical pillars of hybrid process integration: toolpath planning and synchronization, advanced software and control systems, and material compatibility and bonding strategies.

Toolpath planning in hybrid systems requires the generation of coordinated instructions for both AM and SM operations. While AM builds geometry layer by layer and SM removes material to refine features, their coexistence demands careful scheduling to avoid tool interference, collision, or overcutting. Transitions between deposited rough geometries and precision-machined areas must be meticulously handled. In metal-based processes such as Directed Energy Deposition (DED), residual stresses from AM are mitigated through SM passes. Grzesik [14], highlighted the use of feature-based toolpath segmentation, wherein additive and subtractive operations are applied selectively based on part geometry and functionality. Additionally, adaptive slicing techniques in AM allow for variable layer thickness, optimizing the balance between build efficiency and machining accuracy in subsequent SM stages.

Table 2: Comparison of hybrid system architectures

Architecture Type	Description	Process Integration	Flexibility	Cost	Application Suitability
Sequential	Additive and subtractive processes occur one after another, using the same or shared workspace.	Low to Moderate	Moderate	Moderate	Prototyping, low-mix, medium-volume production
Concurrent	Both processes operate simultaneously in the same system or workspace.	High	High	High	Complex parts requiring real-time adjustments
Integrated (Monolithic)	A single machine with combined AM and SM functions controlled via unified software.	High	Moderate to High	High	High-precision components, aerospace, biomedical
Modular	Separate AM and SM units connected physically or digitally for coordinated operations.	Moderate	High	Moderate	Job shops, reconfigurable production lines

The effectiveness of HM hinges on robust integration between Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and machine control systems. Traditional CAD/CAM tools are typically tailored to either additive or subtractive processes, but hybrid workflows require unified platforms that support both. Essential capabilities include simultaneous representation of material addition and removal, cross-process toolpath optimization, collision detection, and process simulation. Advanced hybrid CAM solutions such as Siemens NX Hybrid, Autodesk PowerMill Hybrid, and Materialise Build Processor enable synchronized command generation for both additive heads and subtractive spindles [14]. Modern control systems further enhance integration through multi-axis controllers, real-time feedback loops, and AI-based monitoring, facilitating adaptive adjustments to parameters like tool wear, deposition rate, and thermal distribution.

A significant challenge in HM systems is achieving material compatibility and reliable bonding at the interface of AM and SM zones. Success depends on the creation of strong metallurgical or mechanical bonds, managing heat input to minimize distortion, and ensuring compatibility in thermal expansion, hardness, and chemical properties. In DED systems for instance, preheating and post-deposition treatments are often necessary to alleviate residual stresses. Additional bonding strategies include interlayer rolling, laser re-melting, and precision post-machining to enhance surface quality. As noted by Cortina et al. [9], careful selection of material combinations is essential to prevent delamination, galvanic corrosion, and phase mismatches. Emerging trends in functionally graded and composite materials offer promising avenues for tailoring material properties across hybrid-manufactured parts.

Flowchart of toolpath generation and process planning

Figure 3 illustrates the flowchart for toolpath generation and process planning in HM. It outlines the sequential steps for integrating additive and subtractive operations, emphasizing coordinated toolpath design, process scheduling, and optimization to ensure efficient material deposition and precision machining within a unified manufacturing workflow.

From the figure, the process begins with CAD model import, which provides the geometric and functional design of the component. Next is process segmentation, where the model is analyzed to determine which regions require AM and which are better suited for SM. Following this, toolpaths are independently generated for both AM and SM processes, taking into account material deposition strategies and cutting tool paths. These paths are then aligned through process scheduling and optimization, ensuring minimal interference and efficient sequencing. Simulation and verification are performed to detect collisions, validate the toolpaths, and optimize transitions between processes. Finally, the validated toolpaths are deployed to the hybrid machine. This structured planning ensures accuracy, efficiency, and high-quality part production in HM environments.

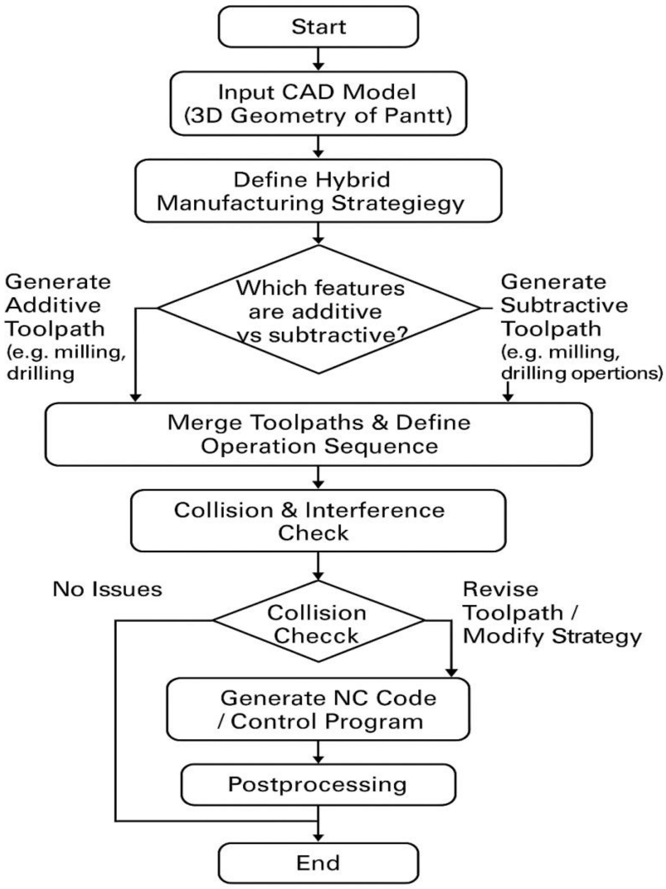

Figure 3: Flowchart for toolpath generation and process planning in HM systems

6. Industrial Applications of HM: A Sectoral Perspective

HM, which integrates AM and SM, is revolutionizing industrial production by enabling the fabrication of complex, high-performance components with superior precision, functionality, and material efficiency. Its increasing adoption across diverse industries is driven by the demand for customization, reduced lead times, and enhanced mechanical performance. In the aerospace sector, HM has proven invaluable for the repair and re-manufacturing of critical components such as turbine blades and jet engine parts. Techniques like DED, when combined with CNC machining, allow for localized material restoration followed by precise finishing, thereby extending part life and reducing both cost and waste compared to full replacement. Manepalli et al. [22], reported that Hybrid-Assisted Machining (HAM) enhances the processability of difficult-to-machine alloys such as nickel-based superalloys through innovations like laser-assisted and cryogenic machining, which significantly improve tool performance and production efficiency. Moreover, HM facilitates the integration of internal cooling channels within turbine components, aligning with modern thermal management needs.

In the automotive industry, HM is increasingly employed to produce lightweight, high-strength components for engines, chassis systems, and performance-critical assemblies. Additive techniques such as PBF enable the fabrication of intricate lattice structures and topology-optimized geometries that reduce weight without compromising strength. These components are subsequently finished using precision machining to meet stringent surface and dimensional requirements, especially at interfaces and mating surfaces. Rabalo et al. [39], highlighted the role of HM in producing custom-engineered parts such as brake calipers, intake manifolds, and transmission housings, contributing to improved fuel efficiency and enhanced vehicle dynamics critical for electric and high-performance vehicles. The ability to combine structural efficiency with precise finishing makes HM an ideal approach for automotive innovation and rapid prototyping.

The biomedical and tooling sectors have also benefited significantly from the integration of AM and SM. In biomedical applications, HM enables the production of patient-specific implants such as dental crowns, orthopedic plates, and spinal cages. Additive processes support the generation of porous structures for improved osseo-integration, while subtractive methods ensure surgical precision and bio-compatible surface finishes. Callisti and Dimatteo [8], observed that HM significantly minimizes the need for extensive post-processing, thereby improving efficiency and contributing to better clinical outcomes. In the tooling and mold-making domain traditionally dominated by subtractive methods hybrid approaches enable the integration of conformal cooling channels and complex internal geometries that were previously unattainable using conventional machining alone. Subsequent machining operations ensure tight tolerances and high surface quality, essential for injection molding and die-casting applications.

As Graybill et al. [13], observed, HM significantly reduces mold development cycles and supports agile manufacturing strategies, marking a transformative shift in industrial tooling practices. Okpala et al. [34], and Okpala and Dara [35], explained that agile manufacturing is a term applied to a firm that has created the processes, tools, and training to enable it to respond quickly to customer needs and market changes while still controlling costs and quality. They noted that at the mention of agile manufacturing, maximum flexibility comes to mind, as it refers to fast thinking methods and clever approaches to timely response to consumer needs, despite unforeseen occurrences in market situation.

7. Benefits and Challenges

One of the most notable benefits of hybrid manufacturing is its ability to achieve unprecedented design freedom. Additive processes enable the fabrication of complex geometries such as internal channels, lattice structures, and conformal cooling systems that are difficult or impossible to produce with traditional subtractive techniques alone. When combined with precision subtractive finishing, these complex features can meet stringent dimensional and surface quality standards. This hybrid synergy enhances product functionality and supports applications across demanding sectors, including aerospace and biomedical engineering. Rabalo et al. [39], emphasized that HM enables the creation of highly intricate parts, pushing the boundaries of conventional design. Moreover, additive methods reduce material waste by depositing material only where they are needed, which, when integrated with selective machining, leads to optimized resource utilization, reduced raw material costs, and lower environmental impact [15, 39]. The subtractive component further ensures superior surface quality and dimensional precision, particularly critical in industries where tolerance and finish are non-negotiable. Seamless transitions between AM and SM operations within the same platform enable enhanced mechanical performance and part accuracy [15].

Despite these advantages, HM faces significant technical hurdles. A major challenge is thermal distortion arising from the rapid heating and cooling cycles typical of additive techniques such as DED and PBF. These thermal fluctuations can lead to residual stresses, warping, and cracking, and thus complicating subsequent machining operations and compromising dimensional accuracy. Effective integration of additive and subtractive stages requires meticulous coordination of toolpaths, thermal compatibility, and machine dynamics. Misalignments, collisions, and software incompatibilities remain concerns, thereby necessitating robust, unified CAM systems that support concurrent and synchronized operations. Okuyelu and Adaji [36], underscore the importance of advanced CAM integration in enhancing efficiency and customization. Additionally, subtractive tools encounter accelerated wear when machining additively produced surfaces due to their variable hardness, residual stress, and surface roughness. These factors complicate machining consistency and raise concerns about surface integrity, including the formation of micro-cracks or defects, which must be carefully managed to ensure the reliability and longevity of hybrid-manufactured components.

8. Enabling Technologies

The advancement and widespread adoption of HM systems are increasingly driven by enabling technologies that enhance process control, precision, and operational efficiency. Central to this progress are innovations in sensing, digital simulation, and Artificial Intelligence (AI), which are collectively transforming HM into a smarter and more autonomous manufacturing paradigm. AI is transforming personalized product design by enabling manufacturers to efficiently meet the growing demand for tailored products while maintaining scalability [30, 31, 33].

Sensor technologies play a critical role by delivering continuous, real-time feedback on key process parameters such as temperature, melt pool characteristics, vibration, tool wear, and part geometry. This data enables early detection of anomalies or defects during both additive and subtractive stages. Advanced sensor systems including infrared cameras, laser profilometers, and acoustic emission sensors are integrated into HM platforms to monitor layer deposition and machining accuracy. Lawal [18] emphasizes that real-time monitoring enables adaptive process control, allowing systems to dynamically adjust laser power, feed rates, or tool paths, to ensure optimal performance and minimize process deviations.

Digital Twin (DT) technology, which creates a virtual replica of the physical manufacturing environment, has emerged as a crucial tool in HM. DT technology has become an innovative tool that offers real-time monitoring, process optimization, and enhanced environmental sustainability [24, 42]. These digital models simulate additive-subtractive workflows to predict performance outcomes, optimize parameters, and anticipate issues before actual fabrication begins. By incorporating real-time sensor data and historical performance information, DTs facilitate multi-physics simulations of thermal behavior, material flow, residual stress formation, and machining effects. According to Boddu et al. [7], this comprehensive modeling approach enhances process planning, supports risk mitigation, and streamlines quality assurance. It significantly reduces reliance on trial-and-error methods, thereby accelerating development cycles and improving production consistency [28].

The application of AI and ML further elevate HM, by enabling intelligent process optimization and predictive maintenance. AI is defined as an array of technologies that equip computers to accomplish different complex functions like the capacity to see, comprehend, appraise and translate both spoken and written languages, analyze and predict data, and also make proposals and suggestions [30, 32, 33]. Defined as algorithms that can examine and also interpret patterns in data, thus enhancing their performance over time as they are exposed to more data. ML helps computers to study and learn from data and thereby make decisions or predictions even when it is not clearly programmed to do so [1, 24, 25].

These technologies analyze vast datasets from sensors to identify trends, correlations, and anomalies that traditional methods may overlook. AI-driven algorithms refine toolpath generation, optimize energy usage, and improve part quality. Additionally, ML-based predictive analytics support early fault detection and accurate prediction of tool wear, reducing machine downtime and also enhancing operational reliability. Lawal [18], asserted that AI integration is pivotal in transitioning toward autonomous HM systems capable of continuous learning, self-correction, and adaptive decision-making.

9. Future Directions and Research Opportunities

As HM evolves, new research directions and technological innovations are emerging to address current limitations and expand its industrial impact. Future advancements are expected to focus on increasing system autonomy, innovating material capabilities, standardizing processes, and enhancing sustainability. One critical area is the development of autonomous, adaptive HM systems that are capable of real-time monitoring and decision-making without human intervention. With the integration of AI, ML, and sensor fusion, these systems can dynamically optimize both additive and subtractive operations, and thereby respond to challenges such as thermal distortion, tool wear, and geometric inaccuracies. Syed [41], highlighted the importance of closed-loop feedback and predictive analytics in enabling such systems, which can improve product quality, reduce scrap rates, and lower operational costs. According to Besigomwe [6], AI-driven optimization in closed-loop HM environments can reduce raw material usage by 12% and operational costs by 15%, thus emphasizing both economic and ecological benefits.

A parallel research priority is the development of advanced, multifunctional materials tailored for hybrid processes. These materials are expected to combine mechanical strength with additional properties such as self-healing, thermal regulation, or embedded sensors. Additive manufacturing enables the fabrication of gradient or composite materials with spatially varying properties, while subtractive techniques fine-tune surface features to enhance performance characteristics like wear resistance and biocompatibility. Basinger et al. [5], underscore the progress in metal matrix composites and functionally graded materials, which are particularly suited for hybrid applications in aerospace, automotive, and biomedical engineering, where multifunctionality and precision are crucial.

Despite these technological strides, a lack of process standardization continues to hinder broader HM adoption. Ensuring consistent part quality, safety compliance, and repeatability requires the development of specialized testing protocols, certification standards, and material characterization methods. Pahlevannejad et al. [38], emphasized on the need for qualification frameworks tailored specifically to hybrid processes, particularly in regulated sectors such as aerospace and healthcare. Collaborative efforts between industry, academia, and regulatory bodies are essential for establishing these standards. Additionally, sustainability has become a driving force in HM research. Hybrid systems enable circular manufacturing practices by reducing material waste, facilitating part repair, and supporting recycling. Syed [41], advocated for embedding sustainability metrics into process planning and system design to position HM as a key enabler of environmentally responsible manufacturing.

Figure 4 presents the future roadmap of HM technologies, outlining key advancements such as autonomous systems, multifunctional materials, AI-driven optimization, and sustainable practices. This roadmap highlights emerging trends and research directions that are essential for enhancing the capabilities, scalability, and industrial adoption of HM in the era of Industry 4.0.

Figure 4: Future roadmap of HM technologies

From the figure, the roadmap begins with enhanced process integration and real-time monitoring, followed by the development of autonomous, adaptive systems that are capable of self-optimization. Future advancements include the use of multifunctional and smart materials, greater reliance on AI and machine learning for predictive maintenance and decision-making, and improved CAD/CAM systems for complex design execution. Standardization, certification protocols, and circular manufacturing principles are also highlighted as critical enablers. Collectively, these developments will drive the widespread adoption and scalability of HM.

10. Conclusion

HM represents a transformative convergence of subtractive and additive technologies; it offers unprecedented advantages in modern production systems. This article has examined the integration of these methods, and underscores their combined potential to enhance design flexibility, reduce material waste, and improve overall part quality. By fusing additive manufacturing’s capacity to create complex geometries with the high-precision finishing of subtractive techniques, hybrid systems will effectively mitigate the limitations of each approach when applied independently. As industries move towards more adaptive and efficient manufacturing models, HM emerges as a powerful enabler of innovation, capable of meeting the rigorous demands of customization, complexity, and speed.

In the broader context of Industry 4.0, HM aligns seamlessly with intelligent, interconnected production ecosystems. Integration with technologies such as digital twins, real-time monitoring, and AI-driven control systems facilitates adaptive, autonomous workflows that boost productivity and reduce operational disruptions. However, mainstream adoption still hinges on overcoming integration challenges, including thermal distortion, software compatibility, and the absence of universal quality standards. Addressing these gaps will require strategic investments in research, workforce training, and cross-disciplinary collaboration. As these barriers are gradually overcome, HM is poised to become a cornerstone of next-generation manufacturing, enabling scalable, sustainable, and precise production across a range of sectors.

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