

## ***Add–Sub Hybrid Manufacturing: Integration of Additive and Subtractive Processes for Advanced Manufacturing***

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### **ABSTRACT**

*This paper explores the synergistic integration of additive manufacturing (AM) and subtractive manufacturing (SM) within a single hybrid manufacturing (HM) system. By combining the geometric freedom of 3D printing with the precision of CNC machining, hybrid systems offer unprecedented advantages in terms of design flexibility, surface finish, and production efficiency. This review highlights the architecture, operational planning, toolpath optimization, and challenges of hybrid manufacturing systems. Additionally, the paper provides a roadmap for future directions, emphasizing applications in aerospace, biomedical, and automotive sectors.*

**KEYWORDS:** *Hybrid Manufacturing, Additive Manufacturing, Subtractive Manufacturing, 3D Printing, CNC Machining, Toolpath Optimization, Process Planning, Industry 4.0*

### **INTRODUCTION**

Additive–subtractive hybrid manufacturing combines the strengths of additive and subtractive methods to form an efficient and flexible system. Additive manufacturing allows layer-by-layer material deposition to create near-net shapes, while subtractive manufacturing delivers high dimensional accuracy and superior surface finish through cutting and milling processes.

Integrating these two methods reduces production time, minimizes material waste, and increases overall manufacturing capability. This paper provides a comprehensive analysis of

hybrid systems, focusing on the underlying architecture, toolpath strategies, and industrial relevance.

## **FUNDAMENTALS OF HYBRID MANUFACTURING**

Hybrid manufacturing represents the convergence of two distinct yet complementary production paradigms: additive manufacturing (AM) and subtractive manufacturing (SM). This fusion leverages the strengths of both approaches, enabling the creation of complex geometries while ensuring high dimensional accuracy and superior surface quality. In essence, hybrid manufacturing allows a part to be built up layer by layer using additive processes, and then refined using subtractive processes within the same setup. This seamless integration not only accelerates production cycles but also minimizes the need for extensive post-processing and manual intervention. Hybrid manufacturing systems can be classified into three major categories based on their operational strategy and dominance of process stages:

### **Additive-Dominant Systems**

In additive-dominant configurations, the manufacturing cycle is primarily initiated through additive processes. Components are fabricated using techniques such as Direct Energy Deposition (DED) or Selective Laser Melting (SLM), followed by subtractive machining for surface finishing, dimensional tuning, or support structure removal. These systems are particularly useful when building complex parts that require high geometric freedom during initial formation.

### **Subtractive-Dominant Systems**

In contrast, subtractive-dominant systems begin with conventional machining processes such as CNC milling or turning to shape a foundational substrate. Additive processes are then employed to build features or geometries that are difficult to machine conventionally. This approach is beneficial when pre-machined blanks or precise base geometries are required for load-bearing or assembly-critical components.

### **Fully Integrated Systems**

Fully integrated hybrid systems combine additive and subtractive operations in a tightly coupled or even simultaneous manner. This integration facilitates continuous feedback loops between the processes, enabling in-situ corrections and optimization. These systems demand

sophisticated process control, sensor fusion, and toolpath synchronization but offer the highest level of automation and part complexity.

**Table 1: Comparison between Additive, Subtractive, and Hybrid Manufacturing**

<b>Criteria</b>	<b>Additive Manufacturing</b>	<b>Subtractive Manufacturing</b>	<b>Hybrid Manufacturing</b>
Material Efficiency	High	Low	High
Surface Finish	Poor to Fair	Excellent	Excellent
Design Flexibility	High	Moderate	High
Tool Wear	Minimal	High	Balanced
Production Time	Long	Short	Optimized

This comparison illustrates how hybrid manufacturing integrates the complementary strengths of both AM and SM, delivering superior outcomes in precision, efficiency, and material utilization.

### **Integration Architecture and Machine Configurations**

The architecture of hybrid manufacturing systems is central to their operational efficiency and scalability. These systems integrate mechanical, software, and control components to execute complex additive-subtractive cycles with high accuracy and repeatability. Depending on the degree of integration, hybrid systems can be broadly categorized into three architectural models:

#### **Single-Platform Systems**

These systems feature a unified machine architecture in which both additive and subtractive tools are housed within the same platform. Tool heads are typically exchangeable and are automatically or manually swapped during the process. Single-platform systems offer compact footprints and real-time process coordination, making them suitable for industrial settings with spatial constraints.

### Modular Systems

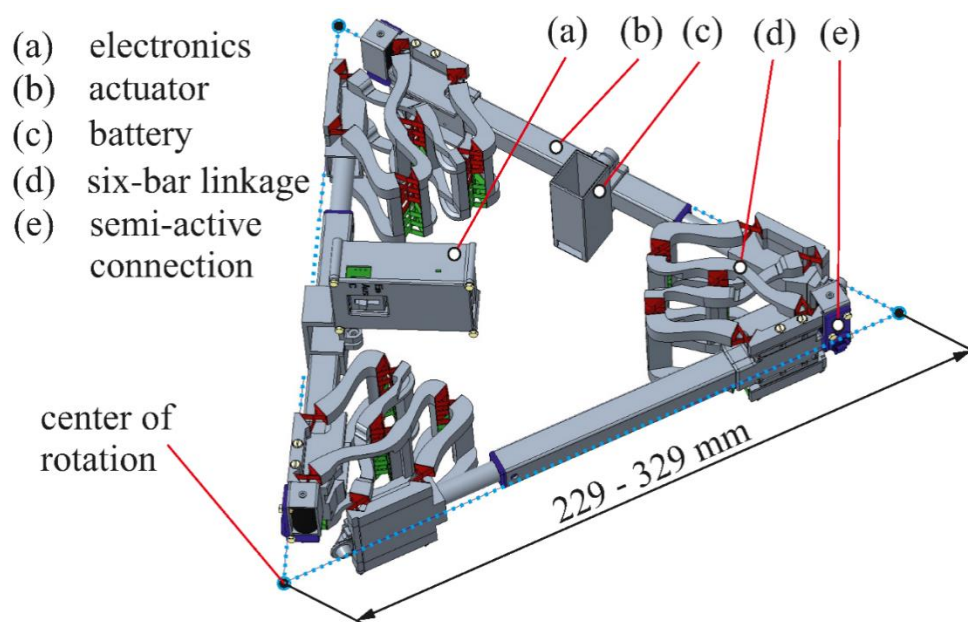
Modular architectures separate the additive and subtractive units but utilize a shared workspace or robotic platform. The workpiece is transferred between the modules using a linear rail, rotary platform, or robotic arm. While offering higher flexibility in tooling and scale, these systems require advanced calibration and synchronization to maintain part accuracy.

### Robot-Assisted Systems

These systems employ industrial robotic arms for part manipulation between standalone AM and SM units. Robot-assisted integration enhances adaptability, especially in large-scale or non-uniform geometries. They are ideal for aerospace and construction-scale hybrid applications where mobility and custom part orientations are essential.

### Process Planning and Control Strategies

Effective process planning in hybrid manufacturing is essential for ensuring seamless coordination between additive and subtractive operations. Given the complexities of multiple process dependencies, hybrid systems require dynamic scheduling and precise control over toolpaths, tool changes, material deposition rates, and geometric tolerances.



**Figure 1: Types of Hybrid Machine Configurations**

**Sequencing**

The core aspect of hybrid planning is determining the correct sequence of operations. This includes defining whether an additive step should precede a machining step or if an interleaved strategy is optimal. Sequencing depends on material behavior, required tolerances, and thermal effects.

**Collision Avoidance**

Toolpath planning must account for potential tool-part collisions, especially in additively manufactured parts with overhangs, internal cavities, or support structures. The use of simulation-based digital twins has become essential for visualizing and mitigating such risks before actual production.

**Inter-process Calibration**

The alignment between AM and SM stages is critical. Tool offsets, workpiece fixtures, and coordinate transformation matrices must be precisely defined and synchronized to maintain continuity across operations. Optical sensors and laser-based metrology are often employed for in-process calibration.

*Table 2: Process Planning Parameters in Hybrid Manufacturing*

<b>Planning Aspect</b>	<b>Description</b>
Layer Planning	Number and thickness of additive layers
Machining Strategy	Tool path type, direction, and tool selection
Support Structure Use	Necessary for AM; removed using SM
Heat Management	AM-induced heat mitigated by SM-based cooling
Accuracy Control	Precision of critical features ensured by SM

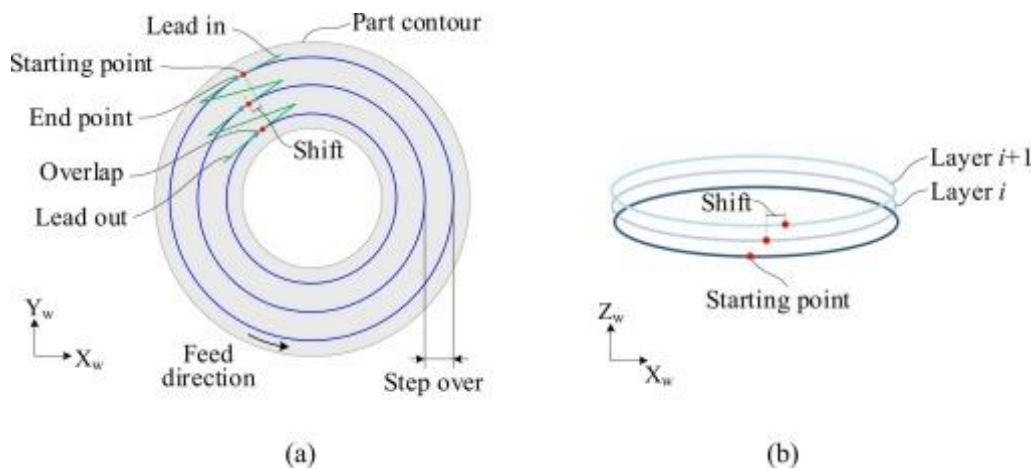
**Toolpath Generation and Optimization**

The generation and optimization of toolpaths in hybrid manufacturing is significantly more complex than in traditional systems due to the need for inter-process compatibility. Toolpaths must not only be efficient but also dynamically adaptive to the evolving geometry of the part.

In additive stages, layer-wise deposition paths are determined based on CAD models, material type, and build orientation. These paths are optimized for minimal retraction, heat distortion, and build time. In subtractive stages, contouring, drilling, and pocketing paths are generated with reference to the additively produced geometry.

Advanced hybrid toolpath strategies involve:

- Adaptive toolpath refinement based on real-time feedback
- Offset toolpath generation to compensate for AM-induced dimensional errors
- In-situ detection and adjustment of surface quality prior to SM operations



**Figure 2: Toolpath Strategy in Hybrid System**

### Material Considerations and Multi-Material Capabilities

Hybrid manufacturing unlocks new possibilities in material engineering by allowing the integration of diverse materials within a single manufacturing process. While additive techniques offer compositional and structural flexibility, subtractive processes ensure the final geometry conforms to design specifications with high fidelity.

### Metallic Alloys

Materials like titanium, stainless steel, nickel alloys, and aluminum are commonly used due to their favorable strength-to-weight ratio, corrosion resistance, and machinability. These alloys are essential in aerospace, medical implants, and high-precision tooling.

**Functionally Graded Materials (FGMs)**

FGMs are characterized by a gradual variation in composition or structure over volume, allowing for tailored mechanical or thermal properties. Hybrid manufacturing enables the localized deposition of varying materials and post-deposition machining to refine interfaces.

**Multi-material Builds**

Some hybrid systems support the simultaneous use of dissimilar materials such as ceramics, polymers, and metals. This opens new frontiers in biomimetic structures, smart materials, and customized prosthetics, although challenges remain in bonding strength and thermal compatibility.

*Table 3: Common Materials Used in Hybrid Manufacturing Systems*

<b>Material Type</b>	<b>Application Areas</b>	<b>AM Process Type</b>	<b>SM Process Type</b>
Titanium Alloys	Aerospace, Medical	DED, SLM	CNC Milling
Stainless Steel	Tooling, Automotive	LMD, FDM	Turning, Milling
Nickel Alloys	Turbine Components	DED	Grinding, Milling
Aluminum Alloys	Automotive, Robotics	WAAM, SLM	Drilling, Milling

This table illustrates the common material-process combinations used in hybrid systems, highlighting the diversity and adaptability of the technology.

**INDUSTRIAL APPLICATIONS**

The integration of additive and subtractive manufacturing has opened transformative possibilities across a range of industries by combining geometric versatility with surface precision and mechanical strength. Hybrid manufacturing is especially beneficial in sectors where product performance, customization, and quick turnaround times are critical.

### **Aerospace Sector**

The aerospace industry has been a pioneer in adopting hybrid manufacturing due to its demand for high-performance components with intricate geometries and minimal weight. Hybrid systems allow the creation of lightweight parts like turbine blades, engine mounts, and structural brackets with internal cooling channels or lattice reinforcements.

After additive deposition, CNC milling is used to ensure critical surfaces meet tight tolerances. This synergy reduces the number of parts required, leading to significant weight reduction and enhanced fuel efficiency.

### **Biomedical Sector**

Patient-specific implants and surgical instruments are increasingly being produced using hybrid systems. Additive manufacturing facilitates the creation of personalized structures tailored to a patient's anatomy, such as dental crowns, orthopedic implants, and prosthetics.

Subsequent subtractive machining ensures the biocompatible components achieve the necessary surface finish and precision fit. The ability to iterate designs quickly and produce one-off components economically is a unique advantage in this field.

### **Automotive Sector**

Hybrid manufacturing is being adopted in the automotive industry for both prototyping and the production of end-use components. Complex manifolds, heat exchangers, and engine parts can be rapidly produced with minimal material wastage.

AM is used for rapid form development, while SM enables the attainment of critical tolerances for performance validation. Additionally, hybrid systems are now playing a role in tooling and mold fabrication, reducing time-to-market and improving production agility.

## **BENEFITS AND LIMITATIONS**

Hybrid manufacturing presents a revolutionary step forward in production engineering, yet it also comes with its own set of constraints. A balanced understanding of its advantages and drawbacks is essential for its optimal deployment in industry.

**Benefits****1. Design Flexibility**

Hybrid systems offer an unprecedented degree of freedom in designing components with internal channels, overhangs, and complex geometries that would be impossible or inefficient using traditional methods alone.

**2. Improved Mechanical Properties**

By combining near-net shaping with precision machining, parts exhibit both structural integrity and surface quality, which improves fatigue life, wear resistance, and dimensional stability.

**3. Reduced Lead Time**

Additive processes reduce the need for tooling, while subtractive stages ensure immediate readiness for use. This integration significantly cuts down development and production cycles.

**Limitations****1. High Equipment Cost**

Hybrid machines, due to their dual functionality and automation needs, are expensive to acquire and maintain. This poses a barrier for small- and medium-scale enterprises.

**2. Complex Software Requirements**

Hybrid manufacturing demands specialized CAM software that can seamlessly generate toolpaths and coordinate additive-subtractive transitions. Integration with CAD systems also adds complexity.

**3. Post-processing Challenges**

Residual stresses from AM stages may still require heat treatment, and removing support structures from intricate geometries remains a manual or semi-automated task in many cases.

## RECENT ADVANCES AND RESEARCH DIRECTIONS

Ongoing research in hybrid manufacturing is aimed at enhancing efficiency, adaptability, and intelligence through emerging technologies. Several innovations are currently shaping the future of this field.

### AI-driven Toolpath Optimization

Machine learning algorithms are being incorporated to generate adaptive toolpaths based on part geometry, thermal history, and machine feedback. These intelligent algorithms reduce material usage, improve deposition uniformity, and prevent tool collisions in real-time.

### Real-time Process Monitoring

The integration of advanced sensors—such as thermal cameras, acoustic sensors, and laser profilometers—enables monitoring of deposition rates, surface roughness, and dimensional deviations during manufacturing. This real-time feedback helps reduce defects and supports closed-loop control systems.

### Digital Twin Integration

Digital twins create virtual replicas of physical hybrid systems, allowing manufacturers to simulate production processes, predict outcomes, and preemptively resolve issues. These virtual models are synchronized with real-time data to continuously improve production reliability.

## FUTURE DIRECTIONS

As the manufacturing industry moves toward automation and customization, hybrid manufacturing is poised to play a central role in the factories of the future. The following areas are expected to guide its evolution:

### Autonomous Hybrid Manufacturing Systems

Next-generation hybrid platforms are expected to integrate artificial intelligence, robotic material handling, and autonomous process decision-making. Such systems will be capable of dynamic tool changeovers, automatic defect correction, and unmanned operation.

### **Expansion into Large-Scale Construction Applications**

Hybrid technologies are being adapted for architectural applications such as bridge components, precast molds, and prefabricated housing structures. Scalable additive systems combined with robotic subtractive modules can revolutionize civil construction workflows.

### **Eco-Friendly Hybrid Processes with Recyclable Materials**

Sustainability will remain a driving force in manufacturing. Researchers are developing hybrid processes using recycled powders, bio-based polymers, and low-energy deposition techniques to minimize the environmental footprint of production.

### **Open-Source Hybrid Manufacturing Software Platforms**

To democratize hybrid manufacturing, the development of open-source CAM software and process planning tools is underway. These platforms aim to reduce entry barriers for innovators, startups, and educational institutions, thereby broadening the technology's adoption.

## **CONCLUSION**

Additive–subtractive hybrid manufacturing represents a powerful evolution in modern manufacturing systems. By fusing the strengths of 3D printing and CNC machining, this integrated approach addresses long-standing challenges in speed, precision, and functionality. While challenges remain in terms of cost and control complexity, ongoing innovations and interdisciplinary research continue to propel hybrid manufacturing toward widespread industrial adoption.

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