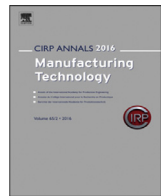




Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

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Hybrid metal additive/subtractive machine tools and applications

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ARTICLE INFO

Article history:

Available online xxx

Keywords:

Hybrid

Additive manufacturing

Machine tool

Additive manufacturing creates parts by depositing a preform, typically layer by layer. Subtractive manufacturing involves removing material from a preform to create parts. Hybrid machine tools combine both additive and subtractive processes in the same workspace. They can be used to create parts that meet functional tolerance and surface finish requirements, or to create features that are difficult to produce using additive or subtractive processes alone. This paper describes hybrid metal additive/subtractive machine tools. It covers design considerations, sensors and controls, process management, programming and software, and the impact on the design space. It also identifies future research challenges.

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1. Introduction

This keynote paper focusses on hybrid metal additive/subtractive machine tools and their uses. Hybrid additive/subtractive means that both material deposition and material removal processes exist in the same workspace and use the same control system, as opposed to the cellular approach shown in [9].

Almost since the creation of additive manufacturing, there was a drive toward using the additive processes to create a part as close to the finished geometry as possible. Many researchers thought that machining processes could be eliminated, or at least material removal operations could be treated as post-processing. More recently, the entire additive/subtractive process chain has been analyzed holistically to minimize lead time and/or cost. Fig. 1(a) [163] shows a hybrid propeller blade made by wire arc additive manufacturing followed by high-speed machining. The machined surface (top) is specular, while the as-deposited surface (bottom) is not. Similarly, Fig. 1(b) [145] shows a commercial aerospace Boeing 787 titanium structural component preform and the part after machining.

1.1. CIRP keynotes related to hybrid additive/subtractive machine tools

There have been ten CIRP keynote papers related to additive manufacturing (AM) and hybrid manufacturing that are relevant to hybrid additive/subtractive machine tools. Kruth [109] provided an overview of rapid prototyping techniques available at the time. Although most of the processes he described focused on polymers, selective laser sintering, shape melting technology, and laminated object manufacturing could be used to create metal parts. In [110], a comprehensive summary of more than a decade of research was provided including at least six distinct processes for making metal parts. Bartolo [18] described the manufacture of biological implants using

additive process, and he provided some consideration of machining as a post-additive process. Veld [203] described micro additive manufacturing with a very fine resolution, but with a slow deposition rate. Using femto- and pico-second laser pulses, he described additive manufacturing at the micrometer and nanometer length scale. Thompson [198] provided a history of additive manufacturing and described the challenges and opportunities in design for additive manufacturing. She considered machining as a post-additive process, but she also envisioned a hybrid process, alternating between printing and machining activities. Bourell [25] described hybrid machine tools using ultrasonically welded metal foils and directed energy deposition (DED) processes with metallic powder or wire to create the preforms. Schmidt [172] specifically called out hybrid machine tools (additive and subtractive) as a research challenge. Leach [115] described the similarities and differences among metrology artifacts used for additive and subtractive processes. Vaneker [200] described design for additive manufacturing including consideration of later machining operations. In [112], hybrid manufacturing processes were understood as being processes that "... are based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance." This definition includes, for example, laser-assisted turning and grind-hardening. Such hybrid processes are not the focus of this paper. Rather, this paper considers the machine tools that incorporate metal additive and subtractive processes in the same machine.

1.2. The need for hybrid additive/subtractive machine tools

Many parts created by additive manufacturing technologies need subsequent machining, either partially or fully, to produce functional components. Machining is often required to meet geometrical tolerances, surface finish requirements, or produce features that are difficult to create additively, such as threads and high aspect ratio holes. According to [138], "... almost all additively manufactured parts must be post-processed in order to fulfil geometric tolerances, surface quality demands, and the desired functional properties. Thus,

E-mail address: smithss@ornl.gov (S. Smith).<https://doi.org/10.1016/j.cirp.2024.05.002>

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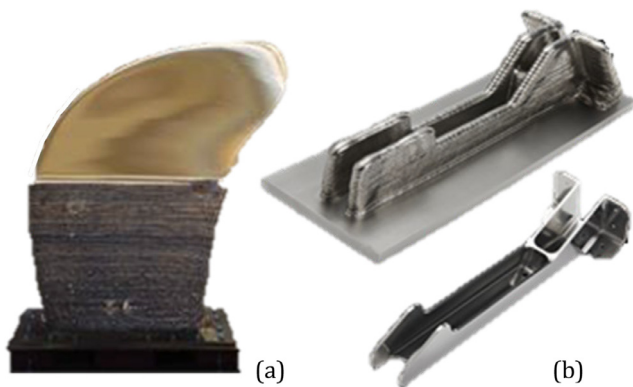


Fig. 1. Improved surface finished using hybrid additive/subtractive manufacturing: (a) A partially finished hybrid propellor blade. Modified from [163]. (b) Boeing 787 titanium structural component preform and finished part. Modified from [145], Courtesy Norsk Titanium AS.

additive manufacturing actually means the implementation of additive-subtractive process chains.” Jones, quoted in [154] said, “People talk about metal 3D printing as if what comes out of the printer is finished, and that’s rarely the case.” Bagehorn [15] said that surface finishing was required for notch sensitive materials like Ti6Al4V. Due to the roughness of AM surfaces, [23] indicated the desirability of finish machining for almost all additively manufactured parts.

The poor surface finish may arise from the feedstock materials (e.g., powder characteristics) and the thermal history from AM, which is largely based on energy density and print strategy, or from the surface tension and weld bead shape. Dávila [39] noted that metal parts fabricated and repaired by directed energy deposition present poor surface finish and geometrical tolerances due to factors like non-uniform cooling, porosity, inhomogeneities, anisotropy, the stair-step effect, and the chordal error of STL files. According to [129], “The generation of residual stresses, which in turn, induce distortion on the component, was inherent to additive processes since thermal cycles occurred during the deposition of successive layers. The manufacturing of an end-use component with good surface quality and dimensional accuracy by AM only is still far off.”

The industrial demand for hybrid additive/subtractive machine tools is growing and machine tool builders are providing integrated solutions. Strong [190,191] presented survey results that showed high interest among machine tool builders to include hybrid additive/subtractive capability in their current production capabilities. The primary driver is that users shorten lead times with a hybrid multi-tasking machine tool.

1.3. Definition of hybrid machine tools

Hybrid machine tools are defined by first contextualizing machine tools and additive manufacturing. Mori [140] said “A machine tool is a machine used to make manufactured components in various [materials] utilizing a subtractive cutting process. Machine tools contain the four basic elements of the manufacturing process, which are an energy source for constrained relative motion, a means to keep the work secure, a means to secure and orient the tool, and a means to control the previous means.” The ISO/ASTM standard 52900 [12] says that additive manufacturing “... is the general term for those technologies that, based on a geometrical representation, create physical objects by successive addition of material.” Further, the standard defines additive manufacturing as the “... process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing technologies.”

Within this work, a “hybrid metal additive/subtractive machine tool” is defined as a machine tool capable of both additive manufacturing and material removal by cutting processes in the same workspace, without refixturing of the part. Cellular configurations of separate additive and subtractive equipment, or material

removal by other processes, such as electrical discharge machining or electro-chemical machining, are not considered. While some examples of polymer hybrid machine tools may be used to illustrate process planning, the focus of this keynote is on hybrid machines for metals.

1.4. Scope

This keynote begins with design considerations for hybrid additive/subtractive machine tools, then follows with sensors and controls, process management, programming and software, and impact on the design space. The keynote concludes with a view toward future research challenges.

2. Design considerations and configurations

2.1. Types of commercially available hybrid metal additive/subtractive machine tools

Flynn [63] provided a comprehensive review of hybrid machine tools. The following configuration discussion is patterned after his categorization. The ASTM/ISO standard 52900 [12] identifies seven categories of additive processes: 1. Binder jetting, 2. Directed energy deposition, 3. Material extrusion, 4. Material jetting, 5. Powder bed fusion, 6. Sheet lamination, and 7. Vat polymerization. Almost all these categories can be used as the basis of hybrid metal additive/subtractive machine tools:

- 1. Binder jetting** – The binder jet process begins by spreading a thin layer (10s of micrometers) of metal powder across a build chamber. A liquid binder is then selectively deposited (jetted) onto the powder to define the part’s geometry in that layer. Another thin layer of metal powder is deposited (recoated), and the process repeats. The green-state part is then removed from the powder bed. Binder jet parts in the green state are brittle and they typically have high porosity. For this reason, metal binder jet parts usually undergo secondary operations, such as heat treatment in a furnace to burn out the binder and sinter the metal particles, or infiltration with a low-melting-temperature metal such as bronze. The requirement for heat treating or infiltration would seem to make a binder jet hybrid machine tool difficult to realize; however, there is at least one example of a hybrid machine tool using this technology.

3DEO developed the Intelligent Layering system, as shown in Fig. 2 [83]. In this process, a layer of metal injection molding (MIM) powder is spread, and then a low-cost spray head evenly distributes binder across the whole layer. In a second pass, a micro end mill is

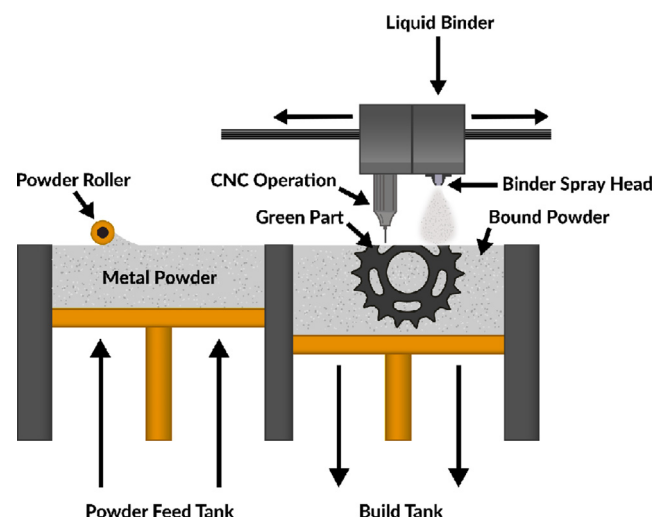


Fig. 2. The 3DEO Intelligent Layering system combines binder jet additive with micro milling [83].

used to define the perimeter of the part, including all the internal and external features in that layer. The green part created this way still needs heat treatment or infusion, but it is more precise than the binder jet process alone. After sintering, these parts have a surface roughness of about $Ra\ 6.0\ \mu m$, and the parts are used in aerospace, luxury goods, dental tools, and industrial equipment.

2. **Directed energy deposition** – In the DED process, a laser beam forms a melt pool on a metallic substrate, into which metal powder or wire is fed. The powder or wire melts to form a deposit that is fusion bonded to the substrate. There are several commercially available examples of DED hybrid machine tools.

The Mazak Laser Hot-Wire Series machines [135] feed a pre-heated wire either from the side into the focus of a laser beam as shown in Fig. 3, or coaxially, in the VTC-800G/SR AMHWD to give better omnidirectionality during the deposition process. A flow of shielding gas surrounding the laser prevents oxidation of the melt pool. A number of parameters are adjustable in this process such as laser power, hot-wire power gas flow rate, wire feed rate, and traverse feed rate. The milling spindle is separate from the deposition system. The additive and subtractive heads are supported on the same linear axes on the VC-500A/5X AM HWD, as shown in Fig. 4, but they only share a single linear axis on the large-scale VTC-800G/SR AM HWD, shown in Fig. 5.

The Okuma LASER EX series [147,148], Figs. 6 and 7, and the DMG Mori Lasertec series [44–47], Figs. 8, and 9, both blow metal powder into the laser spot. Adjustable parameters for this technology include laser spot size, laser power, powder flow rate, and traverse feed rate. In these machines, part of the shielding gas flow is used to carry the powder through a nozzle to the work zone. DED hybrid machine tools physically allow for coolant to be used during the machining process.

The Optomec LENS 500 Machine Tool System uses nozzle-based blown powder deposition within a vertical CNC milling platform. The novelty of this system is the optional configuration for a closed atmosphere where a hermetically sealed Class 1 enclosure and an integrated gas purification system maintains oxygen and moisture levels below 10 ppm. This enables reactive materials, such as magnesium and titanium, to be deposited by a hybrid DED-milling system [184]. The system uses a Siemens controller along with the APlus plugin from CAMufacturing Solutions Inc to facilitate additive and subtractive capabilities within MasterCAM.

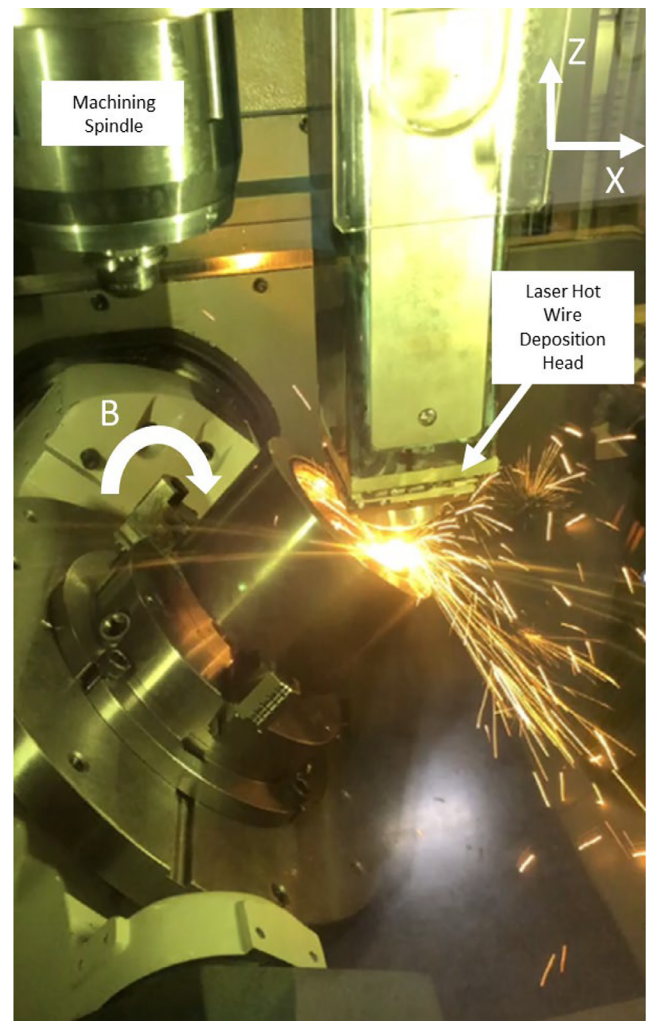


Fig. 4. Mazak VC 500 AM HWD laser hot wire hybrid with XYZBC axes, after [135], courtesy of Mazak.

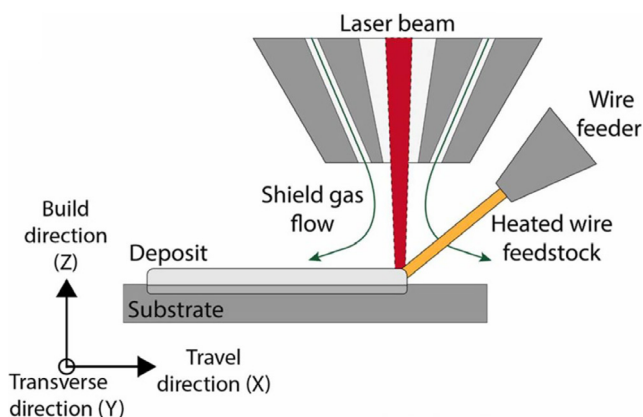


Fig. 3. Laser hot wire additive process from [106].

3. **Material extrusion** – Material extrusion additive manufacturing typically refers to a process like fused deposition modelling (FDM), where a polymer is melted and extruded through a nozzle to build a part layer by layer. In the metal version, the extruded polymer includes metal particles, and the green part requires heat treatment similar to binder jet additive. No examples of hybrid metal machine tools using material extrusion have been found, but there is a related hybrid machine tool using the additive friction stir deposition (AFSD) process. AFSD is similar to friction stir welding in that the pressure and rotation from the deposition



Fig. 5. Mazak VTC-800G/SR AM HWD hybrid machine tool.

head create a plastic, but not molten, state where the metal is stirred together. However, rather than using the friction stir welding pin, AFSD feeds consumable filler material through the center of the rotating tool to deposit an additive layer on the substrate, as shown in Figs. 10 and 11. The MELD Manufacturing Corporation 3P0 hybrid machine tool has independent additive friction stir deposition and machining heads on the same platform, as shown in Fig. 12 [136].

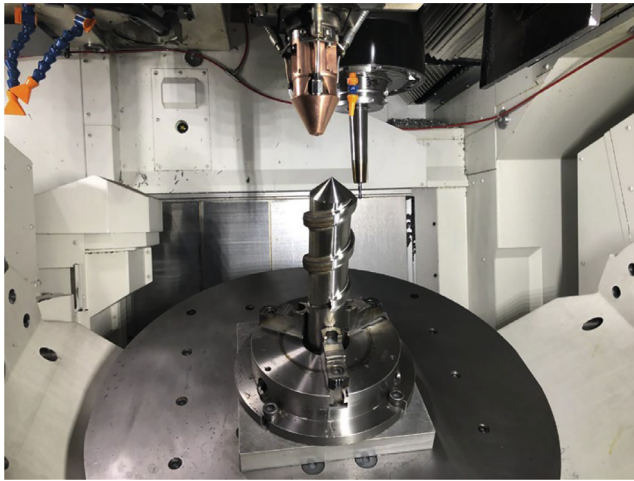


Fig. 6. Okuma Laser EX system.

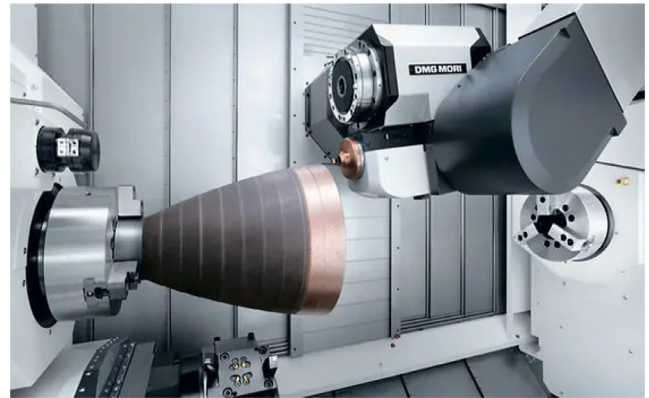


Fig. 9. DMG Mori Lasertec 6600 hybrid machine tool [47].



Fig. 7. Okuma MU 8000V hybrid machine tool.

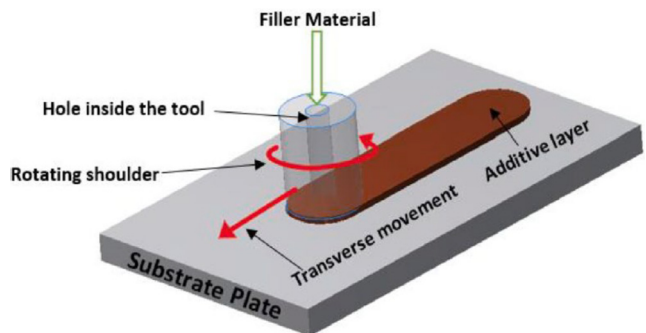


Fig. 10. Additive friction stir deposition [187].



Fig. 8. DMG Mori Lasertec system [45].

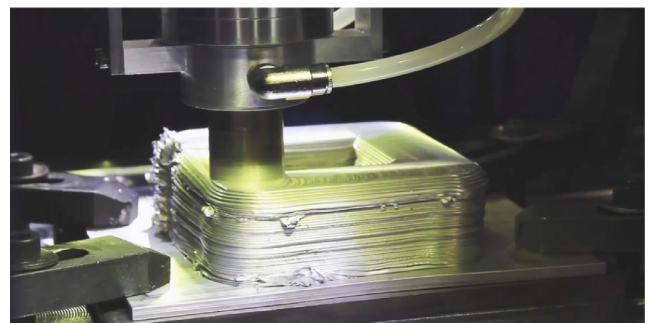


Fig. 11. MELD Manufacturing Corporation additive friction stir deposition [2].

4. Material jetting – Metal material jetting is similar to binder jetting, except that rather than depositing binder material onto metal powder, metal droplets are jetted onto a substrate. No commercial metal material jetting hybrid machine tools are available, but there are examples of hybrid machine tools using metal cold spray. Cold spray is a solid-state powder consolidation process. It uses a heated high-pressure carrier gas, such as nitrogen, to accelerate metal powders through a supersonic nozzle, above a critical velocity for particle adhesion. Particles are deposited on the substrate in a combination of mechanical interlocking and metallurgical bonding at highly strained particle interfaces, as shown in



Fig. 12. MELD Manufacturing Corporation 3PO hybrid machine tool with additive head (left) and subtractive head (right) [136].

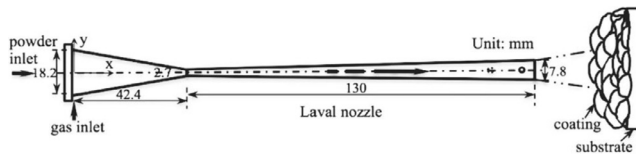


Fig. 13. Metal cold spray from [119].

Fig. 13 from [119]. In the metal cold spray HERMLE MPA 40, a high-energy jet of super-heated steam propels metal powder suspended in nitrogen through a Laval nozzle onto a substrate at supersonic speed. Fig. 14 shows metal cold spray coating on a cylindrical substrate [78]. The machining spindle and the deposition head on this hybrid machine tool are mounted side by side on the same axis as shown in Fig. 15.



Fig. 14. Hermle cold spray coating deposition, from [78], courtesy HERMLE AG.

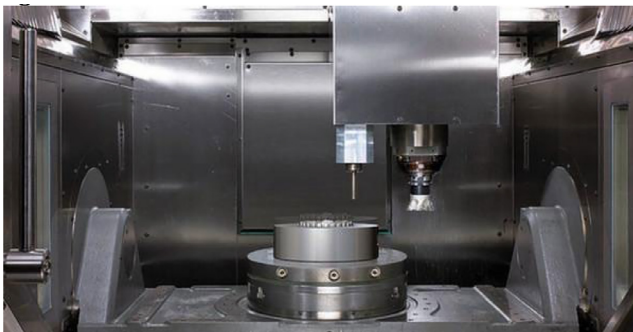


Fig. 15. Hermle MPA 40 hybrid machine tool [78].

5. Powder bed fusion – In powder bed fusion additive manufacturing, a laser or an electron beam is directed toward the surface of a metal powder bed. The beam causes localized metal powder melting, which then fuses to form a solid part. One of the first commercial hybrid machine tools was developed by Matsuura (Japan). The Matsuura Lumex series of machine tools combines selective laser sintering (SLS) with milling using high-speed spindles up to 45,000 rpm, [134]. In this case, the workspace is purged of oxygen and continuously backfilled with shielding gas as needed. After depositing a selected number of layers, machining is used to modify the surface and geometry of the resulting part, see Figs. 16 and 17. The Matsuura Lumex Avance comes in two build envelope sizes: 250mm x 250mm x 300mm (Lumex Avance 25) and 600mm x 600mm x 500mm (Lumex Avance 60). One system option is a disposable filtration system to enable printing of reactive metals (e.g., magnesium and titanium). Deposition of magnesium using a hybrid metal additive/subtractive machine tool was first demonstrated in [176]. Similarly, [49] reported on the use of a

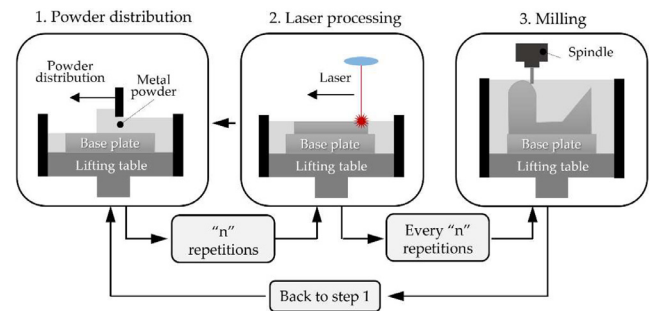


Fig. 16. Laser powder bed fusion and milling [134].



Fig. 17. Matsuura laser powder bed hybrid machine tool work zone during additive (left) and subtractive (right) processes [134].



Fig. 18. AISI 18Ni (300) maraging steel part produced using a Sodick OPM Series hybrid machine tool [49].

Sodick OPM Series [181] hybrid machine tool to produce a sample part in AISI 18Ni (300) maraging steel, as shown in Fig. 18.

One challenge with machining in the Lumex or OPM is interaction with powder during milling [13]. Powder can affect the machining process and accelerate tool wear. To mitigate the effects of powder-tool-workpiece interactions, the fifth generation Lumex added a vacuuming stage that is used prior to milling.

6. Sheet lamination – Sheet lamination is an additive manufacturing methodology where thin sheets of material (usually supplied by a system of feed rollers) are bonded together layer-by-layer to form a single piece that is cut into a 3D object. Laminated object manufacturing (LOM) and ultrasonic consolidation (UC) are both examples of sheet lamination techniques. While sheet lamination can use a variety of materials such as paper, where the sheets are glued together, or polymers, where the sheets can be fused thermally, metal sheets are usually bonded with ultrasonic vibrations under pressure (ultrasonic welding), as opposed to melting or sintering. The SonicLayer series of machines from FabriSonic, [54,55],

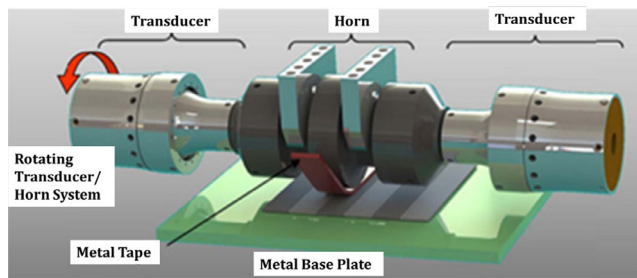


Fig. 19. Fabrisonic ultrasonic additive manufacturing, after [54].

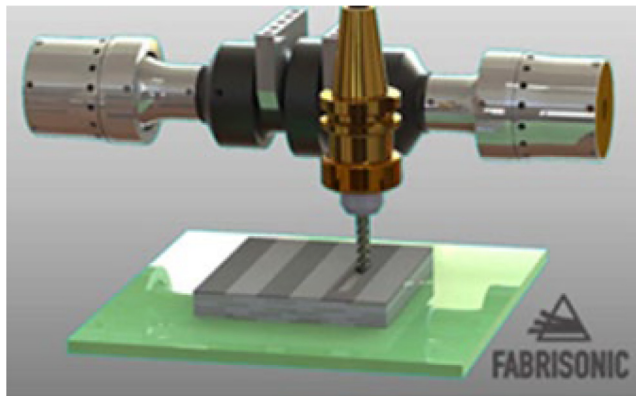


Fig. 20. Fabrisonic ultrasonic subtractive manufacturing, after [54,55].

modify a traditional CNC machine tool by mounting an ultrasonic welding head in the spindle. The welding head is treated as another tool in the tool magazine. Fig. 19 shows the ultrasonic hybrid additive head, while Fig. 20 shows the subtractive head.

7. **Vat polymerization** – Vat polymerization was the first 3-D printing process to be commercialized. In vat polymerization, a light source is used to selectively harden a liquid polymer. Recently, Digital Light Projection (DLP) systems have significantly reduced the process time. No hybrid metal additive-subtractive systems using vat polymerization have been found at the time of this writing.

2.2. Retrofit hybrid metal additive/subtractive machine tools

For many users of conventional machine tools, the quickest path to a hybrid metal additive/subtractive machine tool is through a retrofit of an existing machine tool. In fact, the earliest example of a hybrid metal additive/subtractive machine tool [105] used a laser blown powder head mounted on an Albrecht Rödgers high-speed machine tool to produce several simple geometries for mechanical testing, as shown in Fig. 21.

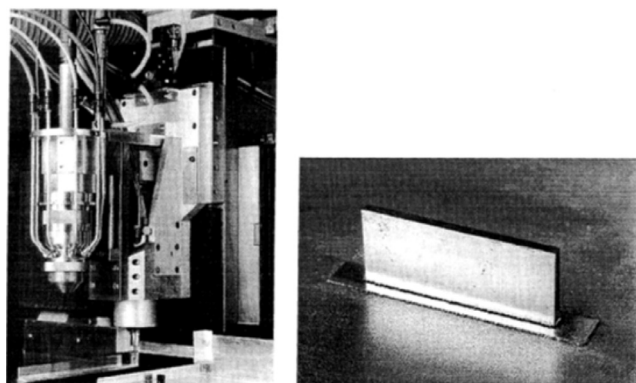


Fig. 21. An early retrofit laser blown powder hybrid machine tool [105].

Karunakaran [95–97] reported a similar retrofit arrangement. Fig. 22 shows a three-axis Tormach machine tool that has been retrofitted with a Tormach robot and a Lincoln Electric MIG welder for wire arc AM. This hybrid machine tool is small enough to fit in the Spallation Neutron Source Vulcan beam line at Oak Ridge National Laboratory to enable in-situ measurement of strain evolution during the additive and subtractive processes [156]. Fig. 23 shows a commercial gas metal arc welding tool mounted adjacent to a machine spindle in a three-axis machine tool [208]. The torch was triggered using a signal from the machine controller. A fixture plate was designed to isolate the machine from the welding process heat and electrical current. The wall shown in Fig. 23 was deposited using a 5356 aluminum wire.

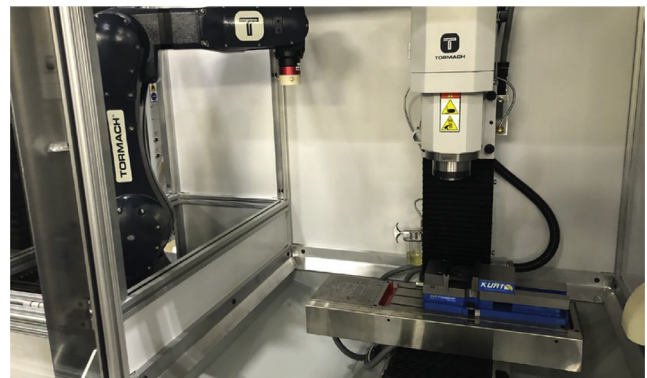


Fig. 22. Tormach machine tool retrofitted with a robotic wire arc AM system.

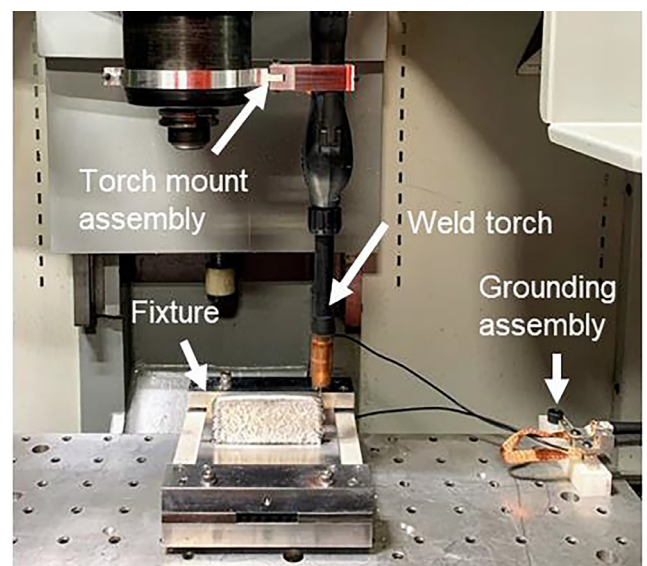


Fig. 23. Retrofit wire arc additive hybrid machine tool [208].

Krimpenis [108] described a robot with an interchangeable head to perform both an additive process and a milling process, as a hybrid machine, although his design study does not indicate whether the robot would have sufficient stiffness for accurately milling metal.

Akula [6] described an experimental arc welding and CNC machine tool, and he considers the need for heat treatment or hot isostatic pressing after deposition. Sutisna [194] described a small-scale desktop hybrid research system. Yamazaki [215] showed the development of retrofit deposition heads for implementation on existing CNC equipment. Brøtan [26] evaluated the integration of powder bed fusion with high-speed machining. Choi [33] described the integration of CO₂ laser deposition on a conventional milling machine. Ye [219] showed the integration of a high-speed milling head on an existing pulsed laser wire deposition machine. Kapil [94]

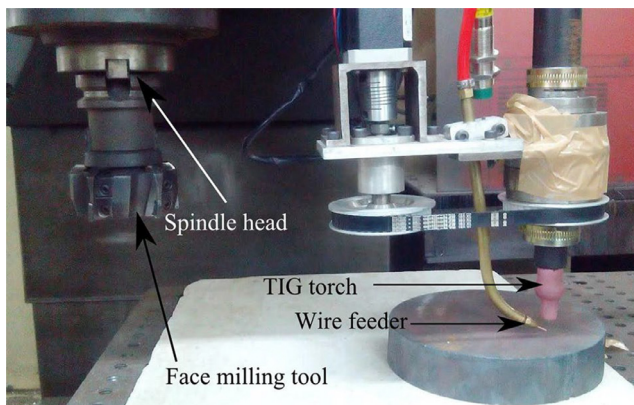


Fig. 24. Machine tool retrofitted with a TIG-based additive system [94].

demonstrated a retrofit system using a tungsten inert gas (TIG) welding head as shown in Fig. 24.

These and similar retrofit hybrid machine tools have mostly been used in research laboratories and as commercial test beds, to create samples for material testing or to demonstrate the feasibility of hybrid metal additive/subtractive manufacturing. However, several companies now make commercial retrofit packages that can be more highly integrated into existing machine tools. Fig. 25 shows some of the retrofit options provided by Hybrid Manufacturing Technologies [82]. Hybrid Manufacturing Technologies primarily focuses on laser cladding, but it offers a variety of other heads that mount directly in the spindle of a machine tool. Hybrid Manufacturing Technologies collaborated with Elb-Schliff WZM GmbH to offer millGRIND, a creep feed grinding machine with blown powder deposition [11]. Mitsui

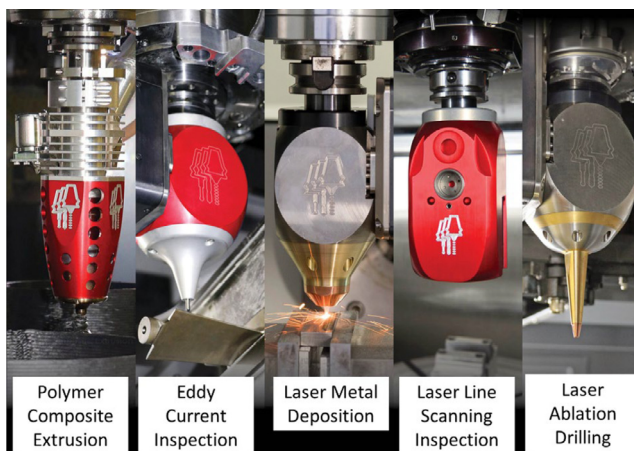


Fig. 25. Hybrid manufacturing technologies spindle-mounted retrofit laser heads, courtesy of hybrid manufacturing technologies.

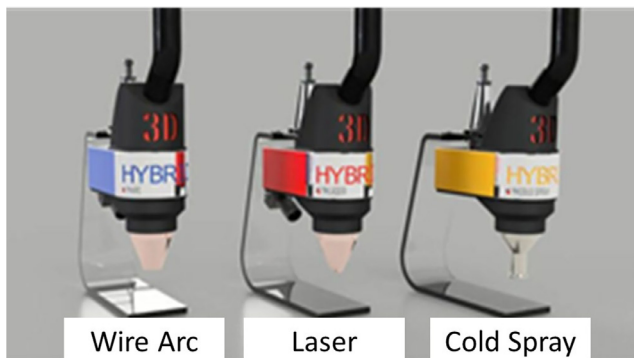


Fig. 26. Retrofit heads from 3D Hybrid [1].

Seiki announced a hybrid machine, the Vertex 55X-H, with spindle mounted laser DED [174]. Fig. 26 displays a selection of retrofit heads provided by 3D Hybrid, that provide wire arc additive, laser hardening, and metal cold spray retrofit options for machine tools [1].

Many retrofit spindle-mounted systems require both a mechanical spindle connection and a separate connection to the machine for power, wire or powder delivery, or sensor output. Fig. 27 shows a commercially available connection and a similar connection developed by [146].



Fig. 27. Retrofit spindle mounted deposition heads showing auxiliary connections [82,146].

Li [118] demonstrated a retrofit hybrid machine tool where a robot arm capable of laser powder DED is mounted adjacent to the pallet load station of a machine tool, as shown in Fig. 28. This arrangement has the advantage of providing better separation between: 1) the heat of the deposition process and the contamination of unmelted metal powder and 2) the precision motion components of the machine tool. Fig. 29 shows a demonstration part made using a 3D Hybrid retrofit machine tool [1].

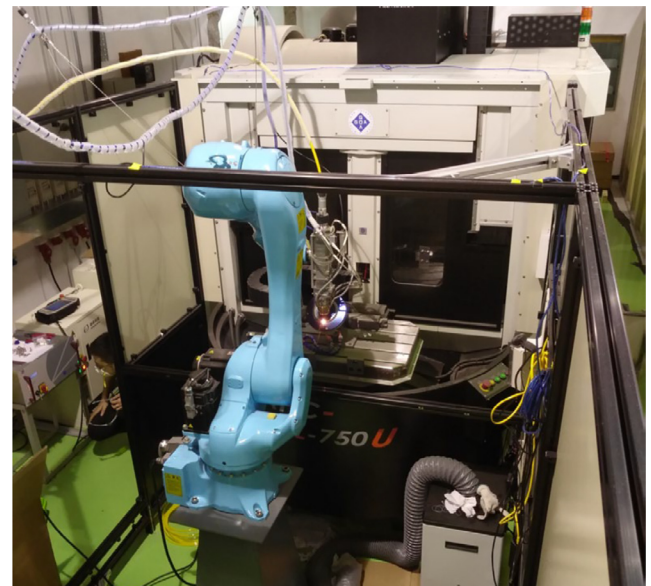


Fig. 28. A retrofit hybrid machine tool with deposition adjacent to the load station of a machine tool with a pallet exchange [118].

2.3. Workspace and reach and access considerations

For hybrid additive/subtractive machine tools, the additive head is typically either mounted side-by-side with the subtractive head or it is mounted directly in the spindle of the subtractive head like a tool. Fig. 30 shows a hybrid additive/subtractive machine tool where Philips Corp. integrates a Meltio deposition head in a Haas machine tool [155].

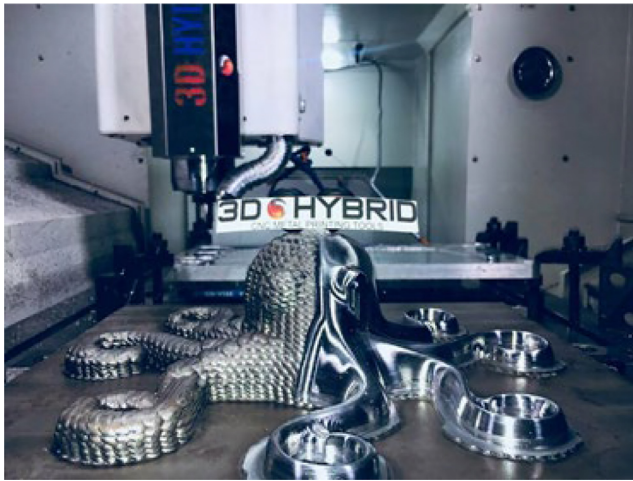


Fig. 29. Retrofit hybrid demonstration part [1].



Fig. 30. Accessible workspace for side-by-side mounting.

Superimposed on the Fig. are two overlapping rectangles that notionally represent the X Z workspace accessible by the two processes. The workspace accessible by the milling spindle is indicated by the green box, and the portion of the workspace accessible by the additive head is indicated in red. In the middle is the overlap area accessible by both systems for hybrid additive/subtractive manufacturing. The side-by-side arrangement limits the available hybrid workspace. Of course, the position of the additive head relative to the subtractive spindle has to be calibrated. These considerations are not unique to this combination, but rather represent a common side-by-side limitation. Both [90,128] argued that a side-by-side arrangement as shown in Fig. 30 restricts the X-direction workspace, and that a spindle-mounted system avoids that problem. However, spindle-mounted deposition systems are larger than typical tools, and they sacrifice workspace in the Z direction.

Fig. 31 shows a Hybrid Manufacturing Technologies additive head mounted in the spindle. In this case, the cutting tools can typically reach the entire workspace of the machine, but the geometry of the additive head consumes some of the otherwise usable workspace. The overlap area is close to the table. Some of the Z workspace is not

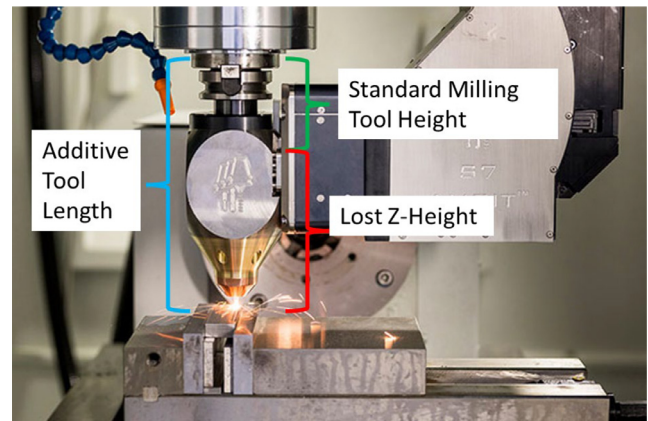


Fig. 31. Common hybrid workspace restriction for a spindle-mounted additive head.

available for hybrid manufacturing, and longer-than-typical tooling may be required to reach the table.

As demonstrated in the Section 2.1 to 2.3 examples, the workpiece location is fixed, and access is provided by motion of the deposition and machining heads in a hybrid additive/subtractive machine tool. The outcome is that the workpiece does not have to be refixedured between material addition and subtraction. Because it is possible to iterate between additive and subtractive operations, new design options are possible for both internal and external features. Additionally, if there is an error in either the additive or subtractive process, it is possible to remove the error, deposit new material, and machine again. This is further described in Section 5.

2.4. Shielding gas delivery and containment

The additive processes in hybrid metal additive/subtractive machine tools typically require shielding gasses, sometimes also called cover gasses. The shielding gas has at least three primary functions:

1. Prevent the hot or molten deposited material from reacting with the environment (usually oxygen, nitrogen, hydrogen, or water vapor),
2. Maintain a stable arc and weld pool,
3. Remove debris and fumes generated at the melt pool, since the fumes could interfere with the laser beam and the debris could create defects in the deposited material.

Different shielding gasses are chosen depending on the metal and the deposition process. Argon and helium are often used because they are unreactive. Argon is obtained from liquified air through fractional distillation. Helium, by contrast, is scarce and expensive (being mined from natural gas deposits, where it is the by-product of decaying uranium and fossil fuels). Other less-expensive shielding gasses include nitrogen and carbon dioxide.

The gasses are supplied to hybrid machine tools in one of several common ways. Fig. 32 shows the shielding gas supplied around the hot wire in laser hot wire deposition [127]. Fig. 33 displays coaxial delivery of metal powder for a DED system [77]. The shielding gas provides a shroud around the laser energy source, blown powder, and melt pool. In both methods, while the build chamber may have some containment features, it is typically not sealed, and the shielding gas is not recirculated. Fig. 34 shows the gas flow system for laser powder bed fusion [206]. For powder bed systems, the work volume is sealed, and the shielding gas is blown across the powder bed in a uniform flow created using a gas flow rail (lower inlet in the figure). The flow is measured with 3 hot-wire anemometers (HWAs), and the gas is recirculated and filtered in this case.

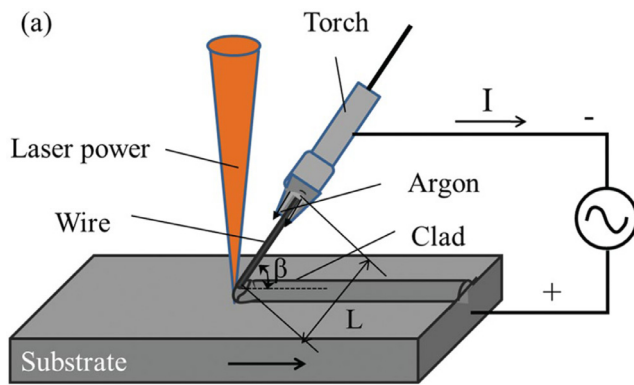


Fig. 32. Shielding gas supplied around the hot wire in laser hot wire deposition [127].

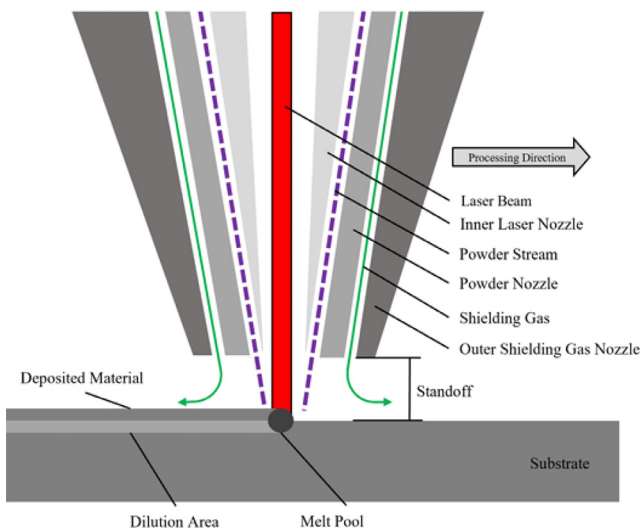


Fig. 33. Coaxial shroud gas for a blown powder system [77].

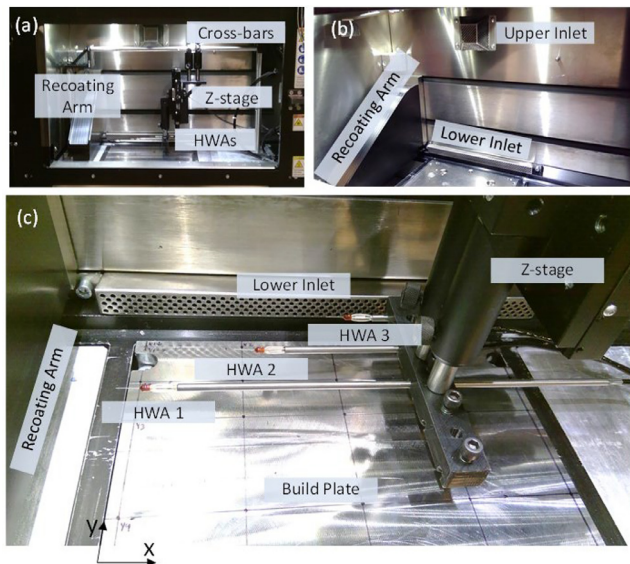


Fig. 34. Shielding gas supply for laser powder bed fusion [206].

2.5. Management of coolant and waste products

Lorenz [128] described the need to shield the laser optics from coolant, chips, and powder in hybrid blown powder systems, both for beam integrity, and to prevent laser damage from the reflected beam. There is also a need to manage the residual powder that makes its way into the coolant collection system. The powder is generally too

small to be removed by the normal chip evacuation system, and it is small enough to enter the fluid lines. Zelinski [221] said that in powder-based hybrid systems, “Because some metal powder invariably escapes, preserving the machining precision demands ensuring that the powder does not affect sensitive mechanical systems such as the ball screws and ways”. He stated that the protection mechanisms engineered for graphite milling are suitable. He also noted that coolant and lasers are generally not compatible, and he described Mitsui Seiki’s solution of first removing the bulk of the residual coolant with an air blast, and then evaporating the rest with the laser on wide focus. However, some recent studies have shown that the increased humidity inside of the build chamber as a result of the cutting fluid does not affect the mechanical properties of the alloys processed in hybrid manufacturing systems [162], although this is material dependent.

2.6. Safety features

The additional safety features required for the addition of hybrid additive processes to subtractive machine tools have much in common with the safety features developed for additive-only equipment. They are not unique, but they are new for machine tools. In an interview with Okuma, [222] described safety tips related to the use of a blown powder hybrid machine tool including laser safety procedures, preventing powder exposure, restricting access to shop air, safeguarding against sparks, and protecting against the coolant/powder slurry using the same features that would be found in a machine for milling graphite. The safety equipment can be divided into several broad categories:

- 1. Protection from laser or arc** – Cortina [36] noted, “Besides protecting the machine operator from collisions, the guarding of the hybrid machines needs to be capable of retaining the high-intensity light generated by the laser inside the machine and to withstand the heat generated during the additive process. Reflections of the laser beam when highly reflective materials are being processed (e.g., aluminum, copper) may result in the melting of specific areas of the guarding or other sensitive elements and, therefore, proper protection must be arranged.” Most (if not all) of the lasers used as heat sources in hybrid additive/subtractive machine tools are Class 4, meaning that the laser is capable of causing eye damage, burning skin, or igniting combustible materials. Laser-safe windows and extra shielding are used on these hybrid machine tools to ensure that they are “light tight.” Similar protection is required to shield users from the UV and visible radiation created in arc welding systems.
- 2. Protection from metal powder inhalation, exposure, explosion** – Similarly to all metal powder additive manufacturing equipment, hybrid additive/subtractive machine tools that use metal powders require special safety precautions. Respirators and flame-resistant clothing are commonly used whenever the powder is handled. Metal powder can produce plumes of dust, and settling time can be an issue. The particulate size range for DED, is typically between 45 and 106 μm [59], which settles quickly, while for laser powder bed fusion the particles are typically below 45 μm and the settling time is long. Metal powders can pose explosion hazards if the powder is dispersed in the air, and there is an ignition source. For powder based hybrid systems, there must be safeguarding against sparks, and special vacuum systems are used to remove the powder from around the part. In blown powder systems, filtration is used to remove the unmelted powder from the coolant to avoid clogging the coolant delivery system and damaging the pumps. Similar coolant regeneration systems are often seen in high performance grinding.
- 3. Protection from shielding gasses** – The shielding gases used in hybrid machine tools are not, themselves toxic, but they are odorless, colorless gases that do pose a risk of oxygen displacement. If the machines are installed on large manufacturing floors with significant open space, that may not be a problem. However, if the equipment is installed instead in smaller rooms, then oxygen

sensors should be used, and may be required by law. Additionally, some deposition processes produce gasses or particulates that should be vented outside of the building or removed using HEPA filtration.

4. Collision avoidance - Many machine tool manufacturers provide simulation and collision detection as part of their human/machine interface (HMI). These systems analyze and simulate the G-code to ensure that no collisions occur due to errors in CAM programming, or due to manual edits after the post-processing of the G-code. DMG Mori's Machine Protection Control, Okuma's Collision Avoidance System (CAS), and Mazak's Intelligent Safety Shield are just a few of the integral collision avoidance systems offered [58]. In addition to the onboard collision detection, many CAM software systems also provide collision detection for additive and subtractive operations. All collision detection requires accurate models of the machine components, workpiece, tooling, fixtures, and especially the very sensitive deposition equipment like the laser head.

3. Sensors and process management

While many sensors are available for both additive and subtractive machines separately, this section highlights some of the most useful sensors for the hybrid metal additive/subtractive machine tools.

3.1. Thermal imaging and heat management

Management of heat in a hybrid metal additive/subtractive machine tool is important for material properties, residual stresses, and machine and part geometry errors. The heat generated during the deposition and removal process is transferred into the machine tool structure by conduction, convection, and radiation mechanisms. The machine tool typically represents a large thermal capacity, so the thermal distortion and associated positioning errors may be small for short deposition times. However, for production runs of hours or days, the thermal load can degrade the machine tool accuracy significantly.

Feldhausen [57] described closed loop control in a hybrid metal additive/subtractive machine tool, focussing particularly on thermal imaging for deposition process and build temperatures. Fig. 35 shows their concept of the available data sources. Kledwig [104] reported a camera-based coaxial temperature measurement system on a DMG MORI LT 65 3D hybrid machine tool. Monitoring the weld pool temperature allows real-time correction of the laser power and feed rate, and subsequently, a stable deposition process. Fig. 36 shows the configuration of the sensor and a representative thermal measurement.

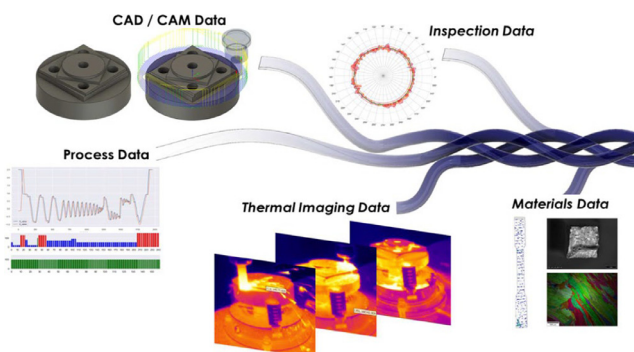


Fig. 35. Integrating multiple data sources including thermal imaging data [57].

3.2. Weld pool size

Nagel [142] described a coaxial measurement using a dichroic mirror, and he compared both melt pool size and temperature

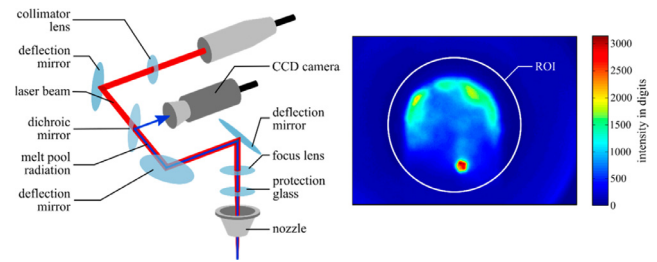


Fig. 36. Coaxial measurement of the melt pool temperature in a blown powder hybrid machine tool [104].

measurements with the results from simulation. Alexander [5] was able to use multiple machine learning methods to predict the bead geometry of a blown powder DED process with less than a 4% error. Gibson [67] showed precise control of DED bead geometry with a closed-loop control system that operated at 200 Hz. This level of melt-pool control is difficult to achieve in machine tools. As described by [60], machine tool builders typically prevent user access to the machine tool control hardware and software, so few robust closed loop control systems have been developed for commercially available hybrid machine tools.

3.3. In-process dimensional metrology of the part

Wang [205] used a laser displacement sensor to scan the geometry of the deposited preform during hybrid additive/subtractive manufacturing. He reported the resolution to be as small as 10 μm . Fig. 37 shows the laser displacement sensor scanning a deposited sample on a Ti6Al4V substrate. Thien [197] recognized that the wire arc deposited preform differs from the intended geometry. They described several methodologies for approximating the deposited preform surface topography using on-machine contact probing. They used the probed approximation of the geometry as the stock model for the subtractive operations.

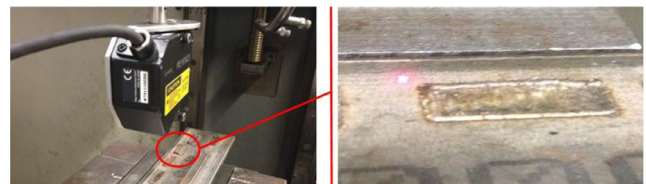


Fig. 37. In process laser displacement scanning of Ti6Al4V [205].

4. Process planning considerations and software

The software systems used to generate numerical control (NC) programs for subtractive machine tools are highly developed, and they are widely available in a range of capabilities and prices. The basic steps involved include:

- definition of the part geometry,
- definition of the stock (preform) geometry,
- selection of the fixturing and cutting tool assemblies,
- generation of the machine motions to remove excess stock, and reveal the finished part geometry,
- simulation of the required motions to check for errors,
- inspection.

The software available to generate machine motions for subtractive are plentiful. The user must choose among available machining strategies (like spiral-in or zig-zag tool paths for pockets) and make other choices, such as axial and radial depths of cut, and spindle speed.

The software for additive machine motion definition is somewhat less well developed, but they are also widely available. The definition

of the part geometry is the same, but the generation of the machine motion is different. In some systems, the part solid model is sliced into layers, and the machine motion that positions the deposition head is then defined for each layer. In other systems, the user starts with the part geometry, and then uses standard subtractive tool path generation to remove all the material. That tool path is then played backward to generate the deposition path [58].

[103] described a process planning system for AFSD and milling that combines additive and subtractive processes with structured light scanning to produce metal components while considering the unique requirements imposed by the hybrid manufacturing process sequences. Fig. 38 depicts his proposed workflow. In a similar way, [38] developed a process planning tool that was intended for Friction Stir AM and milling, using it to create functionally graded materials and embedded structures. He [75] showed a hybrid process planning algorithm that used four manufacturability indexes: 1) material utilization, 2) manufacturing cost, 3) manufacturing time, and 4) local machining complexity, which are combined in a weighted score that is used to judge the suitability of a hybrid part program.

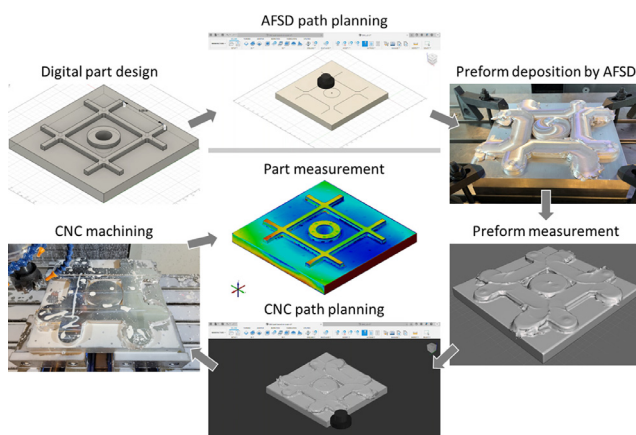


Fig. 38. Process planning for hybrid metal additive friction stir deposition and machining [103].

Basinger [19] described a modular computer-aided process planning (CAPP) system for additive/subtractive hybrid manufacturing of pockets, holes, and flat surfaces. Fig. 39 shows the workflow. Behandish [20] defined a hybrid CAPP approach that used Boolean operations to combine additive and subtractive primitives, while respecting spatial constraints, such as accessibility and collision avoidance. Abdulhameed [3] detailed a CAPP system that attempted to determine preferable part orientations and to minimize both additive and subtractive times.

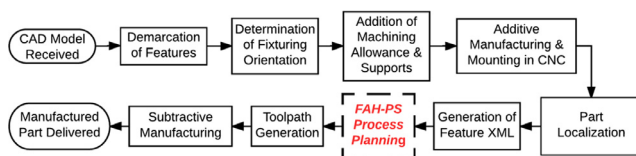


Fig. 39. Proposed CAPP workflow [19].

Chen [30] and [31] proposed a framework to choose the interleaved sequence of additive and subtractive steps considering reach and access. Fig. 40 shows the tool paths for a complex four-column geometry created as a sequence of additive and subtractive stages. The selected part geometry would be difficult to achieve using conventional machining processes. Dávila [40] proposed the creation of modular visual algorithms to allow the progressive extension of the parameters and strategies for infill, machining, grinding, and measuring.

Elser [53] discussed the limitations of producing process plans using separate additive and subtractive CAM systems, particularly when it is desired to iterate between additive and subtractive operations. The key challenge of sharing geometry data between platforms

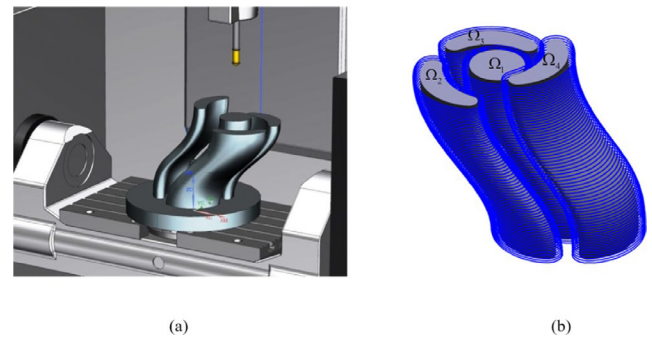


Fig. 40. The finished part geometry (a), and the surfacing tool paths (b) automatically selected for an interleaved additive and subtractive process plan for a complex part [30].

was identified, and the requirement for an integrated hybrid CAM platform was emphasized. Hur [81] presented an automated system to discretize a given workpiece model into deposition features and machinable features for automated hybrid programming. Ruan [170] defined an adaptive slicing algorithm for a five-axis hybrid process. The intent was to generate uniform and non-uniform thickness slices by interleaving additive and subtractive processes. Hu [80] noted that the selection of build orientation impacts the geometrical aspects of build time, required supports, bridges, and subtractive tool reach and access. Joshi [91] proposed a complexity score metric to assist in developing a process plan that integrates both additive and subtractive processes. He used STL slicing and voxelization combined with heuristics to demonstrate the beginnings of a new process planning tool for hybrid part manufacture. Similarly, [98,99, 100], and [101] proposed the decomposition of components into modules, each of which may be preferentially produced by additive or subtractive processes. Fig. 41 shows a sample part with complexity of manufacture indicated by the color scale. Le [113] presented process planning design rules to aid in the sequencing of additive and subtractive operations. For example, in regard to precedence of operations, "...If a machining provides the starting surface for the build of an AM feature, the machining feature is the precedence of the AM feature, and it must be processed before the AM feature. On the other hand, an AM feature is the precedence of machining features, if it provides the rough state for these machining features." Sun [192] proposed an integrated method for geometric simulation of both additive and subtractive processes. Xie [211] provided a detailed description of process planning for a hybrid aviation bearing bracket including machining simulation and thermal modelling.

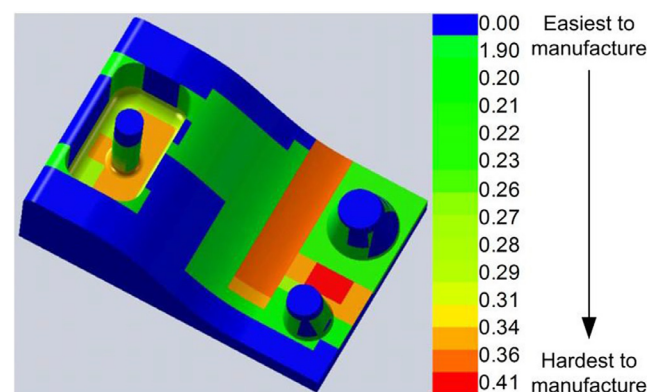


Fig. 41. Modularization of the finished part by ease of manufacture for selection of additive or subtractive processes [101].

5. Part design space

Increased design space motivates the design and development of hybrid additive/subtractive machine tools. Specifically, the

combination of additive and subtractive capabilities in the same work volume enables the creation of features and sequences of operations that would be otherwise difficult. Grzesik [71] listed the primary motivations for the selection of hybrid additive/subtractive processes as:

- enabling part repair,
- improving surface finish of additive parts,
- improving dimensional accuracy of additive parts,
- enabling the creation of difficult geometric features, and
- enabling multi-metal parts.

While the number of hybrid additive/subtractive use cases has significantly expanded. Zhu [224] stated, "... hybrid technology is currently only suitable for small batch production of customised products rather than for mass production." His review showed that the primary application currently is the production of injection molds and dies.

5.1. Difficult-to-create features

One of the major benefits of hybrid additive/subtractive manufacturing is the ability to create parts that would be difficult to produce with additive or subtractive processes alone [177]. An example of a difficult-to-create feature is conformal cooling channels in tooling or functional parts. Cortina [37] showed a conformal cooling channel created by additive manufacturing that closely follows the functional surface, as shown in Fig. 42. The bottom portion of the channel is machined in 316 stainless steel, while the top is deposited H13 tool steel. Note that the top of the channel has a sharp intersection as a result of restricting the build overhang. Boivie [22] reported a larger scale tool with conformal cooling for a chair mold as seen in Fig. 43.

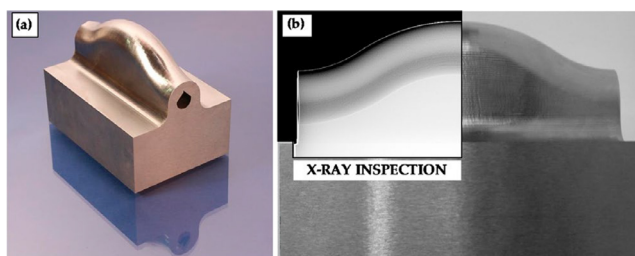


Fig. 42. Conformal cooling channel (a) and X-ray image (b) [37].

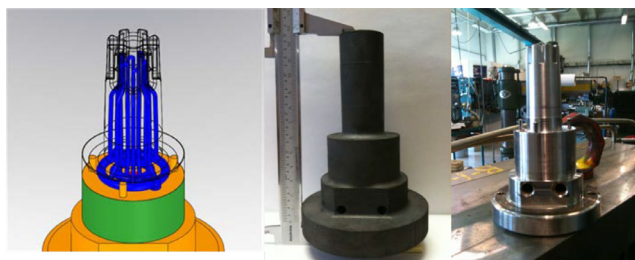


Fig. 43. Conformal cooling chair mold insert [23].

Feldhausen [61] demonstrated the ability to generate conformal cooling channels for a mold using a blown-powder DED hybrid manufacturing system, as shown in Fig. 44. Here, the cooling channels were deposited at an oblique angle to overcome overhang limitations. The unmelted excess powder from the blown-powder DED process, which is often problematic, was also found to provide support of the overhung channel during the deposition process. This is analogous to the bed of powder providing support in laser powder bed fusion. Blakey-Milner [21] described a hybrid process chain for Inconel 718 using DED with wire filler material and conventional machining. The project focused on reducing both material quantities

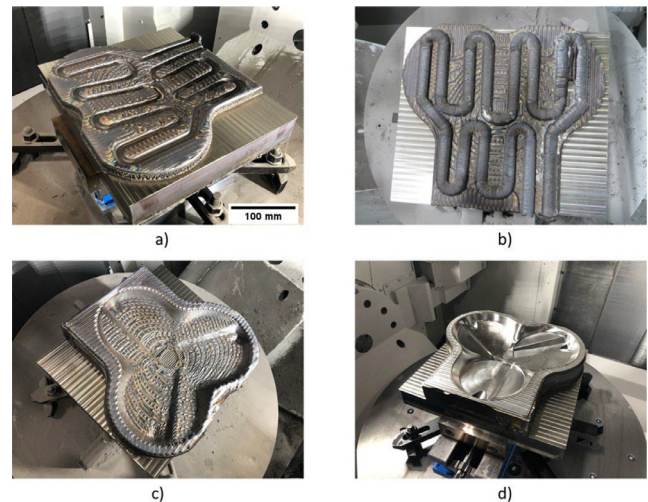


Fig. 44. Various stages of mold manufacturing: (a) bottom half deposited up to mid-point of cooling channels, (b) deposited cooling channels, (c) finished deposition of mold bottom, (d) finished mold [61].

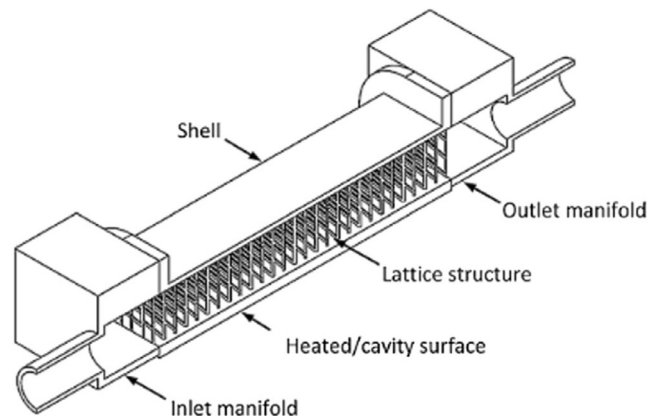


Fig. 45. Hybrid hot stamping die concept with internal cooling [29].



Fig. 46. Mold cavities and the exchangeable inserts (baffle and conformal cooling) [133].

and machining times to decrease tool costs. Chantzis [29] proposed a hybrid design for hot stamping die tooling that included internal cooling as shown in Fig. 45. Marin [133] presented the use of hybrid additive/subtractive processes to create injection molding cavities and exchangeable inserts with both baffle and conformal cooling channels in stainless steel, as shown in Fig. 46. Shinde [179] suggested that the use of hybrid additive/subtractive machine tools to create conformal cooling channels could become a standard procedure in the manufacture of tooling for extrusion, die casting, and more.

Another example of a difficult-to-machine feature is the closed pump impeller described by [167]. The challenge is that the surface finish for difficult-to-access internal features directly affects impeller

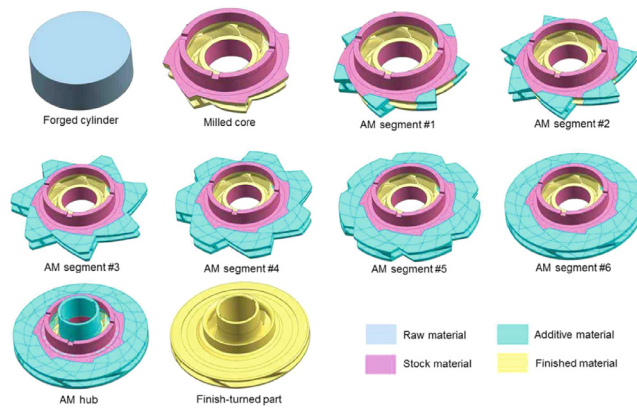


Fig. 47. Hybrid process plan for a closed pump impeller [167].

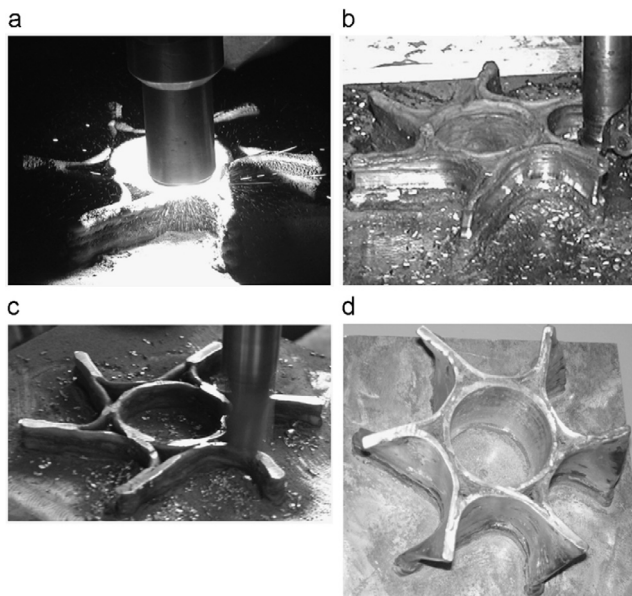


Fig. 48. A Nickel superalloy double-helix impeller [212].

performance. By using a hybrid process, all surfaces of the impeller, even those not accessible for milling tool in the final state, can be machined with high accuracy and surface quality. Fig. 47 shows the hybrid process plan steps. Xiong [213] described the hybrid manufacture of a metal vane, [214] showed the manufacture of a metal vase, and [212] reported the manufacture of a double-helix integral impeller in GH163 nickel superalloy using plasma deposition and milling, see Fig. 48.

5.2. Part repair and modification

Repair of damaged components is a growing application area for hybrid machine tools. Researchers in this area are typically seeking to repair parts that are damaged in service, like turbine blade tips or dies and molds. If the bulk of the part can be retained, and only the damaged section must be replaced, hybrid process repair introduces cost, energy, and time savings.

Similarly, if there is an error in programming or part alignment, or if chatter occurs during material removal during the manufacture of a part on a non-hybrid machine, the part is often scrapped. The loss includes the cumulative embodied energy in the part, the material cost, and the full time invested up to that point. By contrast, in a hybrid machine it is sometimes possible to remove the error by machining, additively redepositing preform material, and then correcting the error. The outcome is saving the part and avoiding the losses that occur when scrapping the part.

Stavropoulos [189] defined a hybrid system to identify, select, and remove damaged sections of an existing component, deposit new material to overbuild the functional surface, and then finish the geometry by machining. Fig. 49 shows the proposed workflow.

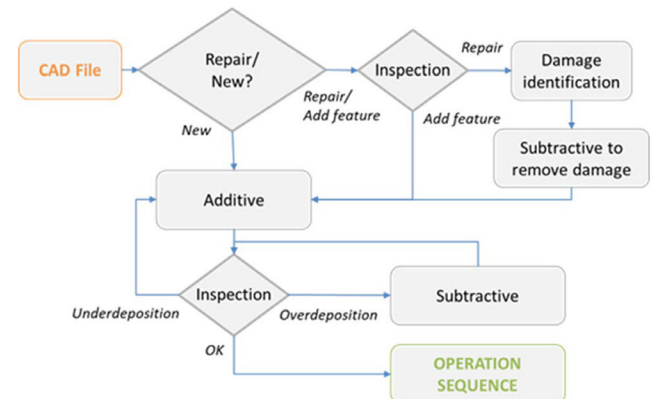


Fig. 49. Process flow for damaged part repair or creation of a new part [189].

Re-Plan, a hybrid process remanufacturing system developed by [144] consists of the steps shown in Fig. 50:

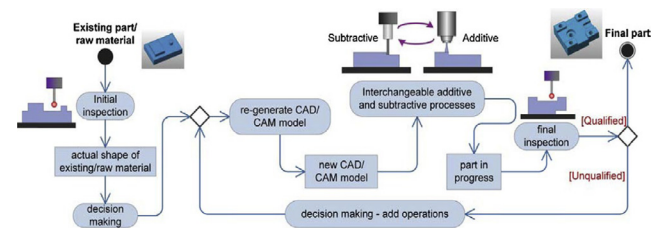


Fig. 50. The Re-Plan process flow [144].

- The existing raw material is measured to obtain its geometry, which becomes the basis of the process planning approach for determining subsequent operations.
- A new CAD model is generated, which defines the material required to produce the new part. Based on the existing part and the new part features and geometries, a feasible manufacturing strategy is selected. Additive, subtractive, and inspection processes are combined to produce the final part.
- The part is further inspected to determine if dimensions are out of tolerance and, if so, to identify the part as unqualified. For such parts, hybrid manufacturing operations may be added to obtain dimensions that are in tolerance.

Jones [89] described remanufacturing of a damaged titanium turbine compressor blade. The steps in the process shown in Fig. 51 highlight that the successful combination of additive and subtractive processes on a machine tool also requires the integration of dimensional metrology.

Ren [164] and [165] discussed hybrid additive/subtractive part repair for damaged dies. Similarly, [52] proposed hybrid additive/subtractive manufacturing for custom modifications of standard part families, increasing the variety of offerings. Grzesik [70] and [72] showed a method for the repair of a large turbine blade using a blown powder deposition head mounted in the spindle of an existing blade machining system, as shown in Fig. 52.

Liu [124] demonstrated the hybrid manufacture of a satellite thruster structure consisting of a machined 316L stainless steel body with an interior cavity, onto which a 316L stainless steel nozzle was deposited by selective laser melting, as shown in Fig. 53. Jeng [87] demonstrated the feasibility of creating a tool for injection molding

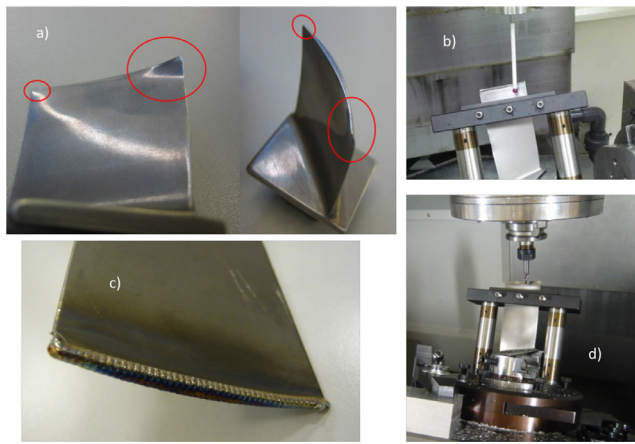


Fig. 51. Turbine blade repair process: a) identifying the damaged areas, b) locating the part in the machine and removing the damaged areas, c) building up a new preform, and d) machining to the finished shape, blending with the previous surface [89].



Fig. 52. Hybrid additive/subtractive repair of the edge of a large turbine blade [70].

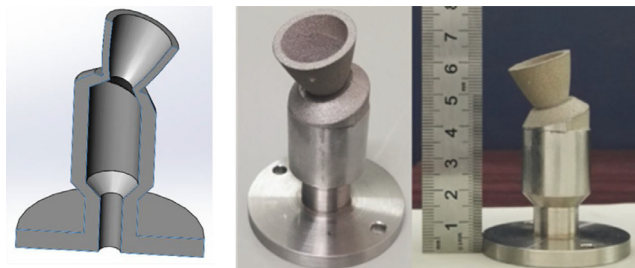


Fig. 53. A 316L satellite thruster structure made by depositing a nozzle onto a machined substructure using selective laser melting [124].

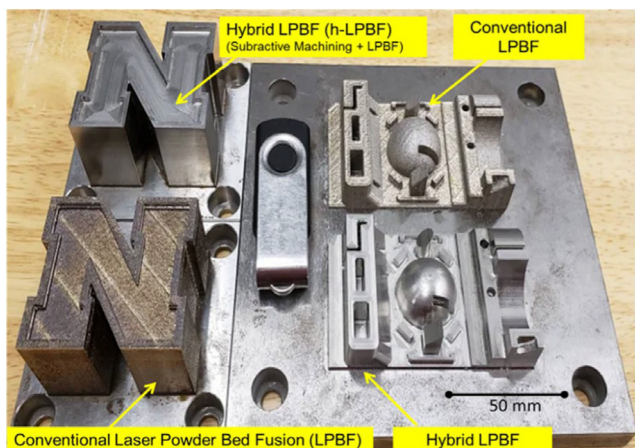


Fig. 54. Example artifacts comparing the surface finish and resolution of conventional and hybrid LPBF processes [168].

and of modifying a tool for injection molding using a combination of selective laser cladding and milling. Riensche [168] showed significant surface improvement in parts made by laser powder bed fusion followed by machining as shown in Fig. 54.

5.3. Multi-material structures

As stated by [143], the combination of multiple materials to produce intricate geometries can provide new functionality, improved mechanical properties, environmental compatibility, and improved interfaces. Application domains include functionally graded materials; aerospace, automotive, and biological components; multi-layered electronics; soft sensors and robotics; and nature-inspired design concepts. For example, [102] described a strategy for cladding materials with dissimilar coefficients of thermal expansion. He demonstrated the principle with the addition of copper cladding to a nickel alloy substrate as shown in Fig. 55.



Fig. 55. Copper clad on a nickel-based alloy, Reproduced from [102], with the permission of the Laser Institute of America.

The repair of a damaged part can include multi-material augmentation. Fig. 56 shows a punch for aluminum sheet in an automotive application. The punch was originally H13 steel, but after the cutting edge became worn, it was replaced with a Stellite edge using a hybrid process. Kannan [93] explored using DED in a hybrid machine tool to generate steel-aluminum bi-metallic structures. These bi-metallic structures are an attractive option for automotive applications where aluminum offers a light-weight solution while steel provides strength and low production costs. While extensive cracking at the interface was observed in this research, others such as [60] have investigated using milling to generate interfacial features that support subsequent deposition. There are also examples of multi-material hybrid processes that combine metals and polymers. Wefflen [207] describes machining interlocking dovetail features in aluminum part to retain an additively deposited polymer layer, while [111] describes the deposition of metals onto polymer support structures.

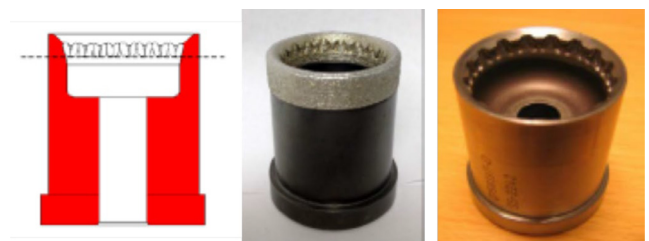


Fig. 56. An H13 aluminum sheet punch repaired with a Stellite cutting edge [24].

5.4. Embedded sensors

Korkmaz [107] points out that "...with traditional manufacturing or forming processes, it's almost impossible to put mechatronic devices inside of a component in a way that makes it structurally sound. However, with hybrid manufacturing, this can be achieved due to the

layer-by-layer manufacturing approach.” He proposes biomechanical devices with a fully enclosed RFID tag, vibration sensors for predictive maintenance of machine tools, and sensors to monitor wear and temperature of metal-forming tools. Soshi [185] describes a new mold fabrication technique that begins with a grid of prefabricated blocks, that comprise the bulk structure, then follows with DED and milling to produce the functional mold surface. The prefabricated blocks, as shown in Fig. 57, can include cooling channels and sensors, such as thermocouples and accelerometers. Juhasz [92] demonstrated a proof-of-concept implementation of an internal, passive sensor printed into a hybrid manufactured metal structure during an in-situ process interruption. An optimized DED process for stainless steel was identified to allow for the inserted piece to be sufficiently thick to protect the sensor from the temperatures of the laser cladding process. Similar work by [62] showed how excess metal power can be used to embed a piece of ceramic into a 316L component produced by DED. Insulator-wrapped optical fibers and electronics were embedded in metallic structures using friction stir AM and milling in [38].

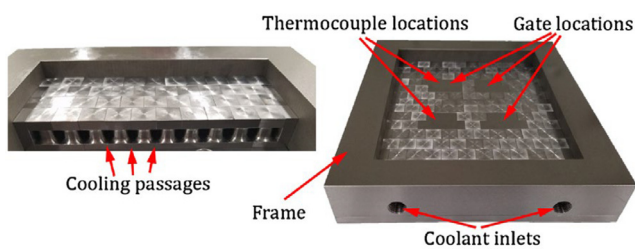


Fig. 57. Grid fabrication for embedded sensors [185].

5.5. Shortened lead times

Mognol [139] used selective laser melting, high-speed machining, and electrical discharge machining, to produce prototype injection molds. He said that prototype injection molds for plastic parts have two primary constraints: 1) they must be designed and manufactured as quickly as possible and 2) their lead time must be short. Riipinen [169] showed a 25 kg part made of EN 1.4316 mold steel using arc welding deposition followed by milling, Fig. 58. The hybrid process was chosen to shorten the lead time.

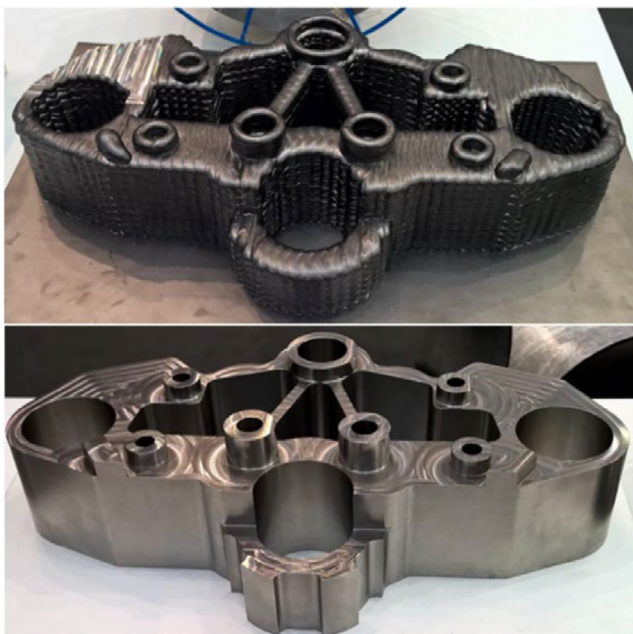


Fig. 58. A 25 kg EN 1.4316 mold steel part made by arc welding followed by milling [169].

6. Outlook and research challenges

Many authors have pointed out pressing research challenges in hybrid metal additive/subtractive manufacturing. Dilberoglu [43] identified in-process measurement, advanced process planning, material testing, tool design, and chip management as the main research opportunities. Guo [73] listed coolant management, thermal condition of the part and machine, powder management and containment, safety related to reflected laser light, the lack of suitable industry standards, integrated additive/subtractive process planning, and real time sensing of the process condition and part geometry as key challenges. Iqbal [84] noted process planning and optimal work distribution between the subtractive and additive modes as areas for further research.

While much previous work has focussed on subtractive processes or additive processes alone, it is their intelligent combination, that provides cost reduction, time reduction, and unique feature creation. Jiménez [88] reported research challenges including machinability of AM parts, optimization of both AM and post processing technologies with a special focus on difficult-to-machine materials, laser-material interactions, part distortion, varying and inconstant mechanical properties and microstructure, powder oxidation inside and outside of the build chamber, the necessity for removing any support structures, and possible collisions. Manogharan [131] said, “The major challenge of integrating AM and subtractive machining in the current hybrid methods is the need for a ‘hybrid process-planning’ protocol for post-processing of AM that accounts for the varying processing nature of AM (material shrinkage, layer thickness, orientation, etc.), machining (tool design, machining allowance, etc.) and part specific attributes (critical features and tolerance requirements)”. Sefene [178] specified the influence of iterative cooling and heating cycles on the properties of the part during the fabrication process and the need for a more sophisticated control and software capability. Dávila [39] listed research challenges as shown in Fig. 59. Yi [220] identified these key research needs:

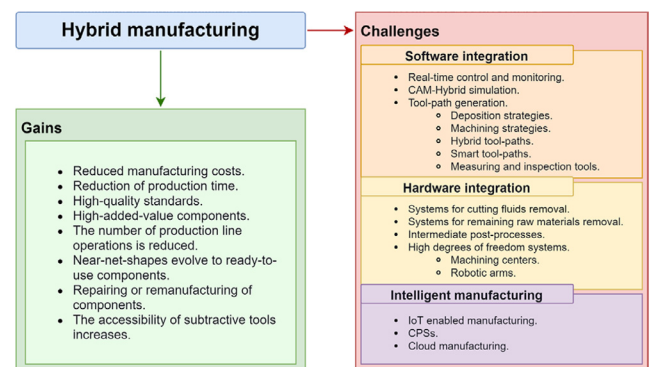


Fig. 59. Hybrid manufacturing opportunities and challenges [39].

- standardization of the method for designing hybrid additive-subtractive process chains,
- development of measures and solutions to monitor, control, and improve the product, and
- improvement in process quality of the additive portion of the hybrid approach

6.1. Material properties

While material properties are generally known for the cast or wrought metal stock used in many machining applications, the site-specific properties of deposited preform materials for hybrid process are not as well understood. The material properties depend on time and temperature histories, deposition settings, deposition strategies, and more. There have been numerous efforts to confirm that materials processed on hybrid machines have suitable material properties

for their intended purposes. Many authors, such as [41], focussed on the creation of tensile test specimens to measure properties of the deposited material, machined material, and interfaces for specific hybrid material systems (AlSi10Mg SLM structures built on AA6082 preforms, in this case). Tomassi [199] reported the mechanical behavior of hybrid AlSi10Mg and A356-T6 aluminum parts. He showed that T6 heat treatment after the additive process improved tensile strength and ductility relative to the as-built properties. Osman [149] suggested that direct aging of maraging steel produced by hybrid additive/subtractive manufacturing is sufficient to achieve comparable hardness and tensile strength to solution heat treatment and aging. Avoiding the solution treatment cycle, with its significantly higher temperatures, could improve the dimensional stability and surface quality of these parts.

Veiga [202] showed that the mechanical properties of a Ti6Al4V wall manufactured by wire arc AM and milling had no significant discrepancies in elastic limit, tensile strength, and elongation to fracture values, compared to conventionally manufactured parts. Yan [216] studied the impact of hybrid additive and subtractive parameters on the microstructure, Vickers hardness, and tensile strength of Ti6Al4V. Similarly, [217] and [218] measured the properties of 316L stainless steel fabricated by blown powder AM and milling, including Vickers hardness and residual stresses. Specifically for interleaved hybrid manufacturing processes, [56] reported that by interleaving additive and subtractive operations to generate a hexagonal structure, overall cycle time was reduced by 68%, average relative elongation to failure was improved by 71%, and the average relative porosity fraction was reduced by 83% when compared to traditional additive manufactured components.

Many authors, such as [7], pointed out the lack of certification and qualification standards for AM, and by extension, hybrid parts. They specified variability in part material properties such as surface defects, voids, and grain structure that depend on the process parameters as an existing limitation to broad implementation. They also noted the significant, typically experimental, effort required to find suitable processing parameters. Gong [68] examined the material properties in a 316L stainless steel part, including the effect of laser parameters on phase, density, microstructure, Vickers hardness, yield strength, and ductility. Hansel [74] considered porosity, yield strength, tensile strength, and percent elongation as a function of blown powder deposition parameters in X2CrNiMo17-12-2 and Inconel 625. Bai [16] studied the material properties and machining characteristics of selective laser melted 6511 steel.

6.2. Alignment

Even though some hybrid additive/subtractive machine tools complete the deposition using the same axes as machining, this does not mean that the preform geometry or its location in the machining work volume is known. In both blown powder and wire-based AM processes, for example, the laser spot may be precisely positioned, that is not true for the melt pool. The melt pool depends on temperature of the substrate, speed of the beam, laser power, the surface tension (which depends on the temperature of the melt pool), and gravity. Additionally, thermal transients can affect the local geometry. In a part with a corner, the machine axes must decelerate when approaching the feature and accelerate afterwards. The change in feedrate affects the local temperature and, subsequently, the material deposition and geometry. Additionally, the combination of heating and cooling transients can embed significant residual strains/stresses in the part. This affects the part geometry, and it can differ significantly from the commanded toolpath. This leads to the same challenges faced when using separate machines for deposition and machining. In either case, the machining tool paths must be generated based on the best location of the CAD model (intended geometry) within the preform using the work coordinate system.

Rather than looking at the part after deposition, both [8] and [69] used sensors to align the additive system with the subtractive system. Amanullah [8] used IR sensors to align the spindle and deposition head, whereas [69] used a vision system to locate a retrofit

deposition robot in the workspace of an existing machine tool. The prediction of distortion and appropriate corrective actions to counteract the distortion remain research challenges.

6.3. Part containment, location, fixturing, and stiffness

The preform created by additive processes must satisfy basic requirements. For example, the preform must contain the part. While that seems obvious, it is not trivial to achieve in practice. Lack of preform containment can result from registration errors between the deposition and removal systems. Additionally, the geometry of the deposited material is not well controlled, which motivates the combination of additive and subtractive capabilities in a single machine. Also, the geometry of the preform changes as it cools due to the coefficient of thermal expansion. Finally, residual stresses may cause part deformation to such an extent that the part is no longer contained. Nagamatsu [141] used a multi-position camera system to create a stock model of the deposited preform, and then adjusted the position of the part in the preform to minimize the amount of material to be removed, see Fig. 60.

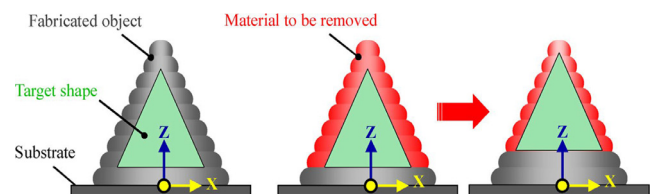


Fig. 60. Movement of the target shape along the Z+ direction to decrease the amount of material removed. (a) Original position (b) Material removed without modification (c) Material removed with modification along the Z+ direction [141].

Even if the part is contained in the preform, it must be possible to locate the part within the preform, and to identify machining tool paths that produce the desired geometry. That is, there must be fiducials or other suitable features on the preform that enable alignment of the part with respect to the machine coordinate system within the computer-aided manufacturing tool path generation software, [50]. Cornelius [34] and [35] described a method to establish and transfer coordinate systems throughout a hybrid process using a fiducial frame that can be temporarily attached to the additively manufactured preform. Structured light scanning is used to create a model of the preform including the fiducial frame. The model of the desired workpiece can then be located within the preform, and the machine tool touch trigger probe can be used to locate the fiducials so that the part contained in the preform can be located in the machine coordinate system. This is shown in Fig. 61.

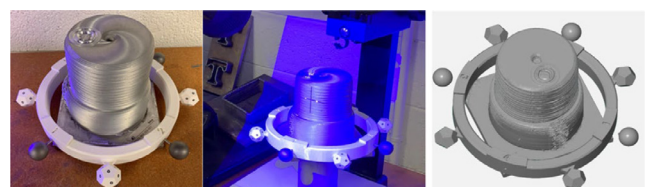


Fig. 61. Establishing and transferring coordinate systems in a hybrid process using fiducials [34].

There must also be features that are suitable for fixturing, and the preform must be stiff enough to support the machining forces that will be encountered. Smith [180] suggested that additive preforms with sacrificial structures could be used to improve the stiffness of the part for later machining. Fig. 62 shows sacrificial buttresses supporting a thin wall and sacrificial ribs supporting a thin floor of a pan. Vaughan [201] also used sacrificial structures to increase the stiffness of thin-walled features. Schmitz [173] shows the creation of an

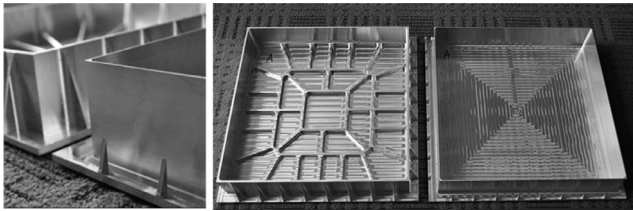


Fig. 62. Sacrificial structures improve the stiffness of a thin pan preform, fully machined on the right [180].

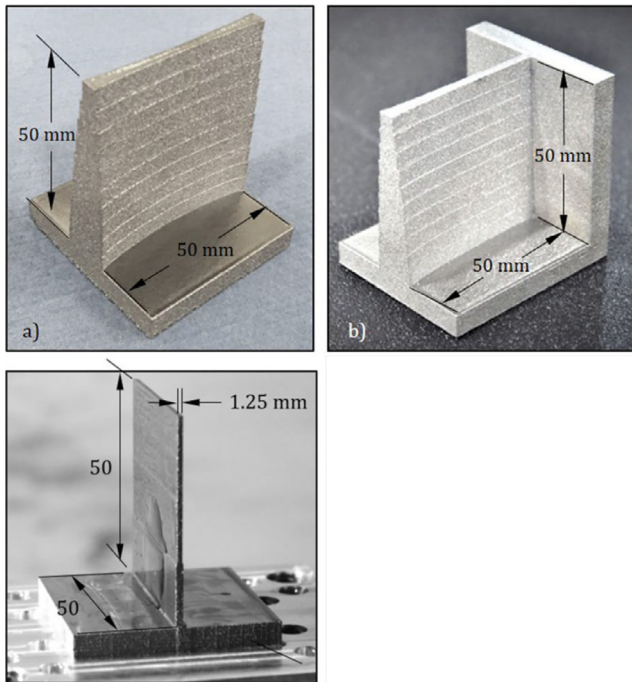


Fig. 63. Variable thickness additive preform to improve preform stiffness for later machining [173].

additive thin wall preform with variable thickness so that the stiffness of the preform is more constant for later machining, see Fig. 63.

Dezaki [42] mentioned the need to “overprint, to make sure that the part is contained in the preform”. This machining tolerance is required to avoid scrapping the additive preform. While conservative overbuilding can guarantee a successful process, it may lead to unnecessarily high costs. Schmitz [173] incorporated the preform design in a cost minimization framework that identified the geometry for lowest cost considering machining stability as a constraint. Liu [123] described a topology optimization algorithm to define the preform shape. This method considered the geometric limits of each additive and each subtractive layer.

6.4. Residual stress

Distortion of the preform due to residual stress is a major unsolved problem in hybrid manufacturing. Liu [122] said that, “... the issue of a proper understanding and definition on inherent strain...,” and “...the manner of dealing with the inherent strain anisotropy...,” are fundamental research issues for successful hybrid additive/subtractive manufacturing.

In most additive processes in hybrid machine tools, the build surface is at the melting temperature of the metal, and there is a thermal gradient through the part, decreasing toward the large heat sink represented by the machine tool structure. As the build layer solidifies, and continues cooling, it changes dimension according to its coefficient of thermal expansion. The previously solidified and cooled material in the structure does not experience this contraction, and the difference leads to internal residual stresses and part distortion.

In some cases, the distortion is so large that the part fractures or tears away from the build plate, or the build plate breaks its mounting clamps. In extreme cases, the preform distorts enough that the part is no longer contained in the additive preform. In general, the geometrical deviation of the finished part is affected, since machining removes some stressed volumes of preform material, but not others. The material removal initiates a redistribution of internal stresses, and therefore additional distortion.

Li [116] proposed a hybrid manufacturing process that combined wire arc AM and milling for the creation of stiffened aerospace panels. He said that despite the advantages, the wire arc AM process introduces undesirable residual stresses and distortions of the preform, especially for thin structures. He suggested that potential solutions to this problem include new welding techniques with lower heat input, such as cold metal transfer (CMT), and preheating approaches such as induction heating could be used to mitigate the thermal gradient. Additionally, he suggested that new fixture designs might reduce the residual stress distortions. Heigel [76] studied the residual stresses created by powder bed fusion of stainless steel using neutron diffraction, and then examined the part dimensions after subsequent machining. It was determined that residual stresses were caused by both operations. Furumoto [66] showed that an iterative combination of laser powder bed fusion and milling reduced the residual stresses in the part. Salonitis [171] showed a modeling and simulation procedure to predict residual stresses resulting from a combination of laser cladding and high-speed machining. Fig. 64 shows his results for a tube geometry.

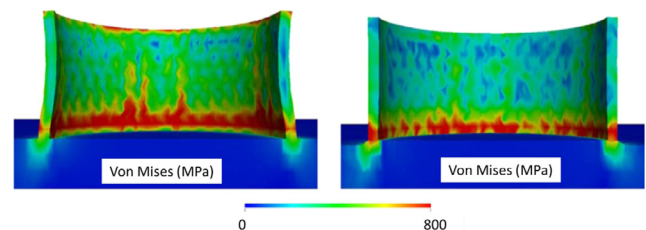


Fig. 64. Modelled residual stress in a cylinder after laser cladding (left) and then high-speed machining the outer surface (right) [171].

Sommer [182] recommended several strategies to reduce the residual stress deformation of hybrid parts made by wire arc AM and milling, including increasing the thickness of the substrate plate, preheating the substrate plate up to 200°C before the deposition, and cooling the part as slowly as possible. Sunny [193] investigated the influence of residual stress from laser powder DED metal additive manufacturing on the machining-induced stress and distortion for hybrid thin-walled components. It was shown that significant tensile and compressive residual stress develops from the rapid thermal cycling during the additive build, significantly influencing the residual stress and distortion induced by high-speed machining. It was also shown that the residual stress and part distortion varied significantly according to the specific tool path, even for the same net material removal.

6.5. Machinability

Many authors have studied the machinability of preforms created by additive processes. During interleaved additive and subtractive operations, it is possible (and often advantageous) to machine the deposited preform while it is still hot. This eliminates the need to wait for the part to cool, and has been shown by [114] to increase compressive strains near the centerline of the produced planar part, see Fig. 65.

Li [117] considered whether there is an advantage for a hybrid process to machine Ti-6Al-4V immediately after deposition while the temperature remains elevated. His measurements show that there is a reduction in the cutting force if the temperature of the titanium is

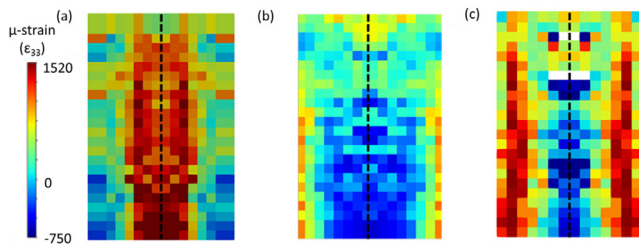


Fig. 65. Z-direction strains, ϵ_{33} as measured by neutron diffraction for (a) as deposited, (b) hot-machined, and (c) cold-machined [114].

greater than 300°C, but that the benefit is not as great as anticipated due to increased tool wear and work hardening.

Sommer [183] evaluated the tool wear in hybrid laser powder bed fusion and high-speed milling of maraging steel. Due to incompatibility of cutting fluid with the powder bed, the machining was performed dry. The subsequent flank wear developed in a typical pattern of rapid initial wear, then linear wear, and finally rapid failure. Other than a lower elongation to fracture, [150] found that the mechanical properties of Inconel 718 walls made by hybrid laser metal deposition and milling as compared with those made by milling of a forged preform were similar. Tang [195] investigated the effect of laser power, scan speed, and milling feed rate on densification level, microhardness, chip morphology, and surface roughness in hybrid additive/subtractive manufacturing of 316L stainless steel samples. Tapoglou [196] found that tool life and surface finish were both better in down milling of 316L stainless steel deposited by blown powder than in wrought material. Liu [125] examined the microstructure, the friction characteristics, and milling machinability of single-pass laser cladding layers (LCLs). The results showed that the Ni60-based LCL was on average 1.38 times harder than the Cr12MoV die steel substrate, and that the tool wear mechanism was mainly oxidation abrasion. In [126], he said that selection of the appropriate material for repairing automobile panel dies and molds should consider not only the die properties, but also the milling machinability.

6.6. Deposition and machining strategy

Frank [64] described the need for simultaneously considering both additive and subtractive processes in the process plan, rather than optimizing them separately. In Fig. 66, for example, he showed preforms created by metal powder bed printing that contained features on both ends for fixturing during machining. Frank [65] also described an iterative additive/subtractive process that allowed the deposition and machining of high aspect ratio walls without long overhang tools, as shown in Fig. 67.



Fig. 66. Powder bed preforms including fixturing features for machining [64].

Amine [10] described a hybrid machining strategy to alleviate reach and access challenges common in conventional machining of deep pockets. He presented iterative deposition and machining, Fig. 68, and he showed using a T-slot tool to leave a shelf that protects

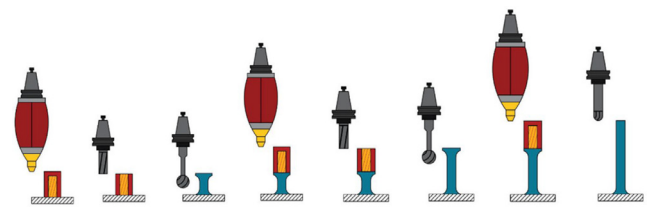


Fig. 67. An iterative hybrid additive/subtractive strategy for creating high aspect ratio walls without long tooling [65].

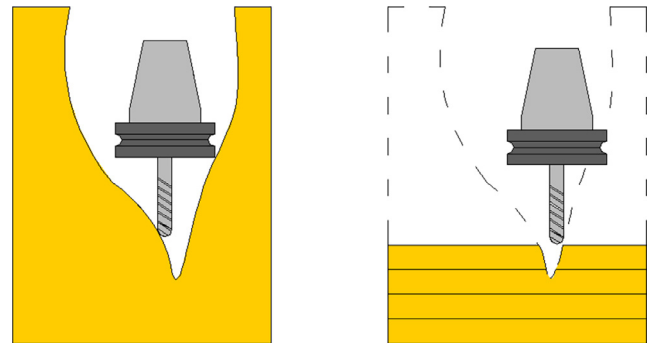


Fig. 68. Iterative deposition and machining to address reach and access challenges common to conventional machining [10].

the machined surface during later deposition, Fig. 69. Similarly, [17] presented a method to use T-slot tooling for machining of overhanging features. Dominguez [48] stated that “Large and complex parts made from Ti-6Al4V with difficult to access features still present a major challenge for surface finishing and metrology operations.” Honeycutt [79] showed a related strategy for the creation of a cone-like structure in titanium, as seen in Fig. 70. Another version of this part was created later by milling the inside in steps while alternating with deposition, and then mill-turning the outside afterward. Pragana [157] described a similar strategy as shown in Fig. 71. Chen [32]

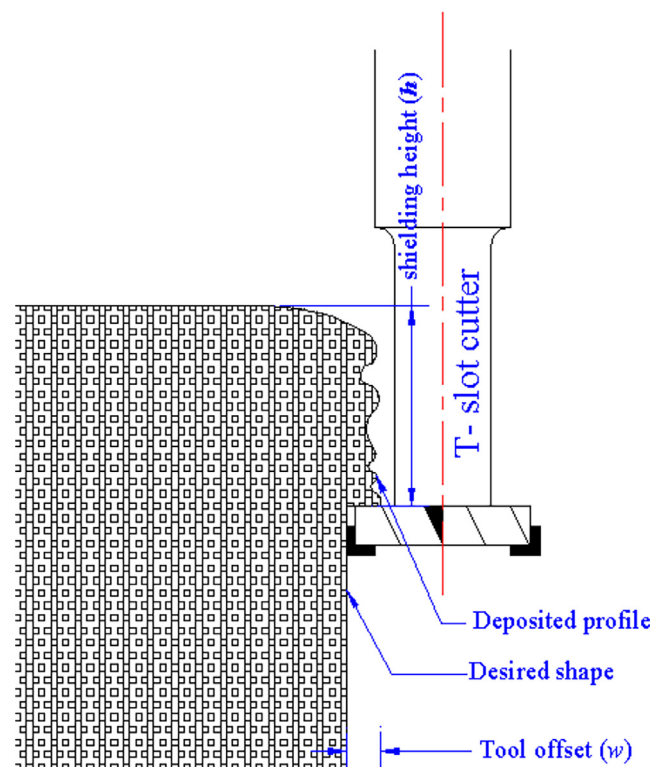


Fig. 69. The T-slot type tool leaves a protective shelf over the machined surface [10].

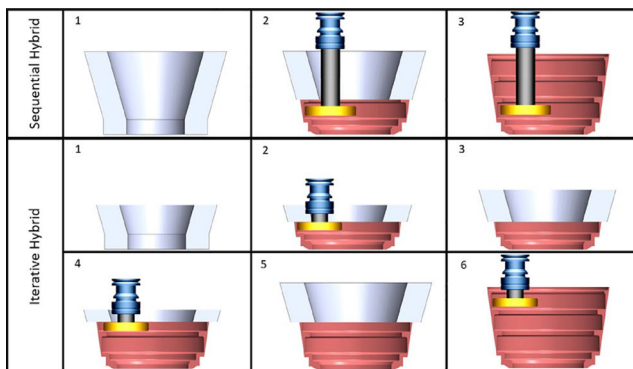


Fig. 70. Iterative hybrid strategy for the creation of a cone-like part with internal features [79].

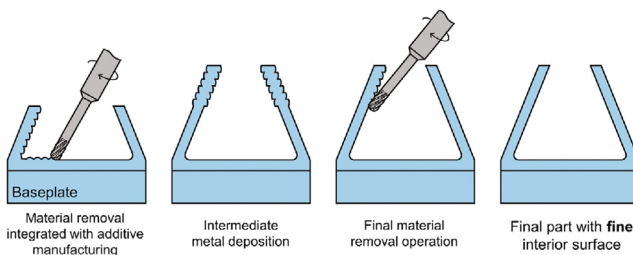


Fig. 71. Iterative additive and subtractive processes can solve a reach and access challenge [157].

reported a hybrid solution where the build plate was created to be an element of the finished component, expanding the idea of what a build plate can be.

Zhu [223] called this iteration between additive and subtractive processes in hybrid machine tools “multi-cycle hybrid manufacturing (MCHM)”. Liou [120] showed that the initial orientation chosen for the part has a significant impact on whether or not sacrificial support structures are needed, and on minimization of the combined time required for deposition and machining. He also demonstrated that the multi-axis capability of a machine tool can simplify the deposition strategy. Abe [4] demonstrated a process planning algorithm that takes into account reach and access, collision avoidance, and total process time in selecting the additive/subtractive strategy. Wang [204] showed that some features that could not be machined in one setup of hybrid laser powder bed fusion and milling could be reached by repositioning the part after the initial build, and he included this option in his process planning model.

6.7. Economic comparison

The question of whether a part can be made by a hybrid process is separate from consideration of under what circumstances hybrid processing is more favorable than conventional processing. That consideration depends on material costs, lead time, processing costs, and production volume. Priarone [158] and [159] provided an economic modelling framework that also included environmental concerns. Campatelli [27] and [28] compared hybrid wire arc AM combined with subtractive manufacturing to subtractive processes alone with regard to energy efficiency. The case study found that the hybrid process enables significant material and primary energy savings, largely by reducing the embodied energy in the workpiece material. El Kashouty [51] found that selective laser melting was sufficient to produce economically competitive tooling inserts for a headlight adjuster clip, but that the surface roughness could be improved by machining. Oyesola [151] provided a cost model for hybrid additive/subtractive manufacturing for maintenance, repair and overhaul activities. Lutter-Günther [130] presented a cost model for blown

powder hybrid additive/subtractive processes including estimates of resources for the operation of a hybrid production machine. Wippermann [209] used energy and time data measured during hybrid manufacturing processes to estimate the break-even point between purely subtractive manufacturing and hybrid additive/subtractive manufacturing based on the material removal ratio, and the ratio of initial mass to the final mass of the workpiece after conventional milling.

Jackson [85] and [86] performed a cradle to gate, or a partial product life cycle from resource extraction (cradle) to the factory gate (before it is transported to the consumer), lifecycle energy consumption comparison between wire-based and powder-based hybrid machine tools, as shown in Fig. 72. Interestingly the production of the wire feedstock consumed more energy than powder, but the deposition of the wire consumed less energy than the powder so that the energy consumption for the two processes was similar. Manogharan [132] presented a cost model including production batch size, material machinability, cost of the material, part geometry and tolerance requirements, and equipment operating cost.

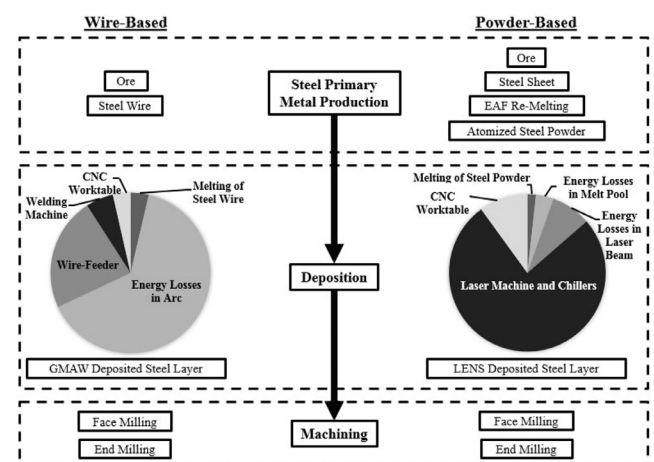


Fig. 72. Components of the energy consumption comparison between wire-based and powder-based hybrid machine tools [85].

6.8. Machine configuration

Recent hybrid machine tool research has shifted toward optimizing the complete system. Park [152] discussed the need to rethink the machine tool structure to support both additive and subtractive capabilities. He presented a study where he optimized for stiffness and dynamic characteristics. Merklein [137] stated that, because additive deposition times are long compared to conventional processes, they should not be used for the production of large workpiece volumes, or conventional shapes readily available by other means. Stavropoulos [188] considered whether it might be preferable to arrange additive and subtractive systems in a cellular configuration (separate additive and subtractive systems next to each other, with part transfer between them).

Many other aspects of hybrid additive subtractive machine tool design remain research questions, including: the number of axes and axis architecture, in which situations a vertical or horizontal spindle would be preferable, the consideration of gravity, automatic exchange laser focussing optics, powder and chip management, calibration and adjustment of the laser spot position, and the whole thermal behavior of the machine.

6.9. Process planning

As noted in Section 4, the software currently available for planning the combination of additive and subtractive operations is not well developed. Ren [166] identified the lack of integrated hybrid process planning tools as a limiting factor for industrial application of the technology. Remaining research areas include the selection of preferable shapes for preforms, and when to switch between additive

and subtractive operations. For example, [121] described an algorithm to select the time to switch between additive and subtractive processes based on collision avoidance and minimizing cumulative error. Other decision criteria for switching include minimizing cost, process time, material usage, energy consumption, or the number of required tools.

CAM software for tool path generation in machining is a mature industry. Key components include the software, representation of the machine model within the post-processor, on-machine probing to identify the work coordinate system (which is applied in the tool paths), and (potentially separate) software to confirm collision avoidance and, more recently, provide mean cutting force prediction for the CAM tool paths. A similar seamless provision for deposition tool path and prediction of the preform geometry will increase hybrid manufacturing productivity.

6.10. Sensors for hybrid metal additive/subtractive manufacturing

Sealy [175] stated that “There is a growing need to include sensor-based monitoring in hybrid-AM processes in order to quantify the multiphysics phenomenon that results in improved processing.” He said that hybrid systems benefit from both traditional machining sensors, such as accelerometers, force sensors, and acoustic emission sensors, and power meters [14], applied to detect variations in cutting regimes in machining and new sensors aligned with additive needs, such as cameras and lasers (to detect surfaces in real time), video cameras, infrared and ultraviolet cameras, pyrometers, photodiodes, and ultrasound [186]. Sealy [175] also reported that understanding and planning for part distortion evolution is critical for the successful integration of additive and subtractive processes. Rabalo [160] added that there is a need for increased inspection, data acquisition capabilities, and processing capabilities so that the hybrid additive/subtractive process data can be managed in real time. Among the research challenges for hybrid additive/subtractive manufacturing listed by [161] are difficulty in self-optimizing CNC systems using real-time material sensing of property and tool conditions, and real-time defect detections by in-situ AM process monitoring.

6.11. Design for hybrid manufacturing

Most examples in the literature show parts manufactured in hybrid processes that are one-for-one replacements for parts originally designed for traditional processes. Rather than considering only the production of existing designs in new ways, there is also a need to rethink designs to leverage hybrid capabilities and to respect the associated limitations. The combination of additive and machining processes naturally influences the design process. While a desirable approach for an additive-only strategy may be minimized material

use, this may not be the best strategy when additive manufacturing is followed by machining. The consideration of the preform's dynamic stiffness at the design stage may change the design relative to another objective function. This approach can be used to inform future topology optimization capabilities [173].

Patterson [153] described a series of constraints when designing parts for hybrid processes. Example constraints include sufficient clearance in deposited features to allow reach and access for cutting tools, and sufficient stiffness for features to support the static and dynamic cutting forces during machining. Sommer [182] proposed design recommendations for hybrid selective laser melting and high-speed machining of maraging steel for tooling, including rules for walls, cylinders, angles, inclinations, overhangs, notches, inner and outer radii of spheres, chamfers in the build direction, and holes of different shapes. He presented an example injection mold with conformal cooling for an electric vehicle charge socket, as shown in Fig. 73.

7. Conclusions

Hybrid manufacturing systems with metal additive manufacturing capability integrated into machining centers have been a topic of research since the early 1990s. However, they have only become commercially available since the late 2010s. The market has since experienced significant growth, with many machine tool builders being early developers and advocates for the technology. All current commercial hybrid metal additive/subtractive manufacturing systems are based on existing machining centers offered by the machine builder. These systems have not been optimized for hybrid operations, and it seems likely that a new class of systems will emerge, with specific kinematic configurations that consider both processes.

The main application spaces for hybrid manufacturing are in the areas of component repair, feature addition, and casting/forging replacement. The use of hybrid manufacturing systems to repair existing components helps streamline and automate repair processes that have traditionally been manual processes. By leveraging readily available components in the supply chain, features can be added to add enhanced functionality. Finally, the additive manufacturing nature of the process lends itself to rapid production of low-volume casting/forging replacements from feedstock to finish, where other processes fall short.

Path planning for hybrid manufacturing systems has increased complexity due to its convergence of multiple processes. Much of this CAM programming is currently done independently, with the only connection being that it may be done within the same software suite. For these hybrid systems to be fully embraced commercially, there should be seamless integration between the programming of the individual processes. Most of the applications for hybrid manufacturing require the use of advanced toolpath strategies, and simultaneous 5-axis motion.

The invention and commercialization of additive manufacturing has revolutionized the manufacturing industry [210]. The availability of hybrid metal additive/subtractive machine tools has opened new application and research areas, and holds promise for lower costs, shorter lead times, and enhanced functionality of manufactured parts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Scott Smith: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Tony Schmitz:** Writing – review & editing, Writing – original draft, Visualization. **Thomas Feldhausen:** Writing – review & editing, Writing – original draft, Visualization.



Fig. 73. Hybrid injection mold with conformal cooling. The example is for a charge socket for an electric vehicle [182].

Michael Sealy: Writing – review & editing, Writing – original draft, Visualization.

Acknowledgement

This manuscript has been authored in part by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the DOE. The US Government retains and the publisher, by accepting the article for publication, acknowledges that the US Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>). The authors also gratefully acknowledge support from the US Department of Defense, OSD Contract W7F35901.

Supplementary materials

Supplementary material associated with this article can be found in the online version at [doi:10.1016/j.cirp.2024.05.002](https://doi.org/10.1016/j.cirp.2024.05.002).

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