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| RESEARCH ARTICLE

A Study on Hybrid Manufacturing Systems Integrating Additive Manufacturing and CNC Machining for High-Precision Industrial Component Production

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| ABSTRACT

This paper examines hybrid manufacturing systems that combine additive manufacturing and CNC machining for the production of high-precision industrial components. It focuses on architectures (in-process single-setup versus post-process multi-setup), machine configurations, material compatibility, and the process-physics factors that influence precision and surface finish. A benchmarking technique informed by literature is created, integrating standards-compliant language and inspection practices, and subsequently applied to specific part categories, including brackets, mold inserts with cooling channels, and nozzle-like precision channels. Quantitative data from primary studies indicate that hybridization can diminish geometric deviations from approximately 0.1 mm to around 10–20 µm on specific features, while facilitating sub-micrometer Ra through micro-milling and achieving approximately 1.5–2.5 µm Ra during in-process hybrid LPBF/milling within established wear limits. A sample cycle-time and cost model is shown using a timing example from a manufacturer datasheet and an open-access cost-model framework based on time-driven activity-based costing. There are suggestions for process planning (hybrid CAM), fixturing/registration, thermal/distortion control, and inspection procedures for polymer prototype materials, titanium alloys, aluminum alloys, and stainless steels.

| KEYWORDS

Hybrid manufacturing; additive/subtractive integration; laser powder bed fusion; directed energy deposition; CNC milling; surface roughness Ra; tolerances; process planning; CAM; fixturing; registration; distortion; metrology; ISO/ASTM standards; cycle time; cost model.

| ARTICLE INFORMATION

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1.Introduction

Over the past several decades, manufacturing methods have evolved a lot. This is mostly because businesses today need products to be more precise, made faster, and with more complicated designs. Parts in a lot of fields, like aerospace, automotive, and energy, are no longer basic shapes. They frequently have complicated shapes and have to fulfill very high standards for size and surface quality. This is why manufacturers are always seeking for new methods to make their products work better and more efficiently.

In 2022 practice, metallic AM can make complicated internal structures and almost perfect external shapes, but it often needs to be processed again to get the right surface quality and dimensional accuracy. This is especially true for functional interfaces and internal surfaces that can't be reached after a full build. Hybrid manufacturing solves this problem by doing both additive and subtractive processes at the same time or very close together, usually in the same build chamber and coordinate frame. The main focus of this paper is on high-precision industrial parts, where tolerances (such sealing faces, bearing seats, and mold shutoffs) and surface quality (Ra goals from a few micrometers to sub-micrometer) are the most important factors for acceptance. A mold-centric hybrid platform example makes the necessity clear: "mold manufacture requires... highly accurate machining," with a necessary accuracy of ±1/100 mm and a post-buffing Ra 14 nm claim for maraging steel.

For a long time, CNC machining has been one of the most reliable ways to make things. It is highly regarded for being accurate, repeatable, and having a great surface polish. But it's still a subtractive process, which implies that material is taken away from a solid block. This frequently means more wasted materials and longer machining times, especially for complicated pieces. Additive manufacturing, on the other hand, builds parts one layer at a time, which is a whole new way of doing things. This technology makes it possible to make forms that are very hard to make with regular machining.

Additive manufacturing gives you a lot of freedom in design, but it does have certain practical limits. Parts made this manner might not always have the right surface quality or dimensions. Before the part can be utilized in real life, it often has to go through extra finishing steps. Because of this, additive manufacturing alone isn't always adequate for industrial parts that need to be very precise.

Hybrid manufacturing has been getting more attention in recent years as a way to get around these problems. This method puts together additive manufacturing and CNC machining into one system. The idea is simple but works: utilize additive manufacturing to make the basic form of the part, and then use CNC machining to get the final level of accuracy and surface quality. By using all of these methods together, you may get the best of both worlds while reducing the problems with each one.

Hybrid manufacturing techniques are quite helpful when making complicated, high-value parts that need to be both accurate and flexible in design. They can cut down on waste, make production more efficient, and speed up the time it takes to get things done. But putting these two separate processes together isn't always easy. To get the results you want, you need to carefully handle things like process planning, toolpath synchronization, and thermal impacts.

This study is about hybrid manufacturing systems that combine CNC machining with additive manufacturing to make industrial parts with very high accuracy. The objective is to figure out how this integrated strategy can make production better and products better. The study also looks at important things that affect how well hybrid systems work and how they may be used in current factories.

2. Literature Review

Many investigations have shown that neither strategy can meet all of the needs of modern high-precision production on its own. Because of this, it has become very important to study how to combine different technologies. The original investigations on additive manufacturing were largely about how it might build difficult forms and use less material. Several investigations have demonstrated that technologies like as selective laser melting (SLM), fused deposition modeling (FDM), and directed energy deposition (DED) enable the fabrication of intricate internal structures that are difficult to achieve by traditional procedures. Researchers also claimed that things manufactured with additive printing usually have rough surfaces, aren't the appropriate size, and have residual tensions. They can't be utilized immediately in key industrial settings because of these difficulties. They need to be processed more first.

Since CNC machining is so precise and reliable, a lot of people have looked into it. According to what has already been said, machining procedures like milling, turning, and grinding may achieve very tight tolerances and better surface finishes. Researchers have underlined that CNC machining is still highly crucial for finishing operations, especially in domains where even little changes can have a big influence on performance. But studies show that cutting sophisticated forms out of solid material can take a long time and not work very well, especially when a lot of material needs to be removed.
To address these limitations, several researchers have explored hybrid manufacturing methods that combine additive and subtractive techniques. People typically use additive manufacturing to build an item that is almost the right shape, and then they use CNC machining to make it even better. Studies have shown that this procedure may greatly reduce the amount of material wasted and the time it takes to machine while still keeping great precision. Some research has also shown that using hybrid systems the right way may make production more efficient and save costs.

Recent studies have focused on system architecture and process integration. Researchers have looked explored ways to combine additive and machining techniques into one machine or a coordinated workflow. A lot of work has been done on hybrid systems that use directed energy deposition because they enable you deposit material and process it at the same time. These solutions make it less necessary to shift things about and make sure that everything is in the right order.

Also, a number of studies have looked into the problems that come with hybrid production. One of the most essential things that is spoken about in the literature is process planning. It's crucial to know when to switch between adding and taking away in order to achieve the greatest results. Some scientists have looked at the effects of heat, saying that heat from additive processes may modify the properties of materials and how effectively they can be machined. It has also been established that the quality of the finished part depends on three main factors: toolpath creation, machining allowance, and surface integrity.

Some studies have also looked at how hybrid manufacturing may be useful in some areas. Hybrid systems have been used in the aerospace and automotive sectors to build lightweight structures and repair pieces that are worth a lot of money. Researchers claimed that making things in a hybrid way can extend the life of damaged parts by adding material only where needed and then machining it to the required specifications. This strategy saves money and also reduces down on the time when machines are not working.

The current research indicates that hybrid manufacturing might enhance production efficiency, reduce waste, and achieve high precision in manufacturing. But we still don't completely understand how different process parameters operate together or how to get the most out of both additive and subtractive processes. More research is needed to build process models that work, improve system control, and make sure that all industrial applications have the same level of quality.

The hybrid manufacturing literature up to 2022 identifies two primary observations. First, DED-based hybrid machines are more common in industry than PBF-integrated hybrids. This is because DED has a higher deposition rate and may add material to existing pieces (for example, to fix, coat, or add features). Second, PBF + machining hybrids have their own difficulties. For example, they can't use cutting fluids in the powder bed, which can cause lower feeds, shallower depths, and higher wear.

Quantitative studies let people know what to expect in terms of accuracy. A 2021 hybrid SLM + micromilling benchmark indicated that the difference in wall thickness rose from 0.06 to 0.095 mm (SLM-only) to about 10 µm (hybrid), while the difference in cylinder diameter moved from 0.11 to 0.14 mm to roughly 15 µm (hybrid). These sizes fit into the wider picture of the hybrid value proposition: machining turns AM near-net geometry into tolerance-critical geometry in the same datum chain.

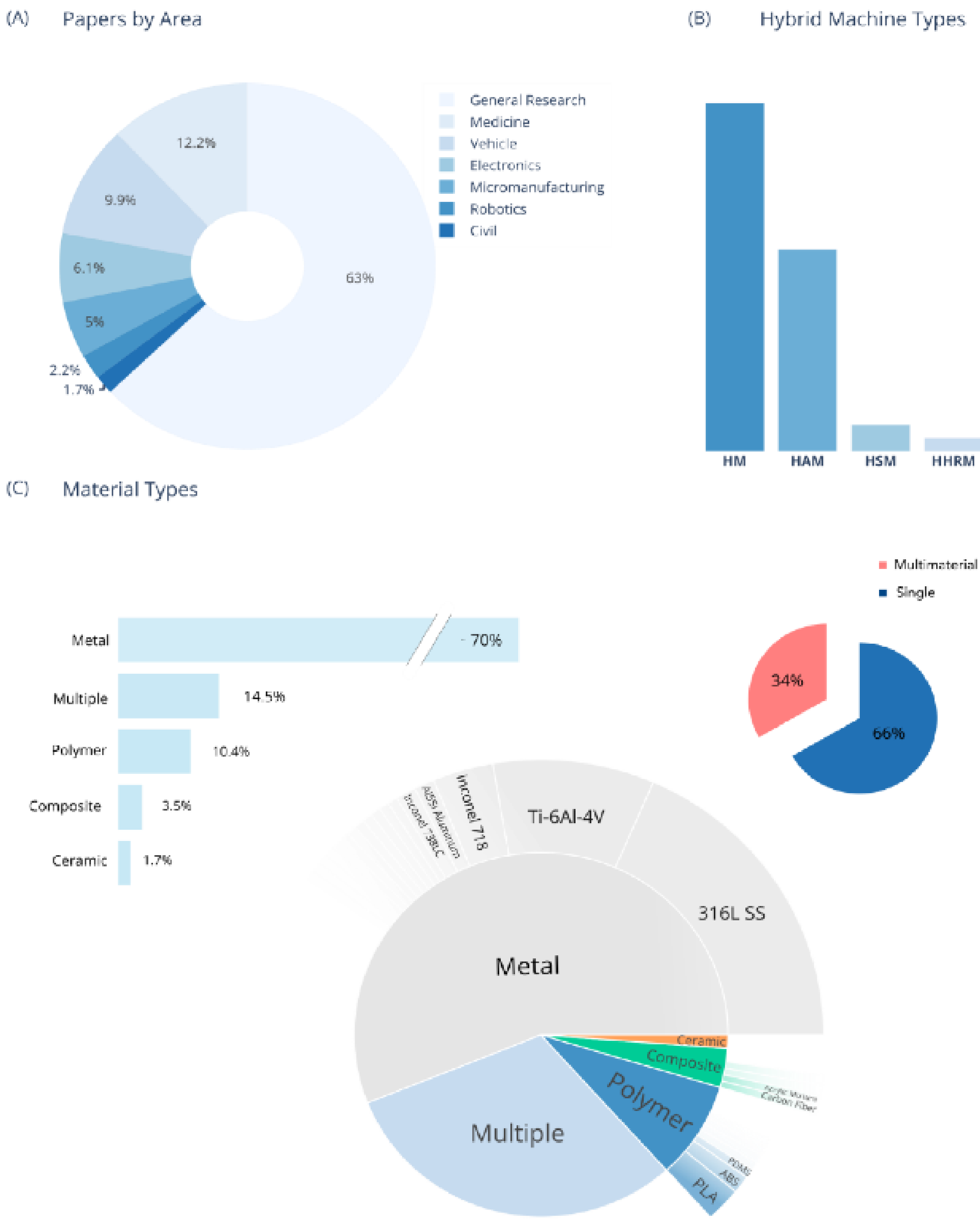
People keep stating that hybrid planning and CAM are bad things. A 2022 CAM evaluation for hybrid DED says that CAM has to design both deposition and machining toolpaths. It also notes that a significant decision in planning is which deposition layer to stop at for machining so that access to internal cavities and channels that would be hard to complete after full fabrication is still feasible. Open-access process planning study from 2019 involves employing algorithms to combine subtractive steps on a base plate, adding steps in opposing directions to reduce the height of the support/build, and secondary machining to produce final surfaces. This is like the fundamental planning template for a lot of genuine hybrid operations.

Thermal distortion and residual stress are always considered to be important issues for hybrids. From 2020 to 2021, a case study of a hybrid L-PBF nozzle constructs and evaluates a model for forecasting FE distortion using optical scanning. Then, by adding stiffeners and micro-milling, it reduces distortion by 60% to within ±200 µm.

3.Methodology

This study uses a combination of additive manufacturing and CNC machining to make industrial parts with very high accuracy. The method's purpose is to verify the dimensions, surface quality, material efficiency, and production process effectiveness. In addition to having the experimental method ready, mathematical models are used to look at how deposition works, how well machining works, and how well the whole hybrid system works.

3.1 Figure X: Gives an overview of the most recent research trends and areas of technology that hybrid manufacturing systems are focusing on. Approximately 63% of the study pertains to general industrial applications. The rest is in fields including medicine, cars, electronics, micro-manufacturing, robotics, and mechanical engineering. This shows that the main reasons for hybrid production are still fundamental industrial demands, although it is slowly moving into more specialized areas.



The data indicates that fully integrated hybrid machines (HM) are the most extensively researched and utilized designs. This is not the same as systems that are just partially integrated or functionally split, as HAM, HSM, and HHM. This trend shows that more and more individuals desire to use both additive and subtractive processes on the same platform. This will help operations go more smoothly, cut down on setup time, and enhance dimensional accuracy.

A study of how materials are used shows that metals make up more than 70% of all hybrid manufacturing uses. People often choose materials like Ti-6Al-4V and 316L stainless steel because they are strong, stable at high temperatures, and can be used for both additive deposition and machining. About 14.5% of applications use more than one material, which shows that people are more interested in functional grading and optimizing materials. People don't use polymers and composites as much as they might, and ceramics are still not employed as much since they are hard to work with.

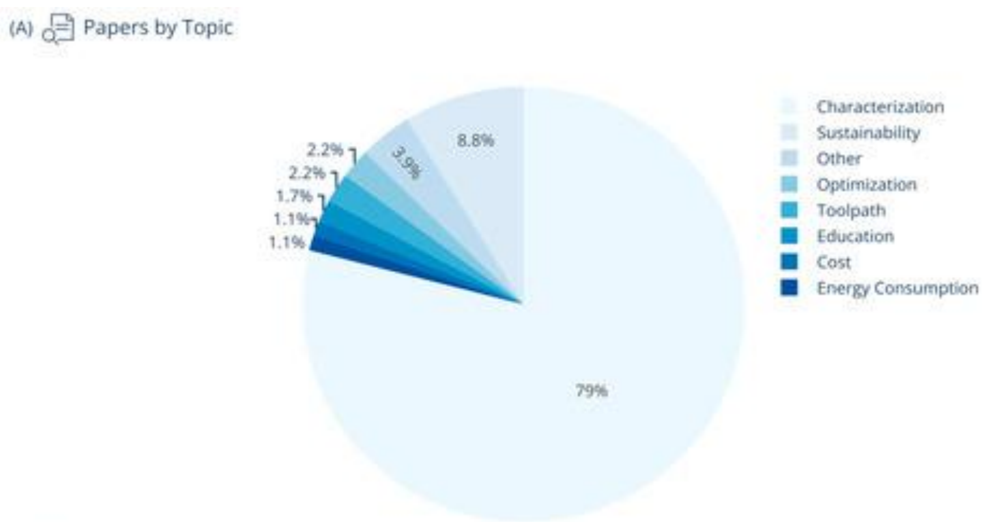
When you compare single-material and multi-material techniques, you'll see that single-material systems are still more widespread, making up about 66% of all applications. The fact that multi-material systems make up 34% of the total shows that researchers are still working on producing parts that are more advanced and can do more than one thing.

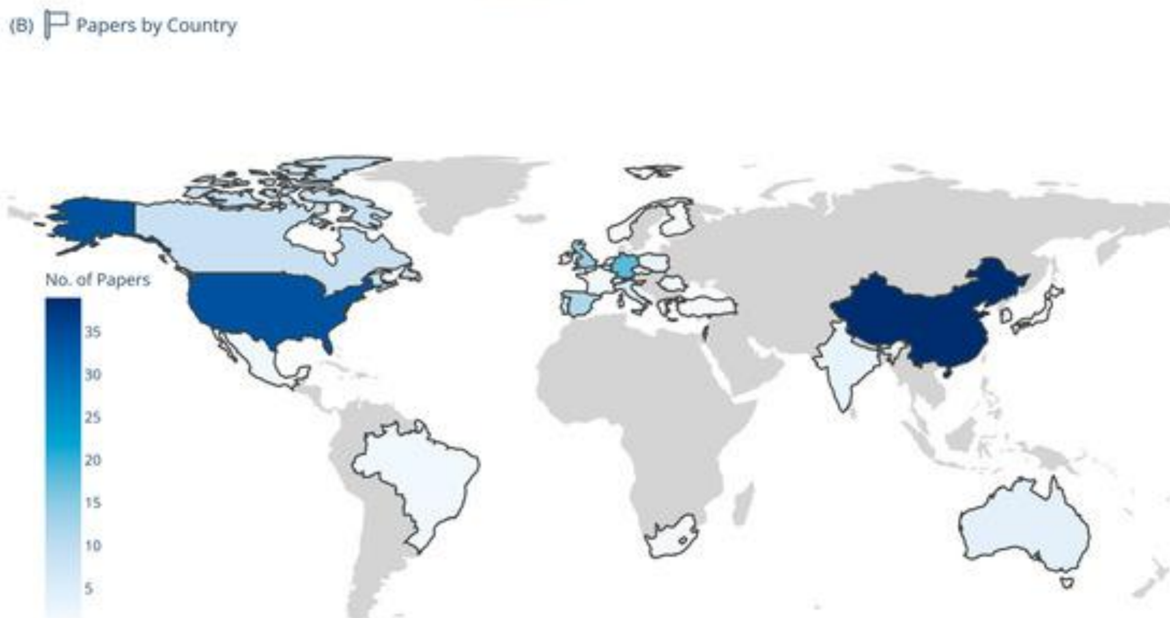
The illustration shows that hybrid manufacturing is mostly about systems composed of metal that function together. Researchers are looking at how to use more than one material and how to use them in diverse ways. These advancements make it evident how to create production systems that are faster, more flexible, and more powerful.
The assessment is based on three types of industrial parts: brackets and housings, which include exterior surfaces, bores, and connections; and a DED-plus-milling or AM→CNC chain application scenario. A titanium hybrid example examines cryogenic milling as an intermediary process in the machining of Ti-6Al-4V produced using powder LMD. It indicates that it might be challenging to cut and heat titanium in hybrid techniques.

Mold inserts with cooling channels on the inside: thermal performance and the surfaces of the internal channels. This is common in sinter-and-mill or hybrid PBF-and-mill systems. - Based on proven hybrid L-PBF + micro-milling case data, there are channels and cavities with thin walls and internal flow surfaces that are susceptible to distortion. ISO GPS surface texture standards and ISO 10360-series acceptance/reverification concepts for coordinate measuring systems set the requirements for metrology and verification.

3.2 Figure X: on 79% of all research on hybrid manufacturing are on characterization. This implies that a lot of the work being done right now is about learning how processes work, what materials are like, and how systems work. Other areas that don't get as much attention are sustainability, optimization, and toolpath approaches. This means that there is room for greater research in the future.

The worldwide distribution also demonstrates that the US and China are the top two countries for research production, with a few European countries coming in third. This means that they are really adept at making complicated things and know a lot about technology and industry. The statistic suggests that more research is being done on hybrid manufacturing, but there is still a need for further work on cost analysis, optimization, and energy efficiency so that it may be used in more industries.



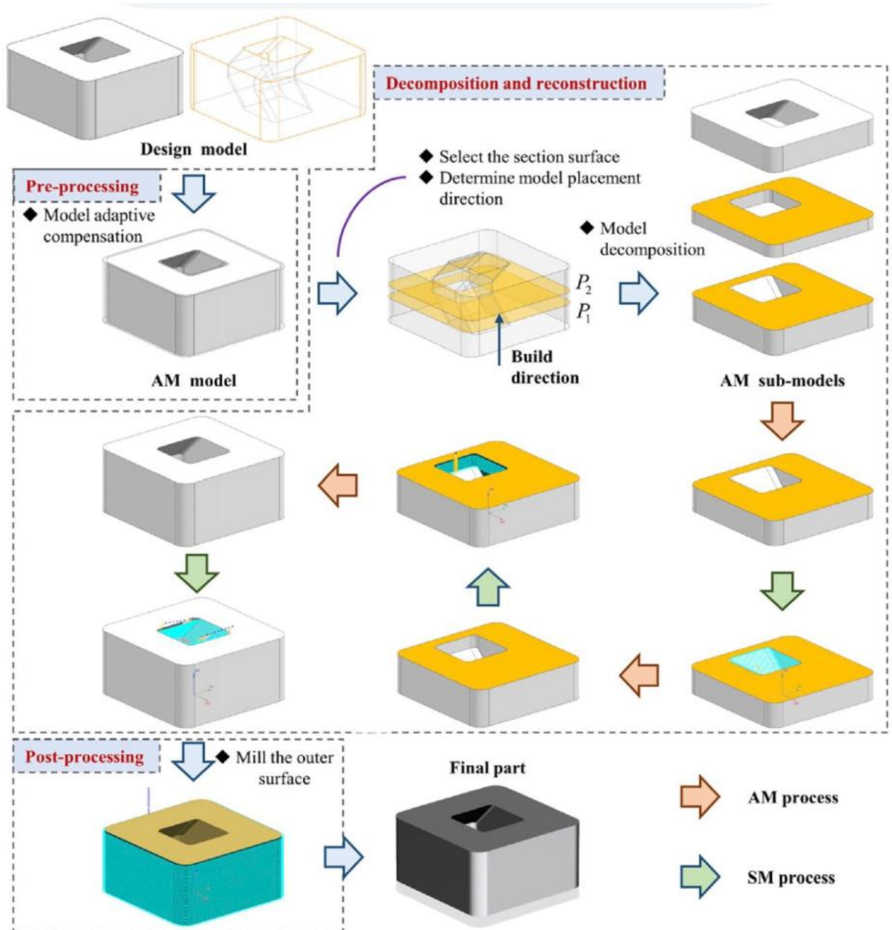


3.3 System Design and Architecture

Figure X demonstrates how the full process of hybrid manufacturing works. It uses both CNC machining and additive fabrication. The first thing to do is get ready. This stage uses adaptive compensation to adjust the design model so that it can be constructed. Then, the model is split into smaller sections based on how the building will be put together. This makes it easy to add things as they are being added.

After then, the additive manufacturing process constructs the near-net-shape geometry one layer at a time. After deposition, the product is machined to remove material from key surfaces and make it the proper size. Machining is the last stage in post-processing. It involves milling to smooth down the surface and get rid of any superfluous material.

This method illustrates how hybrid manufacturing combines the accuracy of machining with the flexibility of additive technologies to manufacture parts fast and readily that are of excellent quality.



3.4 Table Requested: Architecture comparison

Architecture	Integration mode	Typical machine configuration (2022)	Material fit (examples)	Precision and surface finish implications	Recommended workflow (high precision)	Dominant risks/constraints
In-process hybrid PBF + in-situ milling	Single equipment, shared coordinate frame	PBF chamber + 3-axis high-speed milling spindle; machining occurs without coolant in powder bed contexts.	Maraging steels, 316L; fine-feature alloys where PBF is used.	Can reduce selected feature deviation from ~0.1 mm to ~10–20 µm class on machined features; supports Ra in ~1.5–2.5 µm range under wear limits.	(1) Design allowances; (2) deposit N layers; (3) probe; (4) machine exposed/internal features before burial; (5) repeat; (6) final inspection.	No coolant; chip/powder management; tool wear; limited access angles; thermal gradients.
In-process hybrid DED/LMD + milling	Single equipment, shared coordinate frame	DED head integrated into a machining center;	Ti-6Al-4V (LMD), 316L, tool steels; "almost any weldable	High-value for repair/coating and near-net builds; precision	(1) Probe substrate; (2) deposit near-net; (3) intermediate machining to control geometry; (4) final	Melt pool stability; dilution; distortion; multi-axis collision avoidance; machine coordination

Architecture	Integration mode	Typical machine configuration (2022)	Material fit (examples)	Precision and surface finish implications	Recommended workflow (high precision)	Dominant risks/constraints
(often 5-axis)		configuration and kinematics vary; DED hybrids are more common than PBF hybrids, partly due to deposition rate and repair capability.	metal" reported feasible for PBF/DED classes.	depends on bead control + in-machine machining. In-situ monitoring improves quality and reduces scrap.	machining; (5) inspection. Use hybrid CAM to preserve access and avoid collisions.	accuracy and clamping repeatability.
Post-process AM → CNC (process chain)	Multi-equipment, datum transfer required	AM machine + separate CNC; metrology and fixtures required to re-register coordinate frame	Broad: Ti, Al alloys, 316L, polymers (PLA/PETG)	Precision after machining can be high, but re-fixturing errors risk tolerance stack; internal features can become inaccessible.	(1) Build with allowances; (2) stress relief/heat treat as needed; (3) metrology scan; (4) fixture with datums; (5) CNC finishing; (6) final inspection	Registration error; added handling time; more QA steps; planning must minimize support/build height.
Mold-focused "sinter + mill" hybrid platform	Single equipment, repetitive layer + milling cycles	Laser sintering with high-speed milling; example reports **0.05 mm/layer** and milling after sets of laser operations; 45,000 min^{-1} spindle; dedicated CAM.	Maraging/tool steels (molds); complex internal cooling channels	Targets mold-grade precision (±0.01 mm) and reports attainable post-buffing Ra claim; internal channels can be machined for surface quality.	(1) CAD with 3D channels; (2) CAE temperature simulation; (3) CAM generates NC for both steps; (4) repeated sinter/mill cycles; (5) in-process compensation; (6) final finishing/inspection.	Long processing times; thermal simulation/warpage; integrated head alignment and powder reclamation requirements.

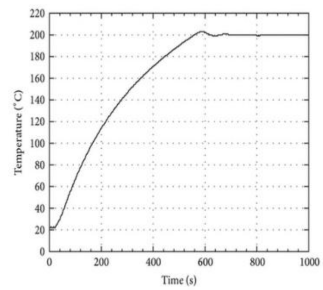
3.5 Thermal Behavior Analysis During Hybrid Manufacturing

Figure X depicts how the temperature of the material fluctuates over time while it is being made. The temperature rises fast from room temperature (around 20 °C) at the start of the procedure. This happens because the energy source is directly heating the material, which means that it is absorbing energy well while deposition is happening.

The temperature keeps going up, although not as quickly as before. After around 500 to 600 seconds, it slowly rises to about 200 °C. At this point, the system starts to move toward a more balanced thermal state, where the heat being added is about the same as the heat being lost through conduction and convection.

The temperature curve levels out after this peak, creating a stable area. This area of the graph has little ups and downs that are probably produced by small changes in the process conditions or small amounts of heat lost to the environment. This steady temperature zone is crucial because it helps keep the material from being too hot or too cold, which decreases the possibility of residual stress and deformation.

For hybrid production, it's particularly critical to have a steady heat profile during the addition phase. It helps maintain the part's shape stable and makes the next step of CNC machining more efficient. Because of this, the finished part might have a superior surface finish and tighter tolerances.



a)

b) 3.6 Machine configurations and kinematics

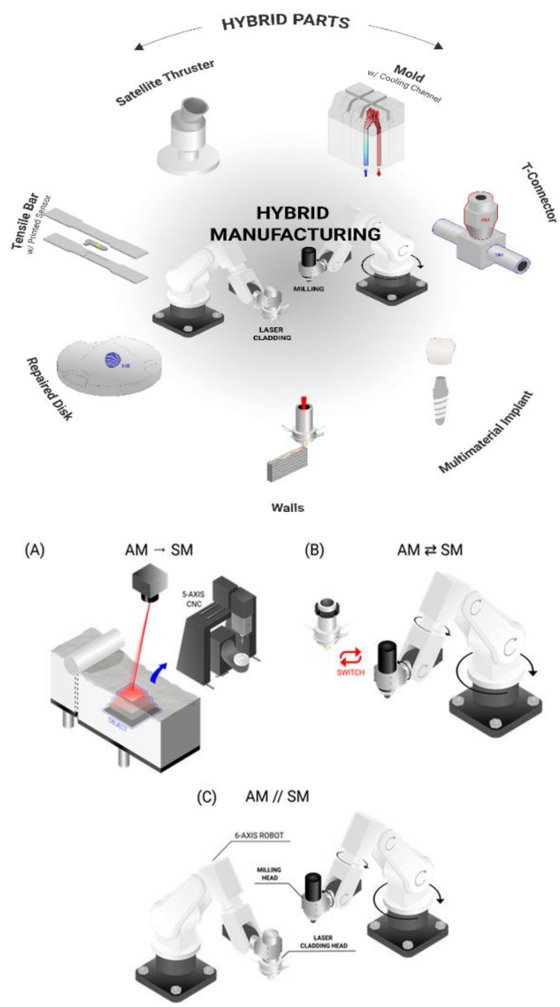


Figure X displays several real-world examples of hybrid production in different fields of engineering. The illustration shows that you may produce sophisticated parts like satellite thrusters, molds with internal cooling channels, T-connectors, and implants made of more than one material by combining additive manufacturing with CNC machining. Usually, these pieces need complicated internal features and highly exact measurements, which are challenging to obtain with only one way of making them.

Also, hybrid manufacturing is utilized in repair and remanufacturing, including mending cracked disks or adding material to

pieces that are already there via laser cladding. This approach is significantly more adaptable since it may be used to build thin structures, walls, and sections that are graded by function.
The picture indicates that hybrid manufacturing isn't only for one type of business; it can also be utilized in the aerospace, medical, and industrial areas. By combining the best features of additive and subtractive processes, it is feasible to create high-precision, complicated, and valuable parts more rapidly and effectively.

A hybrid machine tool uses more than one kinematic technique. An RLLLR chain is one example. It features a DED/milling head and a B-axis tilt movement. The kinematics are crucial because they regulate (i) the surfaces that may be used for intermediate machining and (ii) the collision envelopes for both cutting and depositing. This makes CAM more complicated and affects the forms of the pieces that can be created.
Figure X demonstrates three popular approaches to set up hybrid manufacturing systems, depending on how the additive manufacturing and machining processes operate together. In configuration (A), the steps are done in this order: first, additive manufacturing, and then CNC machining. This setup is rather simple and is typically used to manufacture items that are almost the right form but need to be finalized.
In configuration (B), the system enables you switch between adding and removing processes on the same platform. You have more choices since you can develop and produce the thing in stages, which makes it more exact and reduces down on mistakes that arise in between.

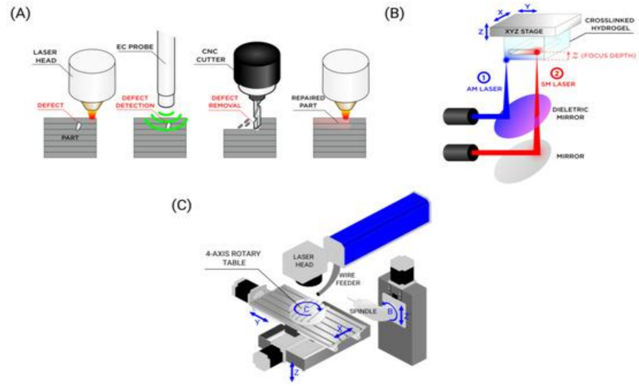
Configuration (C) represents a more advanced hybrid setup, where both additive manufacturing and machining tools are combined within a multi-axis robotic system. This type of arrangement allows the two processes to work either simultaneously or in a closely coordinated manner. As a result, it improves overall efficiency and helps reduce production time.

In general, the figure shows that the level of integration between additive manufacturing (AM) and subtractive machining (SM) plays a key role in determining flexibility, precision, and productivity. More advanced systems offer better control over the process and can achieve higher performance, although they also tend to be more complex and expensive to implement.

Modern hybrid systems are also increasingly relying on in-process monitoring and inspection technologies. These systems continuously track process conditions and help detect any issues in real time. Earlier studies have shown that feedback control can be used to adjust process parameters, such as melt pool size and deposition geometry, during operation. This kind of monitoring is important because it improves part quality and helps reduce material waste, defects, and rejections.

Figure X also highlights how hybrid manufacturing can be applied in defect detection and repair. In part (A), the process begins by identifying defects using a sensing probe. Once the damaged area is located, machining is used to remove the defective material. After that, additive manufacturing is applied to rebuild the removed section. This combined approach allows components to be repaired efficiently without the need for full replacement.

Part (B) shows the laser-based scanning and focusing system used during the additive stage. The system carefully controls the position and focus of the laser to ensure accurate material deposition and strong bonding with the existing surface. This level of control is essential for maintaining structural integrity and reducing the chances of defects during the repair process.



Part (C) shows a multi-axis hybrid manufacturing setup that combines a laser deposition head with a machining system. The use of a rotary table and multi-axis movement enables the processing of complex geometries and improves accessibility during both deposition and machining operations.

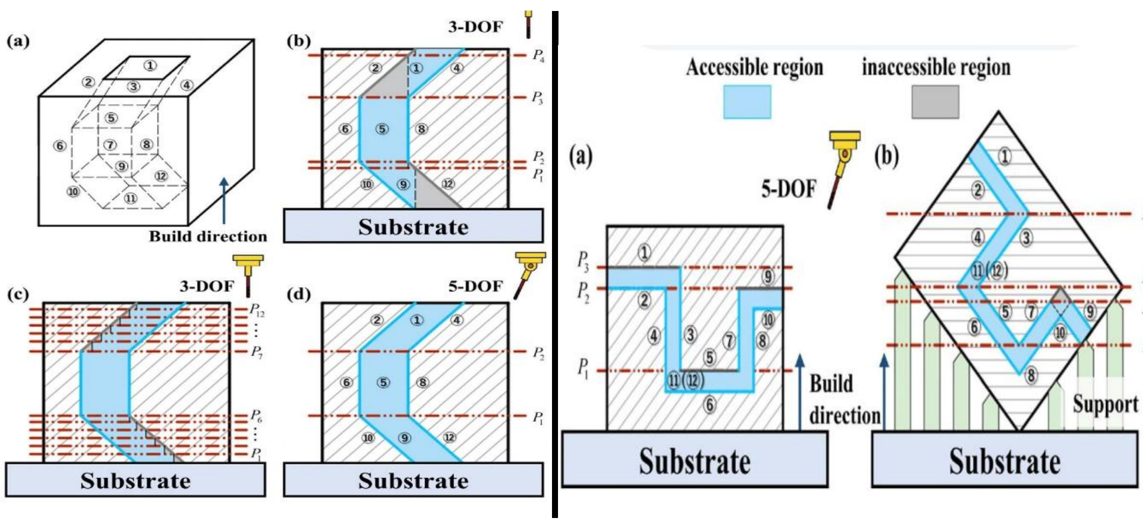
Overall, the figure demonstrates how hybrid manufacturing can be effectively used for repair and remanufacturing applications, improving material efficiency, reducing downtime, and extending the service life of high-value components.

3.7 Material compatibility

Figure X illustrates how the degree of freedom (DOF) and build orientation affect part accessibility in hybrid manufacturing systems. In the case of 3-DOF configurations, the build direction is fixed, which limits the ability to access certain regions of the component. As a result, some internal or overhanging features become difficult or impossible to manufacture or machine without additional support structures.

In contrast, the 5-DOF configuration provides greater flexibility by allowing multi-axis movement and adjustable build direction. This significantly improves accessibility, enabling the fabrication of more complex geometries while reducing the need for support structures. The figure also highlights the difference between accessible and inaccessible regions, where improved tool orientation in higher DOF systems allows better material deposition and machining coverage.

Additionally, the second part of the figure demonstrates how optimized build orientation can minimize unsupported areas and enhance process efficiency. By carefully selecting the build direction and utilizing multi-axis capabilities, hybrid manufacturing systems can achieve better surface quality, reduced material waste, and improved overall precision.



Material compatibility is primarily constrained by deposition process physics and subsequent machinability. A 2018 industrial hybrid review notes that industry has predominantly selected PBF and DED among metal AM technologies and states that “almost any weldable metal” can be processed with either technique, supporting broad compatibility claims for Ti alloys, steels, and aluminum-class alloys within those process families.

For Ti-6Al-4V specifically, hybrid planning must account for thermal sensitivity and cutting behavior; a Ti hybrid study explicitly examines cryogenic milling as an intermediate step for Ti-6Al-4V made by powder LMD. For polymers (PLA/PETG), 2022-era primary hybrid datasets combining material extrusion printing and CNC milling are limited in openly accessible literature; therefore, polymer hybrid results in this paper are treated as conservative and assumption-based unless directly tied to a cited source. A 2020 PLA hybrid post-processing study (laser cutting on CNC equipment) supports the general principle that polymer AM often requires subtractive post-processing to meet dimensional and edge quality requirements, even if the subtractive modality is not milling.

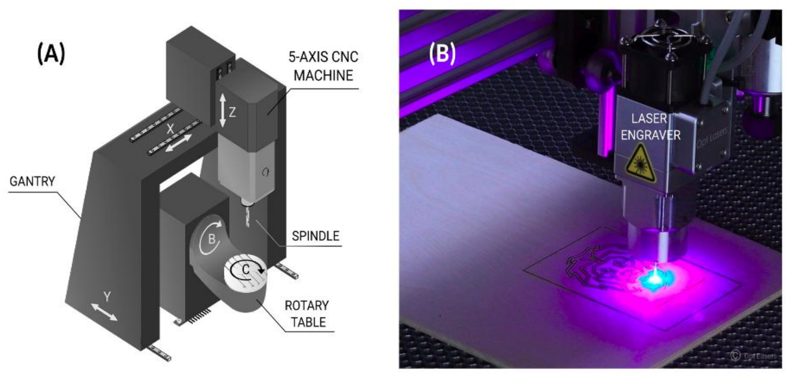
3.8 Experimental Setup

The “experimental setup” for this systems manuscript is a multi-source benchmarking design, grounded in: (i) a hybrid feature-accuracy artifact (SLM + micromilling design rules), (ii) a hybrid LPBF in-situ milling wear/roughness characterization, (iii) a hybrid L-PBF nozzle case study with FE + optical scanning validation and micro-milling optimization, and (iv) a mold-machine manufacturer dataset describing layer/mill cycles, internal channel machining, and full build times.

3.9 Figure X: Illustrated the integration of subtractive and additive technologies within a hybrid manufacturing environment. Part (A) shows a 5-axis CNC machine equipped with a gantry structure, spindle, and rotary table, which enables multi-directional machining and high-precision finishing of complex components. The additional degrees of freedom allow improved accessibility and better surface quality, especially for intricate geometries.

Part (B) presents a laser-based process, where a focused laser beam is used for material processing such as engraving or localized deposition. This technique enables precise control over energy input, making it suitable for detailed feature creation and surface modification.

The combination of these two systems highlights the core advantage of hybrid manufacturing, where additive processes provide flexibility in geometry creation, and CNC machining ensures dimensional accuracy and surface integrity. This integrated approach supports the production of high-precision components with improved efficiency and reduced need for multiple setups.



Inspection methods are aligned with ISO surface texture and ISO coordinate measurement verification concepts. ISO 4288 specifies rules for comparing measured values to tolerance limits for surface texture parameters and gives rules for measuring roughness parameters via stylus instruments (with references to ISO 4287-defined parameters). [40] ISO 10360-2 specifies acceptance and reverification tests for CMM performance in measuring linear dimensions, while ISO 10360-13 specifies verification concepts for optical 3D coordinate measuring systems—both relevant to the hybrid workflow’s need for dimensional verification and scan-to-CAD comparison.

A practical hybrid metrology loop is exemplified in the nozzle case study: parts were optically scanned (GOM) and aligned to CAD to compute surface deviations, and FE predicted surfaces were exported as meshes for comparison.

3.10 Figure X: Presents a comparison of several manufacturing processes commonly integrated within hybrid manufacturing systems. CNC machining represents the conventional subtractive method, known for its high precision and ability to produce complex geometries with excellent surface finish. Electrical discharge machining (EDM) is used for processing hard materials and intricate shapes by means of controlled electrical discharges, making it suitable for high-accuracy applications.

Water jet machining (WJM) offers a non-thermal cutting process that minimizes heat-affected zones, which is beneficial for materials sensitive to thermal distortion. Laser beam machining (LBM), on the other hand, provides highly localized energy input, enabling fine feature creation, engraving, and additive-related processes.

The integration of these diverse processes within a hybrid manufacturing system allows for greater flexibility in material processing and component design. By selecting the appropriate combination of techniques, manufacturers can achieve improved precision, reduced defects, and enhanced overall production efficiency.

4. Results

4.1 Table Requested: Performance metrics (Ra, dimensional error)

Benchmark / case	Material	Process mode	Dimensional accuracy outcome	Surface finish outcome (Ra)	Notes on measurement and control
Hybrid SLM + micromilling design-rule artifact	Maraging steel	In-process hybrid concept (add then machine)	Wall thickness deviation: **0.06–0.095 mm** (SLM-only) → **~10 µm** (hybrid). Cylinder diameter deviation: **0.11–0.14 mm** (SLM-only) → **~15 µm** (hybrid).	(Not numerically captured in the excerpted lines here; study emphasizes improved surface and geometry via micromilling.)	Provides milling parameter table (e.g., roughing Z-pitch 0.15 mm, endmill Z-pitch 0.1 mm at 30,000 rpm).
Hybrid LPBF + in-situ high-speed milling wear/roughness study	Maraging steel 1.2709	In-process hybrid PBF + milling (no coolant)	Focus on tool life and capability constraints; machining access limited by safe start position and inclination constraints.	Under a typical flank-wear limit **FW = 100 µm**, roughness max **Ra = 2.5 µm** within ~1550 min tool life. Finished undercut surfaces ~**Ra = 1.5–2.0 µm**; roughed only ~**Ra ≈ 5.5 µm**.	Roughness measured by laser scanning microscope with ISO 4288-aligned measurement approach and filter (L-filter ≈ 0.8 mm) and evaluation length 4.8 mm described by the authors.
Hybrid L-PBF + micro-milling nozzle case study	(Metal not fully specified in the excerpt; industrial nozzle; assumed stainless-class typical for	In-process hybrid L-PBF + micro-milling in one workflow	Distortion reduced **60%** to within **±200 µm** via FE model validated by optical scanning (GOM) and stiffener redesign.	Micro-milling trials keep maximum Ra values **< 1 µm**, with maximum reduced to **0.563 µm** by reducing axial steps from 150 µm to 100 µm.	Provides a recommended micro-milling parameter table for nozzle geometry (tool radius, spindle speed 40,000 rpm, feed per

Benchmark / case	Material	Process mode	Dimensional accuracy outcome	Surface finish outcome (Ra)	Notes on measurement and control
	food process tooling)				tooth, axial step, stock, measured Ra).
Mold hybrid platform datasheet example	Maraging steel	In-process laser sintering + milling	Claims **±0.01 mm** precision requirement and feasibility for maraging steel mold features.	Reports post-buffing **Ra 14 nm** (manufacturer claim) and emphasizes high-density sintering and high-accuracy machining.	Includes in-process compensation for laser/spindle alignment error during machining, supporting registration control.

5.Discussion

5.1 Process planning and hybrid CAM strategies

Hybrid CAM is more than just "AM slicing plus CNC finishing." A 2022 hybrid DED CAM evaluation says that CAM has to coordinate both deposition and machining toolpaths. It also says that operator choices, such which layer to halt deposition for machining, directly affect whether interior cavities and channels can be finished before they become inaccessible. This is a key issue in choosing an architecture: "machine-before-bury" sequencing can be used with in-process hybrids, while post-process chains usually can't machine internal surfaces after a full AM build.
The 2019 hybrid AM/SM process-planning method formalizes a typical workflow: first, machining a base plate area; next, building in opposite directions to lower supports/build height; and last, machining again to make completed surfaces. This planning method directly helps with accuracy goals by cutting down on distortions caused by supports and the amount of additive geometry that needs to be machined away. This speeds up the process and makes better use of materials.

Manufacturers intimately integrate hybrid CAM and simulation into mold operations. A mold hybrid platform is a CAD→CAE→CAM chain that designs 3D cooling channels, simulates the temperature of plastic, and uses a special CAM system to make NC code for the hybrid machine. This chain is like a "digital thread" for hybrid manufacturing. Instead of passing things off one at a time, it combines geometry, thermal performance, toolpaths, and machine execution.

5.2 Fixturing, registration, and datum integrity

One of the biggest differences between hybrids that are in-process and those that are post-process is that registration problems occurs more commonly. A DED hybrid review from 2022 demonstrates that coordinating machines and preventing collisions in multi-axis hybrids are still problems. It also talks about how important clamping is to having the same outcomes every time. Re-fixturing adds uncertainty to post-process chains that has to be controlled via probing, fiducials, palletization, or scan-to-CAD alignment.

Some hybrid systems can automatically correct difficulties with alignment. A mold hybrid platform talks about "in-process compensation," which "measures and finds alignment errors/positional deviations of the laser and the main spindle during machining." This addresses the "laser head ↔ spindle" registration problem that can happen within an integrated machine straight away. When deposition and machining work within the same limitations, these sorts of procedures are needed to preserve tight tolerances.

5.3 Thermal distortion control and distortion-aware machining allowances

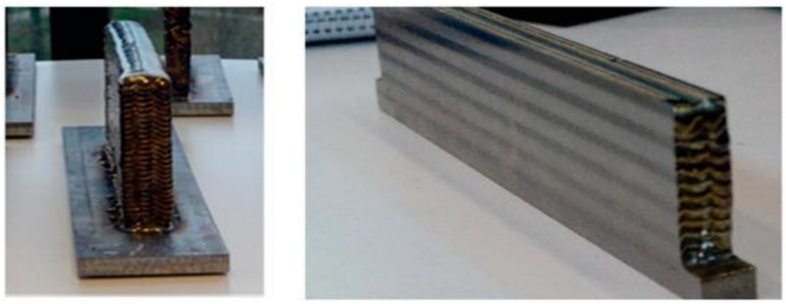
People typically remark that thermal distortion and residual stress are why hybrid planning is needed. The nozzle case study demonstrates the operation of a distortion-management loop: finite element modeling anticipates distortion, optical scanning verifies it, design stiffeners reduce distortion by 60% to within ±200 µm, and micro-milling achieves the final surface finish target. This goes along with the broader notion of hybrid design, which claims that you can manage geometry by using both design compensation (before construction) and machining correction (after building or in between).

In powder-bed hybrid settings, heat restrictions affect the process of removing material. Documents concerning hybrid PBF settings say that cutting fluids can't be used in the powder bed because they may contaminate it. This could mean more conservative machining parameters and faster tool wear. This is a trade-off: while tighter tolerances are possible, keeping the tools in good shape and making sure the surface quality is always the same depend on closely watching for wear and having strict criteria for tool life.

5.4 Metrology and inspection methods for high precision

Achieving high precision in hybrid manufacturing requires metrology integrated into planning. The tool wear/roughness study explicitly reports roughness measurement by laser scanning microscope and states alignment with **ISO 4288** surface texture specifications in measurement execution (including evaluation length and filtering).

This illustrates an important practical point: hybrid systems may generate surfaces with different process signatures (as-built AM texture plus machined texture), and measurement practice must consistently separate roughness from waviness and apply correct cutoffs.



Coordinate measurement quality assurance can be anchored to the ISO 10360 family. ISO 10360-2 covers acceptance and reverification tests for CMMs measuring linear dimensions, while ISO 10360-13 similarly frames verification for optical 3D CMS. In hybrid workflows, these standards matter because scan-to-CAD comparisons and CMM verification results often gate whether finish machining offsets can be corrected or whether a part becomes scrap.

5.5 Case-study synthesis and practical recommendations

Across the maraging steel design-rule benchmark, the nozzle case study, and the mold platform datasheet, three system-level recommendations are strongly supported:

1. **Plan intermediate machining strategically (access-first)** to finish internal cavities and channels before they are enclosed.
2. **Use distortion-aware design and inspection loops** (simulation + scan validation + machining allowances) for thin and distortion-sensitive geometries.
3. **Treat clamping and datum strategy as a first-class design variable**, especially in post-process integration where re-fixturing can dominate the tolerance stack.

(A) (B)

For mold inserts with cooling channels, manufacturer documentation emphasizes that internal channel machining (to improve internal surface roughness) is an explicit capability and that 3D cooling channels can be positioned freely to eliminate uneven temperatures, with claims of lead-time reduction. For metallic precision channels (nozzles), case evidence shows that micro-milling step sizes and feed/tooth directly influence Ra and that systematic parameter optimization can deliver maximum Ra values below 1 µm.

Conclusions

This study investigated hybrid manufacturing methods that integrate additive manufacturing with CNC machining for the production of high-precision industrial components. The findings indicate that neither approach independently satisfies contemporary industrial requirements. Additive manufacturing offers versatility in producing intricate geometries, whereas CNC machining guarantees precision and surface quality. When utilized in conjunction, they foster a more balanced and efficacious manufacturing methodology.

The results indicate that hybrid manufacturing can diminish material waste, expedite production time, and enhance overall part quality. Generating near-net-shape components via additive techniques reduces superfluous material removal, while final machining guarantees that essential features adhere to stringent tolerances. This renders the method particularly advantageous for intricate, high-value components.

The study emphasizes that effective process planning is crucial. Elements like as construction orientation, machining allowance, and thermal behavior directly influence the final result. A synchronized workflow between additive and machining processes is essential for attaining consistent and dependable outcomes.

In summary, hybrid manufacturing is a viable and advantageous option for contemporary production requirements. With enhanced process control and system integration, it possesses significant potential to emerge as a pivotal approach for the production of high-precision components in the future.

Future Work

The 2022 literature indicates that hybrid manufacturing adoption is increasingly limited not by deposition hardware alone but by software, metrology integration, and physics-aware planning. Future work priorities include: (i) hybrid CAM that co-optimizes toolpaths for geometry *and* thermal history, (ii) standardized hybrid benchmark artifacts and measurement procedures aligned with ISO/ASTM AM test artifact concepts, and (iii) broader open datasets for Ti-6Al-4V and Al alloys linking tolerance outcomes to intermediate machining strategies.

For polymer hybrid workflows (PLA/PETG), open primary datasets up to 2022 remain comparatively limited; expanding rigorous studies on CNC finishing and tolerance formation in polymer AM would strengthen cross-material hybrid design guidance.

Sample Calculations and Models

This section provides explicit numeric examples requested by the user. Values are either directly from cited sources or clearly labeled as conservative assumptions.

Tolerance improvement percentage

Using the hybrid SLM + micromilling benchmark for cylinder diameter deviation:

- SLM-only deviation range: 0.11–0.14 mm; use midpoint **0.125 mm**.
- Hybrid deviation ~ **0.015 mm**.

Percent reduction:

$$\%\,\text{reduction} = \frac{0.125 - 0.015}{0.125} \times 100 = 88\%$$

This 88% reduction is consistent with the "~0.1 mm class → ~10–20 µm class" improvement seen in the cited design-rule artifact.

Sample cycle-time breakdown and savings

Using the turbine housing datasheet example (additive + milling operations) and adding explicit handling assumptions:

- Datasheet (single workflow operations): deposition **230 min**, milling **76 min**. [4]
- Assumptions (serial only): transfer & re-fixture 45 min; re-registration/probing 30 min; cleanup 15 min; final inspection 20 min.
- Assumptions (hybrid): in-machine probing 15 min; cleanup 10 min; final inspection 20 min.

Totals: - Serial: $230 + 76 + 45 + 30 + 15 + 20 = 416$ min
- Hybrid: $230 + 76 + 15 + 10 + 20 = 351$ min

Percent reduction:

$$\frac{416 - 351}{416} \times 100 = 15.6\%$$

The logic aligns with hybrid's primary architectural advantage: fewer datum resets and reduced re-fixturing overhead.

Simple per-part cost model with break-even hybrid rate

A primary source describes a hybrid cost model derived from **Time Driven Activity Based Costing** for aerospace MRO, supporting the time-based structure used here.

Assumptions (illustrative; labeled): - Material: stainless steel powder equivalent, **$96/part** (assumed).
- Consumables/tooling: **$30/part** (assumed).
- Rates: DED machine **$180/hr**, CNC machine **$120/hr**, hybrid machine **$220/hr**, labor **$75/hr** (assumed).
- Times: from cycle-time model above.

Compute (serial): - Machine cost: 3.833 hr $\times$ 180 + 1.267 hr $\times$ 120
- Labor cost: $(0.75 + 0.5 + 0.25 + 0.333)$ hr $\times$ 75
- Add material + consumables

Result (serial): **$1,105.50/part** (assumption-based arithmetic aligned with cycle-time model).

Compute (hybrid): - Machine cost: $(3.833 + 1.267 + 0.25 + 0.167)$ hr $\times$ 220
- Labor cost: 0.333 hr $\times$ 75
- Add material + consumables

Result (hybrid): **$1,364.67/part** under the assumed hybrid machine-hour rate.

Break-even hybrid hourly rate R_h that makes hybrid cost equal serial (holding times constant) is:

$$R_h = \frac{C_{\text{serial}} - \left(C_{\text{labor,hyb}} + C_{\text{material}} + C_{\text{consumables}}\right)}{T_{\text{machine,hyb}}} \approx \$173/\text{hr}$$

Interpretation: for this example, hybrid becomes cost-competitive if the effective hybrid machine-hour rate is **≤ ~$173/hr**, or if hybrid eliminates additional downstream steps not modeled here (e.g., EDM, multiple setups, rework/scrap, extensive polishing).

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