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Hybrid Subtractive Additive Machining Processes: A Review of Integrated Manufacturing Technologies

Arun Sriniwas[1], Manish Verma[2], Pooja Tiwari[3]
Associate Professor, Assistant Professor
Department of Production Engineering
Narmada Engineering College, Hoshangabad, India
***Email**: Arunsriniwas16@gmail.com[1], manish46v@yahoo.com[2],*
poojatiwari757@rediffmail.com[3]

Abstract

Manufacturing industries are continuously evolving to meet the demands of complex geometries, high precision, and reduced production time. Traditional manufacturing processes are mainly categorized into additive manufacturing (AM) and subtractive manufacturing (SM). Additive manufacturing builds components layer by layer, while subtractive manufacturing removes material from a solid workpiece using cutting tools. Each process has its own advantages and limitations. Hybrid manufacturing processes that combine additive and subtractive machining have emerged as an effective solution to overcome these limitations. Hybrid systems integrate the flexibility of additive manufacturing with the accuracy and surface quality of subtractive machining. This paper reviews the concept, technologies, advantages, challenges, and applications of hybrid subtractive-additive machining processes. Different hybrid manufacturing systems such as Directed Energy Deposition (DED) combined with CNC machining, Laser Metal Deposition with milling, and hybrid additive-subtractive machines are discussed. The review also highlights the role of digital technologies and Industry 4.0 in enabling these integrated processes. Although hybrid manufacturing has great potential, challenges such as process control, cost, and machine complexity still exist. Future developments in automation, artificial intelligence, and digital twin *technologies are expected to further enhance the capability of hybrid manufacturing systems.*

Keywords: *Hybrid Manufacturing, Additive Manufacturing, Subtractive Machining, CNC Machining, Directed Energy Deposition, Industry 4.0*

INTRODUCTION

Manufacturing technologies are playing a major role in modern industrial development. Industries such as aerospace, automotive, biomedical, and tooling sectors require high precision parts with complex geometry. Traditional machining methods like turning, milling, and drilling are categorized as subtractive manufacturing processes because they remove material from a workpiece to produce the desired shape. These processes provide high dimensional accuracy and good surface finish, but they often generate significant material waste and have limitations in producing highly complex shapes.

On the other hand, additive manufacturing techniques such as 3D printing, selective laser melting, and fused deposition modeling build components layer by layer. Additive processes are capable of producing highly complex and lightweight structures. However, these processes generally suffer from poor surface finish, lower dimensional accuracy, and slower production rate when compared to traditional machining methods.

To overcome the limitations of both methods, hybrid manufacturing processes have been developed. Hybrid manufacturing integrates additive and subtractive techniques within a single machine or production system. In such systems, material can be deposited using additive manufacturing and then finished using machining operations. This integration improves productivity, reduces material waste, and provides better dimensional accuracy.

Hybrid subtractive-additive machining processes have gained significant attention in recent years. These technologies allow manufacturers to build complex structures and simultaneously refine them using precision machining operations. This paper presents a comprehensive review of hybrid manufacturing processes, their technologies, advantages, challenges, and industrial applications.

CONCEPT OF HYBRID MANUFACTURING

Hybrid manufacturing is a modern production concept in which **two or more manufacturing processes are integrated into a single system or machine platform**. The most common combination involves **additive manufacturing (AM)** and **subtractive machining (SM)** working together to produce a final component. This integration aims to combine the strengths of both processes so that the limitations of each method can be minimized.

In conventional manufacturing systems, additive and subtractive processes are usually performed separately. For example, a component might be first produced using a 3D printing machine and later transferred to a CNC machine for finishing operations. This separation often increases production time, alignment errors, and handling cost. Hybrid manufacturing solves this problem by integrating both processes into one coordinated system where **material deposition and machining can occur in sequence without removing the workpiece from the machine**.

The additive manufacturing process in hybrid systems is generally used to build the **initial or near-net-shape structure of a component**. Near-net-shape means that the part is manufactured close to its final geometry but still requires minor finishing operations. Additive manufacturing techniques such as **laser metal deposition, directed energy deposition, and powder bed fusion** are commonly used for this purpose. These processes deposit material layer by layer, allowing engineers to fabricate complex shapes that would be very difficult or impossible to produce using conventional machining.

After the required layers are deposited, subtractive machining operations are performed to refine the geometry of the part. These machining operations typically include **milling, turning, drilling, or grinding** performed by CNC machine tools. The machining stage removes small amounts of material to achieve the required dimensional accuracy, surface finish, and geometric tolerances. In many hybrid systems, machining can be carried out after every few additive layers, ensuring that the final part maintains high precision throughout the manufacturing process.

One of the key features of hybrid manufacturing is the **sequential interaction between additive and subtractive processes**. Instead of performing all additive steps first and machining later, the system may alternate between deposition and machining stages multiple times during production. This step-by-step approach helps maintain dimensional control, reduce residual stresses, and improve overall product quality.

Hybrid manufacturing systems are usually equipped with **advanced computer control and automation technologies**. The integration of computer-aided design (CAD), computer-aided manufacturing (CAM), and process monitoring systems allows engineers to plan the entire manufacturing process digitally. The machine can automatically switch between additive deposition heads and cutting tools depending on the stage of production. Sensors may also be used to monitor temperature, layer thickness, and tool conditions to ensure consistent manufacturing quality.

Another important concept in hybrid manufacturing is **process efficiency and material utilization**. Traditional subtractive machining often removes a large amount of material from a solid block, which leads to significant waste. In contrast, additive manufacturing builds material only where it is required. When these two processes are combined, the component can be produced with minimal material waste while still maintaining high accuracy and surface quality.

Hybrid manufacturing also supports the production of **multi-material components and complex internal structures**. For example, additive manufacturing can be used to build internal lattice structures or conformal cooling channels inside molds, while machining operations finish the external surfaces. This capability is particularly valuable in industries such as aerospace, biomedical engineering, and tooling where complex and lightweight structures are required.

In addition, hybrid manufacturing plays an important role in **repair and remanufacturing applications**. Instead of replacing damaged components completely, additive processes can deposit new material on worn or damaged regions. After deposition, machining operations restore the part to its original dimensions and surface quality. This approach reduces material consumption and lowers maintenance cost for expensive components.

Despite these advantages, the implementation of hybrid manufacturing systems requires careful design and process planning. Engineers must consider factors such as material compatibility, thermal effects, deposition accuracy, and tool path optimization. Proper synchronization between additive and subtractive stages is essential to avoid defects such as distortion, porosity, or poor bonding between layers.

Overall, the concept of hybrid manufacturing focuses on **combining material addition and material removal processes in a coordinated manner to produce high-quality components efficiently**. By integrating additive flexibility with machining precision, hybrid manufacturing systems provide a powerful solution for producing complex and high-performance products in modern industries.

TYPES OF HYBRID ADDITIVE–SUBTRACTIVE MANUFACTURING PROCESSES

Hybrid manufacturing systems can be developed in different ways depending on the type of additive process and the machining technique integrated with it. Among various hybrid techniques, **Directed Energy Deposition (DED) combined with CNC machining** is one of the most commonly used methods in industrial manufacturing. This approach allows material to be deposited layer by layer and then machined within the same setup to achieve precise geometry and good surface quality.

1. Directed Energy Deposition with CNC Machining

Directed Energy Deposition (DED) is an advanced additive manufacturing process in which **metal powder or metal wire is melted using a focused energy source such as a laser, electron beam, or plasma arc**. The molten material is deposited onto a substrate surface and solidifies rapidly, forming a new layer of metal. By continuously feeding powder or wire and moving the deposition head according to programmed tool paths, the system builds the component layer by layer.

In hybrid manufacturing systems, the DED process is integrated with **CNC machining operations such as milling or turning**. The additive stage is first used to deposit a number of layers and create the rough geometry of the part. Once a certain height or structure is achieved, the system switches to machining mode where cutting tools remove small amounts of material to refine the shape, improve dimensional accuracy, and produce smoother surfaces.

One of the important advantages of combining DED with CNC machining is the ability to produce **near-net-shape components**. Instead of machining the entire component from a solid block, the additive process builds the majority of the structure with minimal material waste. Machining operations are then applied only where precision and surface finish are critical. This approach reduces material consumption and manufacturing time.

DED-based hybrid systems are particularly suitable for **metal manufacturing**. Materials such as stainless steel, titanium alloys, nickel-based superalloys, and aluminum alloys can be deposited using the DED process. These materials are widely used in aerospace, energy, and heavy engineering industries. Because DED can deposit material directly onto existing components, it is also very effective for repair and remanufacturing applications.

Another important feature of DED hybrid systems is the **flexibility in deposition direction and geometry**. Unlike some additive processes that require powder beds or fixed build chambers, DED systems can deposit material on complex surfaces and curved structures. When combined with multi-axis CNC machines, the system can create highly complex three-dimensional shapes.

The hybrid DED–CNC process usually involves several stages during manufacturing. Initially, the base component or substrate is fixed on the machine platform. The DED system then deposits layers of molten metal according to the programmed tool path. After the deposition of a certain number of layers, the machine automatically switches to CNC machining mode. Cutting tools then remove excess material, ensuring that the part maintains correct dimensions and surface finish. This cycle of **deposition and machining may be repeated multiple times** until the final geometry is achieved.

Another benefit of this hybrid process is **improved bonding and structural integrity**. Since the deposited material is melted and fused directly with the substrate, strong metallurgical bonding occurs between layers. Machining between deposition stages helps remove irregularities and ensures better alignment of subsequent layers. This improves the overall quality and mechanical properties of the component.

DED combined with CNC machining is widely used in **repair and refurbishment of high-value industrial components**. For example, damaged turbine blades, molds, dies, and heavy machine parts can be restored by depositing new metal onto worn surfaces. After deposition, CNC machining is used to reshape the repaired area and bring it back to the required specifications. This approach saves cost and extends the service life of expensive components.

In addition to repair applications, DED hybrid manufacturing is also used for **producing new complex metal structures**. Components with internal channels, variable thickness, or customized shapes can be fabricated efficiently using this process. Industries such as aerospace and defense utilize this technology for producing lightweight structural parts and engine components.

Despite its advantages, the DED–CNC hybrid process also presents certain challenges. Maintaining stable deposition conditions, controlling heat input, and managing residual stresses are important issues during manufacturing. If the heat generated during deposition is not properly controlled, it may cause distortion or defects in the final component. Therefore, advanced process monitoring systems and precise control strategies are required.

Overall, Directed Energy Deposition combined with CNC machining represents an important hybrid manufacturing technology. It combines the **material efficiency and design flexibility of additive manufacturing with the precision and surface quality of traditional machining**, making it suitable for a wide range of industrial applications. As research in hybrid manufacturing continues to grow, improvements in machine design, process control, and automation are expected to further enhance the capabilities of DED-based hybrid systems.

2. Laser Metal Deposition with Milling

Laser Metal Deposition (LMD) is another hybrid manufacturing technology where metal powder is melted by a laser beam and deposited layer by layer. Milling operations are then performed intermittently during the manufacturing process to achieve precise geometry

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This method reduces the need for extensive finishing operations and ensures better dimensional accuracy.

3. Hybrid Powder Bed Fusion and Machining

Powder Bed Fusion (PBF) processes such as selective laser melting can also be combined with machining operations. In this hybrid approach, the additive process builds a few layers of material and then machining operations are used to finish specific surfaces before continuing the deposition. This approach is useful when high precision internal structures are required.

HYBRID MACHINE TOOLS

Hybrid machine tools are advanced manufacturing systems designed to **integrate additive manufacturing processes and subtractive machining operations within a single machine platform**. These machines allow material to be deposited and machined without removing the workpiece from the setup. Because of this integration, hybrid machine tools are able to produce highly complex parts with good dimensional accuracy, better surface finish, and reduced production time.

Traditional manufacturing usually requires multiple machines for different operations. For example, a component might first be produced using a 3D printing system and then transferred to a CNC milling machine for finishing. This multi-step process can lead to alignment errors, longer production time, and higher labor cost. Hybrid machine tools overcome this limitation by **combining both manufacturing processes into one coordinated system**, which improves efficiency and accuracy.

In a typical hybrid manufacturing machine, the additive manufacturing unit deposits material layer by layer while the subtractive unit performs machining operations such as milling or turning. The machine control system coordinates these processes and switches automatically between deposition and machining stages depending on the production program.

Hybrid machines are widely used in industries where **high precision, complex geometries, and material efficiency** are important. Aerospace, automotive, biomedical, and tooling industries are some of the sectors where hybrid machine tools are increasingly applied.

1. Laser or Electron Beam Deposition System

One of the most important components of hybrid machine tools is the **deposition system**, which is responsible for additive manufacturing. In many hybrid systems, a high-energy source such as a laser beam or electron beam is used to melt metallic powder or wire feed material.

The energy beam creates a small molten pool on the substrate surface. As the feed material is supplied into this molten pool, it solidifies rapidly and forms a new layer of metal. By controlling the movement of the deposition head, complex three-dimensional structures can be built gradually.

Laser-based deposition systems are widely used because they offer precise control of energy input and high deposition accuracy. Electron beam systems are also used in some applications, especially where high energy density and deep penetration are required.

2. CNC Milling or Turning Module

Another essential part of hybrid machine tools is the **CNC machining module**. This module performs subtractive operations such as milling, drilling, turning, or grinding. After several layers of material are deposited through the additive process, machining operations are carried out to refine the shape and improve surface quality.

CNC machining ensures that the final component meets strict dimensional tolerances and surface finish requirements. In many hybrid systems, multi-axis CNC machines are used so that complex geometries can be machined from different orientations. The integration of machining operations also helps remove irregularities created during additive deposition.

3. Powder or Wire Feeding System

The **material feeding system** is another important component in hybrid machine tools. In additive manufacturing, raw material is supplied either in the form of metal powder or metal wire. The feeding system controls the flow of this material into the deposition zone.

Powder feeding systems use controlled nozzles to deliver metal powder directly into the laser or electron beam. Wire feeding systems, on the other hand, continuously feed a metal wire into the molten pool. Each method has its own advantages. Powder feed systems provide better control for fine structures, while wire feed systems generally have higher material efficiency and lower waste. The feeding system must maintain a consistent flow of material to ensure stable deposition and uniform layer formation.

4. Control Software for Process Integration

Hybrid manufacturing machines rely heavily on **advanced control software** to coordinate additive and subtractive operations. The control system integrates computer-aided design (CAD) and computer-aided manufacturing (CAM) data to generate tool paths for both deposition and machining processes.

The software manages parameters such as deposition speed, laser power, feed rate, cutting speed, and tool movement. It also controls the switching between additive and subtractive modes during production. Modern hybrid machines use intelligent control algorithms that optimize manufacturing parameters in real time.

In many cases, simulation tools are used before the actual manufacturing process begins. These simulations help engineers predict potential problems such as thermal distortion, tool interference, or material defects.

5. Sensors for Monitoring Deposition Quality

Sensors and monitoring systems are increasingly used in hybrid machine tools to ensure consistent manufacturing quality. These sensors monitor various process parameters during both additive and subtractive stages.

For example, temperature sensors can measure the heat distribution during deposition, while optical sensors may monitor the shape and size of the molten pool. Vibration sensors and force sensors can also be used during machining operations to detect tool wear or abnormal cutting conditions.

Table 1: Comparison of Additive, Subtractive, and Hybrid Manufacturing

Parameter	**Additive Manufacturing**	**Subtractive Manufacturing**	**Hybrid Manufacturing**
Material Usage	Efficient	High material waste	Moderate waste
Surface Finish	Moderate to poor	Excellent	Good
Design Complexity	Very high	Limited	Very high
Accuracy	Moderate	High	High
Production Speed	Slow	Fast	Moderate

ADVANTAGES OF HYBRID MANUFACTURING

Hybrid subtractive-additive manufacturing offers several advantages over traditional manufacturing techniques.

1. Improved Surface Quality

Additive manufacturing often produces rough surfaces due to layer-by-layer deposition. Machining operations in hybrid systems improve the surface finish and dimensional accuracy.

2. Reduced Material Waste

Subtractive machining generates large amount of material waste. Hybrid manufacturing reduces waste by using additive processes to build near-net shapes before machining.

3. Complex Geometry Manufacturing

Hybrid processes allow the production of complex geometries that are difficult to achieve using traditional machining methods.

4. Repair and Remanufacturing

Hybrid manufacturing is widely used for repairing high-value components such as turbine blades and molds. Additive deposition rebuilds the damaged area, while machining restores the final geometry.

APPLICATIONS OF HYBRID MANUFACTURING

1. Aerospace Industry

Hybrid manufacturing is extensively used in aerospace sector for producing lightweight and complex components. Turbine blades, engine components, and structural parts can be produced with improved efficiency.

2. Automotive Industry

Automotive manufacturers use hybrid manufacturing for rapid prototyping, tooling production, and manufacturing lightweight vehicle components.

3. Medical and Biomedical Engineering

Hybrid manufacturing enables the production of customized implants and prosthetics with high precision. The combination of additive and subtractive processes ensures accurate geometry and better surface finish.

4. Tool and Die Industry

Hybrid manufacturing is also useful in tool and die industry for producing molds and dies with complex cooling channels.

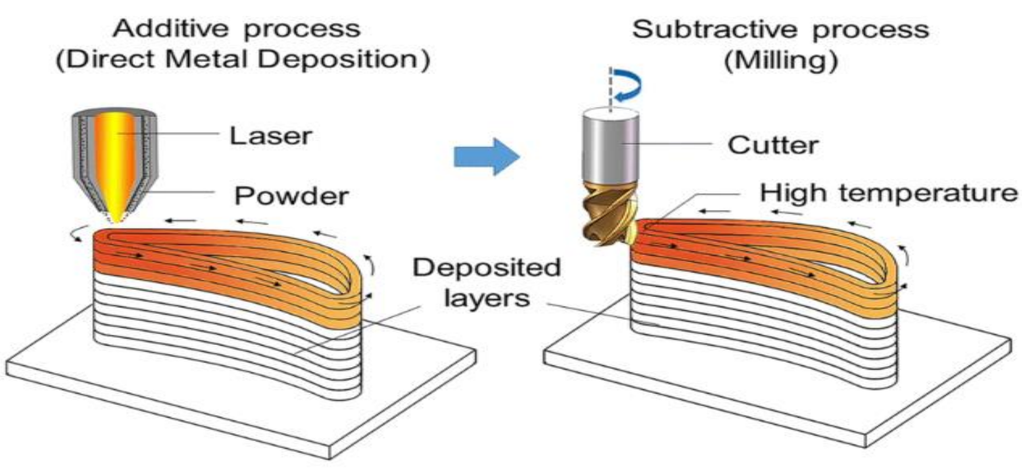

Figure 1: Basic Concept of Hybrid Additive-Subtractive Manufacturing

CHALLENGES IN HYBRID MANUFACTURING

Despite many advantages, hybrid manufacturing still faces several challenges.

1. High Equipment Cost

Hybrid manufacturing machines are expensive because they combine multiple manufacturing technologies in a single system.

2. Process Control Complexity

Maintaining process stability during switching between additive and subtractive operations can be difficult.

3. Material Compatibility

Not all materials are suitable for hybrid manufacturing processes. Material properties must be carefully considered during process design.

4. Lack of Skilled Workforce

Operating hybrid manufacturing systems requires skilled engineers and technicians with knowledge of both additive and subtractive technologies.

FUTURE TRENDS IN HYBRID MANUFACTURING

The future of hybrid manufacturing looks promising due to advances in digital technologies and automation. Integration with Industry 4.0 concepts such as digital twins, artificial intelligence, and real-time monitoring will further enhance the efficiency of hybrid systems.

Artificial intelligence can be used to optimize tool paths, deposition parameters, and machining operations. Digital twin technology allows virtual simulation of hybrid manufacturing processes before actual production.

Another emerging trend is the development of multi-axis hybrid machine tools that can perform complex operations in a single setup. These machines will reduce production time and increase manufacturing flexibility.

CONCLUSION

Hybrid subtractive-additive machining processes represent an important advancement in modern manufacturing technology. By integrating additive manufacturing with traditional machining operations, hybrid systems provide the advantages of both methods. These technologies allow the production of complex geometries with high precision and improved surface quality. Hybrid manufacturing also reduces material waste and enables repair and remanufacturing of high-value components.

However, challenges such as high equipment cost, process complexity, and skill requirements still limit the widespread adoption of hybrid manufacturing systems. Continued research in process optimization, automation, and digital manufacturing technologies will help overcome these limitations. In the future, hybrid manufacturing is expected to play a major role in aerospace, automotive, biomedical, and tooling industries.

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