Article

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Abstract

It is challenging to manufacture complex and intricate shapes and geometries with desired surface characteristics by a single manufacturing process. Parts often need post-processing and to be transported from one machine into another between the processes. This makes the whole process cumbersome, time consuming and inaccurate. These shortcomings play a major role during the manufacturing of micro and nano products. Hybrid Manufacturing (HM) emerged as a favorable solution for these issues. It is a flexible process that combines two or more manufacturing processes, such as additive manufacturing (AM) and subtractive manufacturing (SM) into a single setup. HM works synergistically to produce complex, composite, and customized components. It makes the process more time efficient, accurate and avoids unnecessary transportation of parts. There are still challenges ahead in order to implement and integrate sensors that allow the machine to detect defects, repair or customize parts according to the needs. Even though modern hybrid machines forecast an exciting future in the manufacturing world, they still lack features such as real-time adaptive manufacturing based on sensors and artificial intelligence (AI).

Earlier reviews do not profoundly elaborate in the types of laser HM machines. Laser technology resolutely handles additive and subtractive manufacturing and is capable of producing groundbreaking parts using a wide scope of materials. This review focuses on HM and presents a compendious overview of the types of hybrid machines and setups used in the scientific community and industry. The study is unique in the sense that it covers different HM setups based on the machine axes, materials and processing parameters. We hope that this study proves helpful to process, plan and impart productivity to the HM processes for the betterment of material utilization and efficiency.

Graphical Abstract

Contents

Introduction - Origins of Hybrid Manufacturing

The journey begins with the word. Across illustrious centuries of progress, man expressed feelings and revolutionary ideas using gestures and impactful words. This sparked an incessant need to intimately set in stone thoughts for upcoming generations. Eventually, our hands grabbed carbon pigments, ashes of heartwarming fire, and crafted marvelous paintings and scriptures that still live across millennia. Ink, used as early as 3200 B.C. in fine papyri from ancient Egypt, inevitably expanded over the world and created a landmark for the development of civilization as we know in the present day [1].

Hand painting and writing at its core is a millennial form of "printing", where one presses ink onto paper which, on its turn, impresses emotions into our souls. Nowadays, society industrialized and automated the printing of papers via machines, which then culminated in "3D printing" where words and objects transcended into the spacial dimension. Before arriving at this revolutionary process of additive manufacturing we navigate into the 15h Century where Johannes Gutenberg ingenuously crafted a printing press. His design was based on the roman screw press, used to crush grapes for wine. The Gutenberg machine was responsible to mass produce the famous 15th century Gutenberg Bible throughout Europe.

From the gutenberg press, then the rotary printer (developed by Richard March Hoe in the 1840s), up to our home's inkjet printer we finally arrived at three-dimensional (3D) printers. It was not until the 1980s, thanks to pioneers like Charles Hull, that we left the two dimensional realm and jumped to the third dimension with the development of Stereolithography (SLA, "solid" + "engraving") one of the bullwarks of comtemporary 3D-printing [2] .

In this day and age, we have access to a plethora of manufacturing processes.

With the advent of computer three-dimensional (3D) models it is possible to create highly detailed and intricate parts. Additive manufacturing (AM) is one such process that generates complex parts by depositing and stacking material, layer by layer [3].

On the other hand, subtractive manufacturing (SM) removes excess material from the part and offers a flawless surface finish. Combining AM with SM opens a new paradigm of possibilities, known as Hybrid Manufacturing (HM).

Figure: Hybrid Manufacturing. An infinitude of hybrid parts can be produced and some examples are depicted above: satellite thruster [4], cooling mold [5], t-connector [6], dental implant [7], extruded part [8], repaired disk [9] and a smart tensile bar [10].

Hybrid manufacturing is a recent technology that was only well established in the past decade. Specifically, hybrid manufacturing combines two or more established manufacturing processes that work synergistically in a new combined set-up [11]. Hybrid Manufacturing allows to create, modify or repair the complex parts. This technology may process microstructures, organic surfaces, and larger components such as implants, pistons, and molds. Integrated hybrid machines use material judiciously which reduces waste. Moreover, operation time reduces significantly by the virtue of combining two or more manufacturing technologies [5], [7]. In the upcoming subsections we explore AM, SM, and HM in detail.

Additive Manufacturing (AM)

AM creates a part based on a computer model layer-by-layer. It is a modern technology that only thrived in the last two decades [3]. Common AM processes include fused filament fabrication (FFF) and stereolithography (SLA or SL). FFF utilizes fused filament, traditionally filament derived from polymers such as Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA), to manufacture alluring 3D parts. SLA is a 3D printing technology that uses photopolymerization to create a 3D solid. Simply put, SLA uses ultraviolet (UV) light to "solidify" regions of a liquid photopolymer (resin) that rests inside a container [12]. Incidentally, both FFF and SLA are optimized to solely produce polymeric parts. A solution is to use laser technologies, such as powder bed fusion (PBF) and directed energy deposition (DED). These two unlock access to a vast selection of materials, including steel, titanium alloys, thermoplastics, ceramics, etc. [3].

The seven major additive manufacturing processe are defined by ISO/ASTM 52900:2015 as Material Extrusion (ME, e.g. FDM), Material Jetting (MJ), Binder Jetting (BJ), Material Bed Fusion (BF), Sheet Lamination (SL or LOM), Directed Energy Deposition (DED) and Vat Photopolymerization (VP, e.g. SLA).

In the context of hybrid manufacturing, *DED* and *PBF* are one of the most cherished technologies.

PBF includes selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM). The two former technologies are engulfed in what is called laser PBF (or LPBF). In a SLS process, first a computer-aided design (CAD) model of the part is virtually sliced and several cross sections are obtained. The SLS machine contains a sink ("bed") where metal powder is spread and a laser beam scans the first layer of the part. The laser follows with precision the respective cross section obtained from the virtual model. Only the powder particles that belong to the cross section are sintered (or melted in the case of SLM). Then a second layer of powder is spread over the bottom one and the machine produces the next cross section using laser again. The laser also bonds the top cross section to the bottom one due to the fusion/ melting. This process goes on in a layer-by-layer fashion until the part is produced [13].

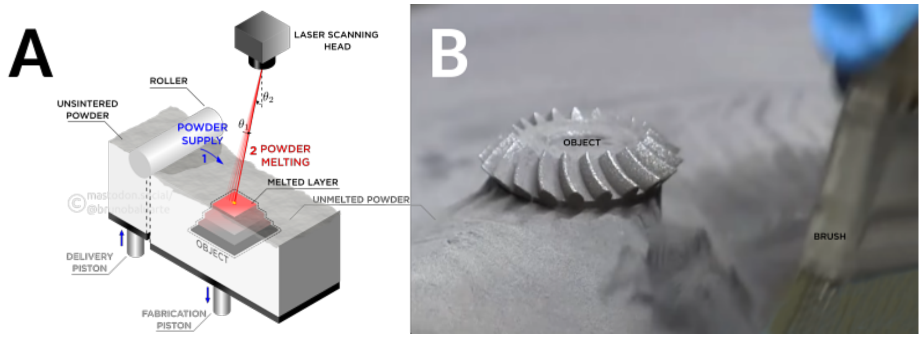


Figure ?: A - Selective Laser Melting. 1 – A roller supplies powder into the fabrication bed. 2 – The laser scans and melts the powder, thus forming one layer of the object. These two steps are performed one after another (layer-by-layer) until creating the entire object. B – Final object, after brushing away excess powder which did not melt.

DED is a generic term for a 3D printing technology that uses an energy source (usually laser) to deposit e.g. metal powder (or wire) onto a surface. Other related names include laser (powder) cladding (LPC), laser engineered net-shaping (LENS), Extreme High Speed Laser Application (EHLA), laser direct metal deposition (LDMD, DMD, LMD or DLD) and Wire and Arc Additive Manufacturing (WAAM, fusion using electric arc). DED has the capacity to produce fully dense, as well as gradient parts using spherical powder particles within the the range of 50–200 μm. These particles should be melted using CO2 laser if one wishes to deposit thick layers (several millimeters). In contrast, Nd-YAG (neodymium-doped yttrium aluminum garnet) laser is the adequate option if one wishes to deposit thin, precise layers (less than one millimeter) with very high precision [14].

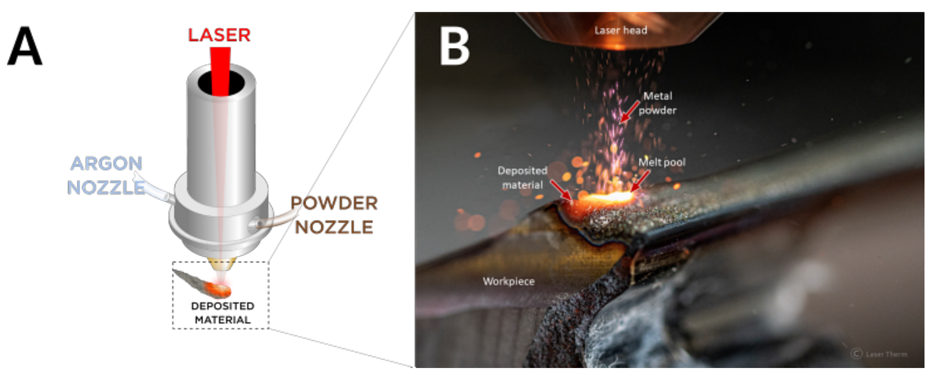
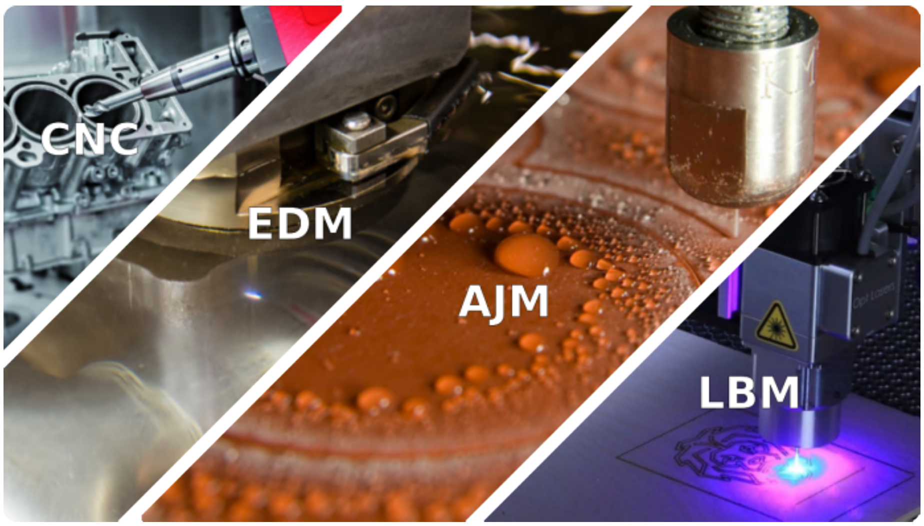


Figure: DED. A – The powder is deposited and melts due to the laser source. B – Close up of the laser metal deposition process (adapted from Laser Therm - creativecommons.org/licenses/by-sa/4.0).

Subtractive Manufacturing (SM)

Subtractive manufacturing is the removal of material from a part either manually-operated or using instructions provided by computer generated models. Machining techniques such as milling, turning, or drilling are all subtractive by nature. One can broadly categorize subtractive manufacturing processes into CNC machining, Electrical Discharge Machining (EDM), Water Jet Machining and Laser Ablation (LA) [15].



In our century, Computer Numerical Control (CNC) machining gained traction and is now extremely popular in emerging manufacturing fields, especially in hybrid machines. However, the origins of Numerical Control (NC) machining are derived from John T. Parsons which in the early 1950s was motivated to improve how helicopter rotors were manufactured [16]. CNC machining is the most widely used subtractive method, however we should also reckon other attractive and competing technologies. These include High Speed Milling (HSM), Electrical Discharge Machining (EDM) and Laser Ablation (LA) [17]. The upcoming discussion section will offer an insight on this topic.

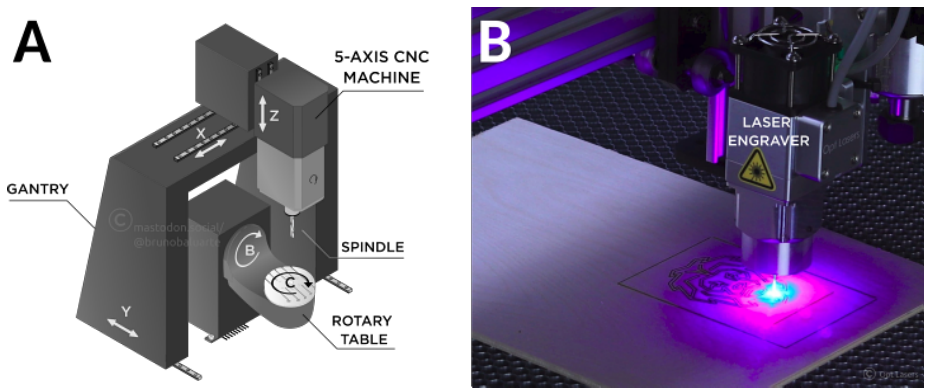


Figure: A – 5-Axis CNC Machine. The CNC head contains a spindle that rotates the end-mill. B – Instead of a spindle, a laser head can be used to machine e.g. a board as shown in the photograph (Opt Lasers)

Hybrid Manufacturing (HM)

Hybrid manufacturing is the holly grail of design and manufacturing since it combines additive and subtractive manufacturing to produce highly complex parts based on a imagined and conceptual model forethought by engineers.

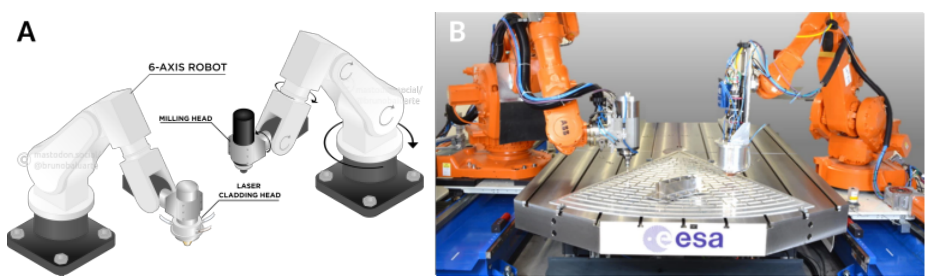


Figure: A – Hybrid Manufacturing with two 6-axis robots, one performing milling and the other laser metal deposition. B – Photograph of two 6-axis robots working synergistically to produce aerospace grade parts [18]. One robot uses cryogenic milling and the other laser metal deposition.

A hybrid machine allows the designer to modify existing parts, manufactured by the conventional, rapid, and large-scale processes such as die casting. Customization as per the users' needs is the major advantage of hybrid manufacturing. HM has a scope in the medical industry including patient-specific hip and knee implants, multimaterial crowns/ veneers, scaffolds and parts with cell-targeted microstructures. Hybrid parts, including multimaterial, high-performance, and fiber-reinforced are also decisive for automotive, aviation, and aerospace industries. Hence, hybrid technology is a step forward in near net shape manufacturing and component repair [11].

Metal and laser-based approaches are typicaly popular in the world of Hybrid

Manufacturing. Exmples of hybrid laser manufacturing are presented in the following figure:

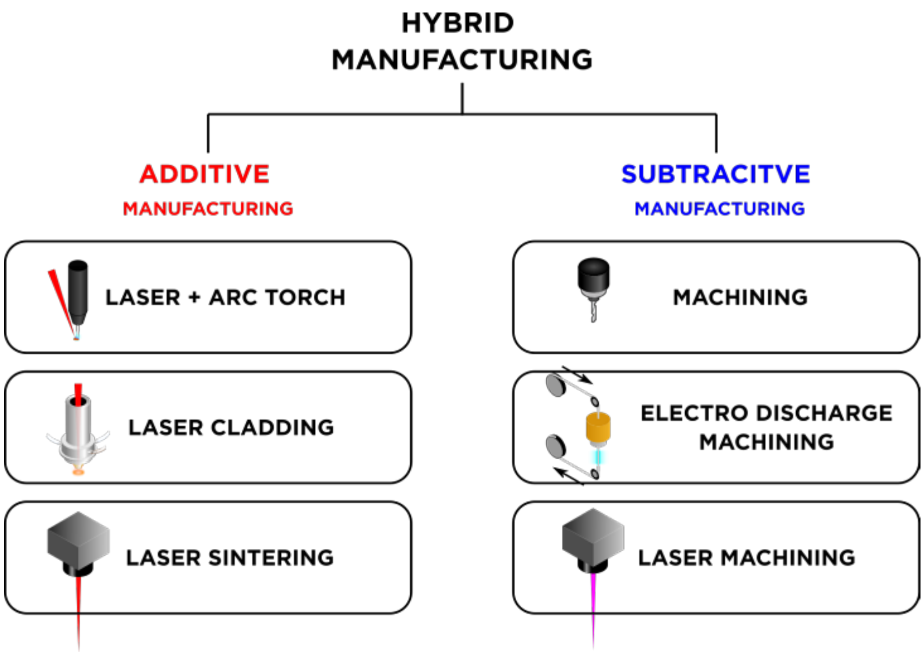


Figure: Types of AM and SM processes that can be used in a laser hybrid manufacturing machine.

Hybrid manufacturing is a technology that offers a combination of different manufacturing flavors. One such combination is EDM (subtractive manufacturing) with SLM (additive manufacturing) which is an effective approach to print micro metallic patterns on pre-finished substrate to be used as a microstructure mold [19]. DED (or LMD) is an alternative process to SLM which can be concerted with machining to handle samples such as Inconel 718 (a nickel-chromium alloy) [20] and produce high-temperature metallic structures [21].

3D dispenser printing is another AM process that can partake in hybrid manufacturing. It is a fruitful technology for developing electrical circuits in parts by dispensing either conductive or ceramic pastes. Combined with laser machining it can fabricate microwave circuits (or antennas) [22]. As expected, integrating electronics with conventional mechanical parts is an exciting way to produce smart components that interact with the environment by sensing or providing stimulus (e.g. piezoelectric actuation).

Laser DED, a layer-wise process, permits the insertion of sensors between the layers, thus creating innovative components such as smart tensile bars. In particular a strain gauge sensor may be incorporated in a layer using screen printing. This technology uses inks to build the strain gauge, in particular ceramic ink for insulation, silver particles for the conductor and platinum particles for the resistor [10].

Integration of sensors into the hybrid manufacturing process itself is a leap forward in terms of part validation, reproducibility and automation. For instance, an Eddy Current (EC) detector (probe) can be integrated into the additive/subtractive hybrid manufacturing (ASHM) process in order to inspect a part for internal defects. After detection, repair operations are conducted through milling and then material deposition [23]. Along this line, United States researchers from Missouri included a stereo vision camera in their hybrid machine, as to detect defects in the component. Afterwards, a laser displacement sensor 3D scans the defect and proceeds to repair the component based on that scan [24].

Milling efficiency in subtractive manufacturing can be improved using several approaches. One such example is the possible reduction in milling forces experienced during titanium alloy workpieces (Ti-6AL-4V) processing. The experiment consists of a KUKA robot with a 2.5-kW Nd:YAG laser for LMD. The additive-manufactured (AMed) titanium piece (Ti-6Al-4V) is placed in a CNC machine that contains a heating device and it is observed a reduction in milling forces when the workpiece temperature is greater than 300ºC, due to the thermal softening effect [25]. Laser-assisted machining (LAM) is another prominent subtracting method where the laser can reduce the cutting force by more than 40% (due to laser preheating) [26]. On the other extreme, cryogenic milling can also be used for hard-to-cut materials, including the aforementioned Ti-6AL-4V. This results in clean, residue-free surfaces compared to dry or cooling lubricant machining [18].

Hybrid manufacturing produces versatile parts and is not restricted to monolithic and mono-material components. Proof of this is the ability to create injection molding inserts with conformal cooling. These inserts can be fabricated using SLM and traditional milling, in particular using the following materials: maraging steel as powder for the SLM processed parts; C5 steel; high-conductivity copper alloy (Ampcoloy 83) for milled parts [27]. Moreover, researchers have used LENS and Wire EDM (WEDM) to fabricate a titanium-titanium diboride (Ti-TiB2) composite [28]. In the biomedical field, dental implants are also components that can greatly benefit from being designed as a multimaterial or hybrid component. For instance, zirconia implants can be textured by first first machining tracks with a Nd:YAG laser, then depositing hydroxyapatite (Hap) powder onto such tracks and finally sinter the powder with a CO2 laser (additive process) [7], [29]. Yet another biomedical application is the fabrication of titanium endosseous implants with optimized surfaces for enhancing osteogenic differentiation of human mesenchymal stem cells. This can be achieved by manufacturing titanium alloy (Ti6Al4V) specimens using SLM and further modifying them using Femtosecond Laser (FS) ablation (subtractive step) [30].

Integrated hybrid manufacturing machines that operate continuously can reduce the production time of complex parts [11]. One example of this type of machine is the DMG Lasertec 65 that integrates a 5-axis coaxial nozzle (DED) with traditional machining [31]. The Mazak VC-500A/5x AM is another powerful and integrated hybrid machine that is able to fabricate a component using 316 L stainless steel wire. This additive process is marketed as hot-wire deposition (HWD). Using such hybrid machine allows to reduce the overall cycle time by 68 % [32]. Finer resolution hybrid machines support the creation of 3D structures in soft materials, including channels, overhangs and undercuts with a minimum resolution of ~ 3 μm. This is the case of Hybrid Laser Printing (HLP) based on femtosecond laser (FS laser) [33].

A more exotic hybrid process is the combination of the additive LMD process and the subtractive jet electrochemical machining (JECM or Jet-ECM) process into a single hybrid technology named LMD-JECM. The setup consists of a 6-axis KUKA robot that contains a LMD head which can be switched to a JECM head which contains a "machining" cathode, a soft brush and a grinding tool (hard brush) [34]. Another interesting hybrid setup is the utilization of a special coaxial nozzle with shielding gas (helium) to produce large titanium (Ti-6Al-4V) components, graded for use in the (ATHENA) telescope [35].

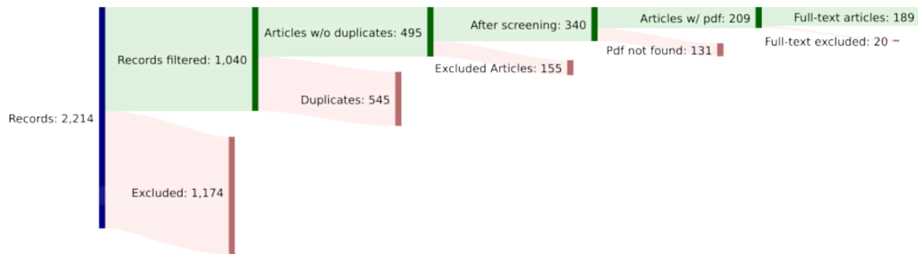
While there are elegant and comprehensive reviews about hybrid manufacturing in the literature, these do not explore in depth the engineering behind laser hybrid machines which dominate the market. Moreover, the intricate details of each type of machine are not analyzed and compared across existing studies. There is a need to provide a compendious overview of existing hybrid machines and setups used in the scientific community and industry. This review gathers and polishes an immensity of raw scientific literature on laser hybrid machines. It further describes modern studies that help pave the way to new and extraordinary developments in this flourishing area of hybrid manufacturing. Furthermore, we provide a panoramic and technical analysis of each hybrid machine, the utilized materials and the respective processing parameters. The goal is to provide intellectual insight about the capabilities of this hybrid technology and its limits.

Search Strategy

Besides the traditional narrative review, we also conducted a systematic review analysis to have a bird's-eye view of the bleeding edge manufacturing processes, techniques, materials and more that are currently being used in the academia.

The present review intends to answer the following question: what are the state-of-the-art hybrid manufacturing machines? To answer this question an electronic database search was performed using the aforementioned databses.

The analyzed articles were acquired until October 4, 2023. The database search included articles from Doaj, Scopus, Web of Science and PubMed using the key term "hybrid manufacturing". The articles were filtered in a first instance and then duplicates were removed. Some of the articles were excluded according to specific criteria and after careful examination a total of 181 articles were included and compared in this review.



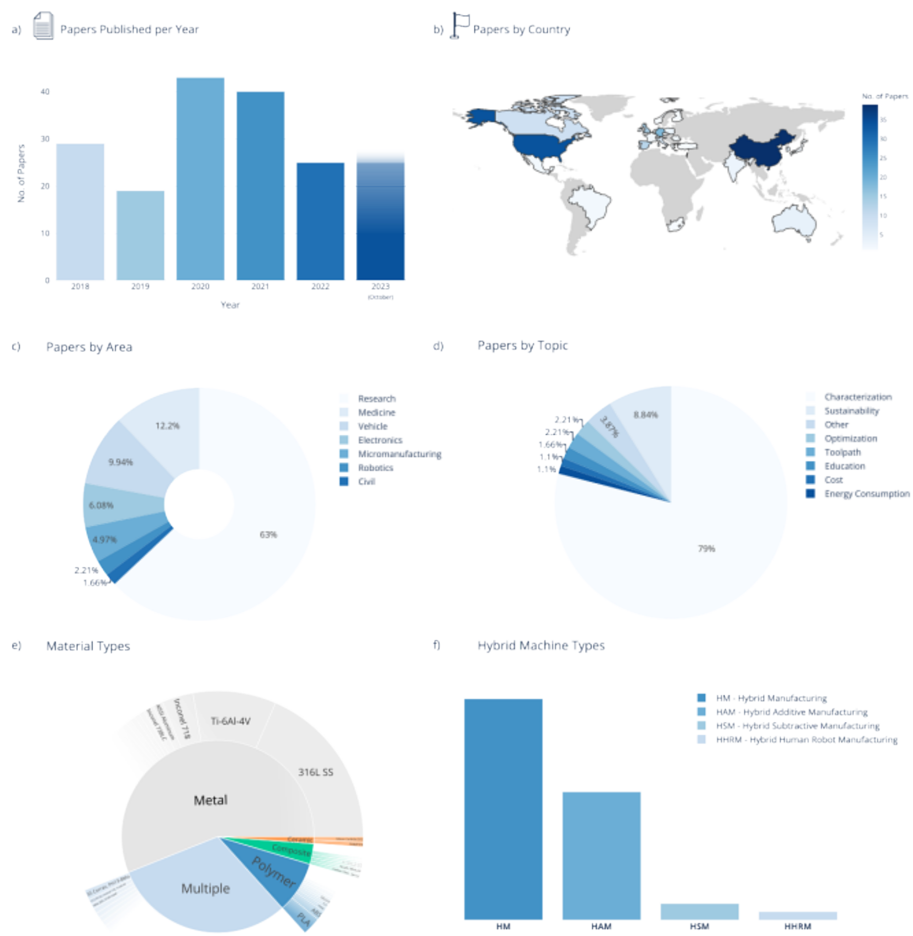
The articles were filtered according to the following criteria:

- No more than 5 years (2018 - 2023)
- Only in English
- Exclude review papers and conference proceedings

Afterwards, the articles' full texts were analyzed for their eligibility accordingly and were excluded if they lacked quality or had no experiments/ testing performed (e.g. only focused on simulation).

Additional articles that span beyong 5 years were also included.

Results



Hybrid Manufacturing Machines

The present discussion is focused on the types of hybrid machines or setups used in the reviewed studies. Moreover we will discuss the materials and parameters used by these hybrid machines.

Machine Types

The collection of reviewed machine setups can be broadly classified into three separate categories:

- **Separate machines**: Two separate machines, one for AM and another for

SM that are operated independently. This is not exactly a hybrid machine (Figure ? A).

- **Single hybrid machine**: A hybrid machine with changeable heads that work in shifts: one head for AM and another for SM. These can either be changed automatically or manually (Figure ? B).
- **Continuous hybrid machine**: A hybrid machine that can perform AM and SM manufacturing synergistically. The AM and SM systems can work in shifts or simultaneously. The worktable can either be fixed or movable, functioning as an additional CNC machine for positioning of the part with respect to the laser head or milling tool. Instead of a milling tool another laser can be used and instead of a worktable a powder bed may be used (Figure ? C).

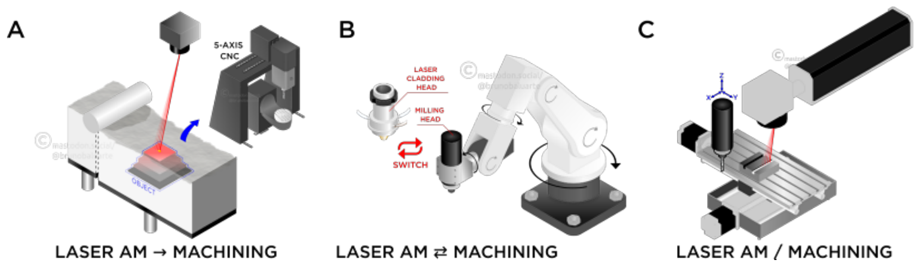


Figure ?: A – Separate Machines. After the part is produced (e.g. using SLS) it is then milled in a separate CNC machine. B – Single Hybrid Machine. A robotic arm (or CNC machine) holds e.g. the milling head, which can be switched to a laser cladding head. C – Continuous Hybrid Machine. There is a laser system such as a Nd:YAG laser and a milling system that with a work table underneath that may be fixed or movable.

The aforementioned picture despite being compact and objective, fails to clarify the nuances of each distinct machine presented in the harvested studies. The present section dissects each unique machine found in the literature to have a deeper understanding of the engineering behind them.

Foresseably, most of the analyzed setups consist of separate machines (Figure ? A), followed by single hybrid machines (Figure ? B). Only a few studies use continuous hybrid machines (Figure ? C) [30], [33], [20], [18]. Furthermore, the authors usually work with 3 or 5-axis CNC machines.

Figure ? below depicts some examples of separate machines. Some of these apparatus fulfill additive manufacturing, such as the customary SLM machine (Figure ? A) and the unusual WAAM (Figure ? B). One of these AM processes are then combined with one SM process, commonly CNC machining (Figure ? C). Occasionally, wire EDM is used instead (Figure ? D).

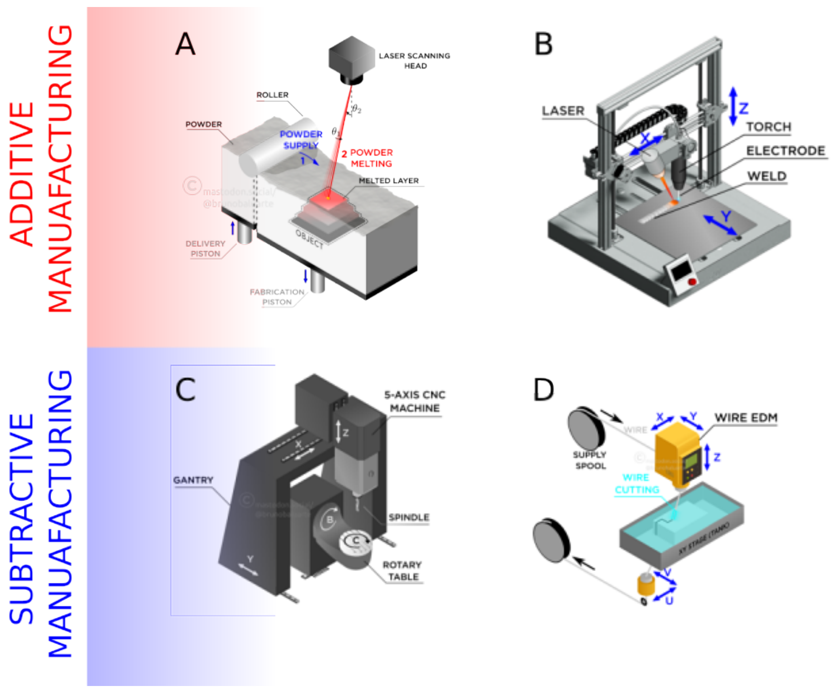


Figure ?: Separate HM machines. A – SLM machine. B – WAAM machine. C – CNC machine. D – Wire EDM machine.

SLM is a popular choice across the existing hybrid machine setups. SLM, SLS or DMLS machines usually contain 2 axes found in the laser head (θ_1 and θ_2), corresponding to 2 mirror galvanometers (galvos) that enable the laser beam to scan the entire 2D plane of the powder-bed. Additionally the bed (worktable) has 1 axis (motor) that elevates the table every time a new layer is to be created (Figure ?).

For example, the Laser M2 Cusing laser powder bed system uses a Yb-fiber laser [36], [37]. One advantage of using a fiber laser such as Yb:YAG or Nd:YAG as opposed to CO2 laser is the ability to better process aluminum, precious metals and other highly reflective materials such as copper and brass. On the other hand, CO2 laser generators can produce higher powers at a lower cost. Thus CO2 laser is the preferred choice when cutting materials with an adequate absorbance such as steel [38]. Another competitive SLM machine, namely SLM 280HL, was utilized to create a workpiece with two sub-regions, a regular block combined with a lattice block which was subsequently machined [39].

The studies that have used SLM, SLS or DMLS usually mognol2007 sepdu2018mc hine for milling the part since sintering AM processes require special conditions (such as the powder bed) to build the part, as previously shown in Figure ? A. Thus most of these studies do not present an actual hybrid machine, but instead present a hybrid technology (or process) that is done in two steps. Usually, the part needs to be manually transferred from the AM machine to the SM machine which is an issue in terms of operation time. A fully integrated hybrid machine that can automatically change between AM and SM processes, greatly reduces this production time and overhead to the manufacturer [11].

Another common setup observed throughout the studies is the single hybrid machine with switchable AM and SM heads, as presented in Figure ? A below. In this setup, a laser cladding head (LMD) is frequently used as the AM head. Incorporation of sensors improves the automation and reliability of the machine (Figure ? B). A robot arm can be used instead to improve the workspace (Figure ? C).

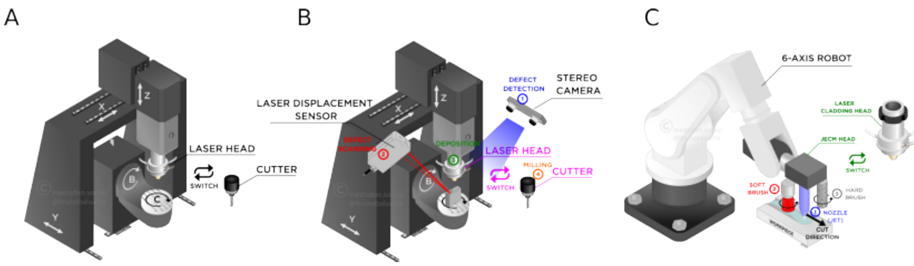


Figure ?: Single HM machines (with changeable AM and SM heads). A – LMD/ Milling machine. B – LMD/ Milling machine with sensors. C – LMD/ Milling robot.

The 5-axis and 6-axis LMD machines (in particular robotic arm machines as shown in Figure ? B) are often capable of working with continuous axes. This contrasts with 5-axis indexed machines (often regarded as 3+2-axis machines), which need to start and stop between part regions. This means that using a 5-axis continuous machine can improve the manufacturing time and may improve the quality of the part [40]. However, this type of machine will likely be more expensive since it uses more complex firmware and hardware. An example of this type of hybrid machine is the DMG LASERTEC65 3D [9], [8], [31]. The machine is composed of a 5-axis machining center, a Siemens 840d NC controller and a 2500-W fiber-coupled diode laser with a 3-mm laser spot diameter, coaxial deposition nozzle and a metal powder feeder system.

The article from Woo et al. [26] was the one that used the machine with more axes (7-axis machine). The kinematic redundancy of using 7 axes (as opposed to 5 axes) may increase the workspace and improve the load (torque) distribution at the joints. However, since more actuators are used the machine cost will naturally be higher [41].

5-axis LMD machines offer the possibility of producing parts or modify them, such as repairing a surface by depositing material or add new features using additive manufacturing. Regarding producing parts from scratch, metal deposition via laser cladding (similarly to most 3D printing processes) is inherently slow compared to traditional processes such as die casting and thus is often used for prototyping parts [3]. The additional time a laser cladding deposition (LCD) machines takes to produce a part from scratch translates to higher costs. However, the issue of traditional manufacturing technologies is the lack of tailoring of the parts for each specific case, since the die cast will produce the same part geometry in bulk. A relevant approach is to produce the part and most of its features using a traditional manufacturing process and then customize each part according to the user needs, be it a patient that requires a custom implant or a automotive industry client that requires a high-performance customized part. Therefore, 5-axis LMD machines can be a viable option for customization of parts specially when combined with traditional processes.

However, LMD samples manuallycompared transfer those from traditional manufacturing processes, such hot rolling, may exhibit worse machinability [42]. Furthermore, the processing of the parts and addition of [18] laser head) have inherent inertia. To overcome this issue, an option is to create a faster system, a hybrid machine that works continuously. One example is two robots operating in parallel (Figure ? A), SLM and Machine head working in turns (Figure ? B), or two laser heads working in turns (Figure ? B).

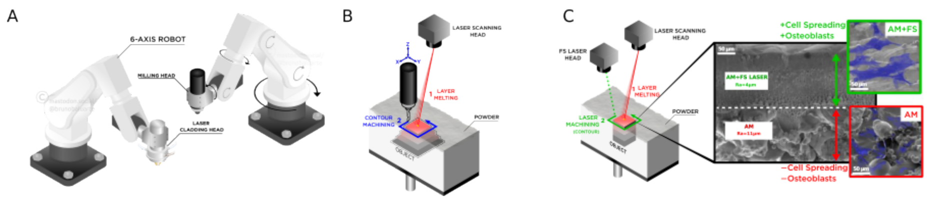


Figure ?: Continuous Hybrid Machines. A – Two 6-axis robots. B – SLM/ Machining. C – SLM/ Laser Machiing.

Another option to improve the hybrid manufacturing speed is to build a system that has a movable worktable (which secures the part) and a fixed laser head that scans the part surface, either to add or remove material. Since the laser head is composed of two galvo mirrors that have low inertia, the machine can quickly move the laser to target distant areas of the part. After scanning one region, the movable worktable can reposition the part in order to scan another region. This approach can be particularly useful for small to medium components since their low inertia allows the worktable machine to move faster compared to a 5-axis machine that includes a laser or machining head.

Other exotic examples of hybrid machines reviewed in this study are presented in Figure ? below.

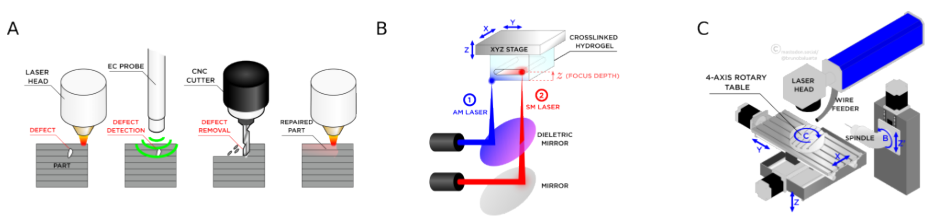


Figure ?: A – LMD/ Machining with EC probe. B – Hydrogel Hybrid Laser Manufacturing. C – Wire LMD (7-axis machine).

Most studies reviewed in this paper present hybrid technologies that deposit material in a layer-by-layer fashion where each layer is planar. However, some machines from the studies, in particular the DED/ LMD machines, have the potential to deposit material in complex curvilinear surfaces [9]. With respect to materials, most of the additive laser manufacturing machines presented in the studies only use metallic materials. This may be restrictive, for example, in biomedical and aerospace applications where multimaterial parts are relevant.

Typically, the hybrid technology setups do not constitute a complete machine that is capable of handling both the additive and the subtractive manufacturing seamlessly. Either the setup requires the user to manually transfer the part from one machine to another or manually switch heads of the hybrid machine. Studies that use a single hybrid machine or setup to handle both the additive and the subtractive manufacturing processes reciprocally include [43], [9], [20], [21], [44], [12]. Most of these are based on exchanging heads automatically and others have two distinct additive and subtractive subsystems that work in shifts. Ideally, the hybrid machine would perform the AM and SM processes synergistically or continuously, however for most applications this is not a necessity.

Hybrid machines may only use laser for the manufacturing process. Generally, one laser head handles the additive process and the other the subtractive process [7], [26], [29], [30], [33]. As already discussed, this has the potential advantage of processing parts faster due to reduced inertia of the machine (there is less machinery to move). However, one disadvantage is that the laser may not be suitable for larger cuts, unless a high power laser, in the kilowatts (kW) order, is used in the SM process.

Just a few setups from the analyzed studies are capable of modifying an already existing component [45], [9], [6]. Here modification means perform additive our subtractive operations over the existing surface of the part. For instance, it is possible to repair an already fabricated part and deposit stainless steel along a curved surface. However, only one type of material was utilized [9]. The deposition and removal of material from a complex surface shows the potential of the hybrid technology to customize existing parts according to the user needs. The market is increasingly demanding the fabrication of custom components, for instance the production of patient-specific implants, custom sports equipment, or optimized parts with high resistance and low weight for the aerospace or automotive applications [46]. A competitive advantage in the field can be obtained by modifying standard parts using hybrid technology and combining two or more materials. Thus, hybrid manufacturing combined with ingenuity can help optimize the part's mechanical performance, stability, compatibility (e.g. osseointegration), durability and many more [30]. Hybrid manufacturing also provides the possibility to include electronic elements inside the parts, such as piezoelectrics and sensors [10] . By increasing the tailoring of the part, the designer can achieve specific project needs, better integration into other systems and thus increase the added value to the customer.

Manufacturing of implants and biomaterials is a field of extreme relevancy. Hybrid manufacturing opens the door to the creation of organic surfaces, cellular microstructures and bioactive materials. For example, medical-grade titanium alloy (Ti6Al4V) specimens can be manufactured using SLM and further modified using Femtosecond Laser (FS) ablation (subtractive step). This hybrid approach offers the opportunity to produce titanium endosseous implants with optimized surfaces for enhancing osteogenic differentiation of human mesenchymal stem cells [30]. Furthermore, the studies [7] and [29] modified the surface of zirconia implants to include the biomaterial hydroxyapatite (Hap) using Nd:YAG laser and CO2 laser for subtractive and additive manufacturing, respectively. As observed across multiple studies, it is important to keep an inert atmosphere when processing metallic parts (such as titanium). This is specially true when dealing with biomedical applications and PBF processes. Laser cladding heads (DED process) also deposit metal using a shielding gas, usually argon [35]. Still, working with a laser head (SLM) and a milling head in shifts [47], [20] seems to be the customary approach instead of having two laser heads operating alternately.

Hybrid Machine Modes of Operation

In a similar spirit to Pragana et al. review [48], we shall classify HM processes as either *Concurrent* or *Sequential*. Herein, we only consider "concurrent" processes the ones that truly have the AM and SM processes working at the same time in parallel. Henceforth, if they work almost at the same time, but actually in shifts, they should be considered "cyclical". For instance, the AM processs creates one layer, then the SM process finishes that layer, and then this sequence repeats cyclically until finishing all the layers of the part. If there is only a sequence of steps that are not cyclical, then it should be called *Sequential*.

- *Concurrent (Concurrent Mixed)*: the two processes manufacture the part concurrently such as two robot arms one that uses AM and the other that uses SM. They can work in parallel.
  - *Assisted or Coupled*: This is also concurrent, but the secondary process only assists the primary process, it is not a full process, this is a typically "coupled process" such as a laser coupled with a milling in a single head that deposits and mills along a direction
- *Sequential*: The two machines work as separate processes, without integration. The part is fabricated using e.g. a AM machine and then is transferred to the SM machine. This can be done manually or automatically.
  - *Manual*: At the end of the first manufacturing process (e.g. AM) the operator manually transfers the sample or object to the other machine (e.g. SM).
- *Cyclical*: Similar to "sequential" in that a layer of the part is created using AM, then applies SM to that layer, and this sequence repeats for each

layer, henceforth cyclically. It is also similar to “concurrent” in the sense that the two processes operate almost at the same time and in-situ, but they are not truly concurrent. We essentially have two machines (or two heads) that work in shifts.

Hybrid Manufacturing Types

Typically the traditional definition of HM is the combination of Additive and Subtractive processes. However, it is getting common to refer to any combination of processes that are hybridized to obtain a final product. Thus we can have two AM processes and this would be called Hybrid Additive Manufacturing (HAM). If the two processes are SM in nature, then we refer to Hybrid Subtractive Manufacturing (HSM). Another modern category was included herein referred to Hybrid Human-Robot Manufacturing (HHRM) where the operator manfuactures or assembles a part in parallel with a robot. This is an important step in the push for Industry 5.0 where the man shall have a crucial role in the integration of the processes that add value to the business.

Another important concept that deserves reference is utilization of hybrid manufacturing to enable the fabrication of multimaterial parts as in multi-material additive manufacturing (MMAM).

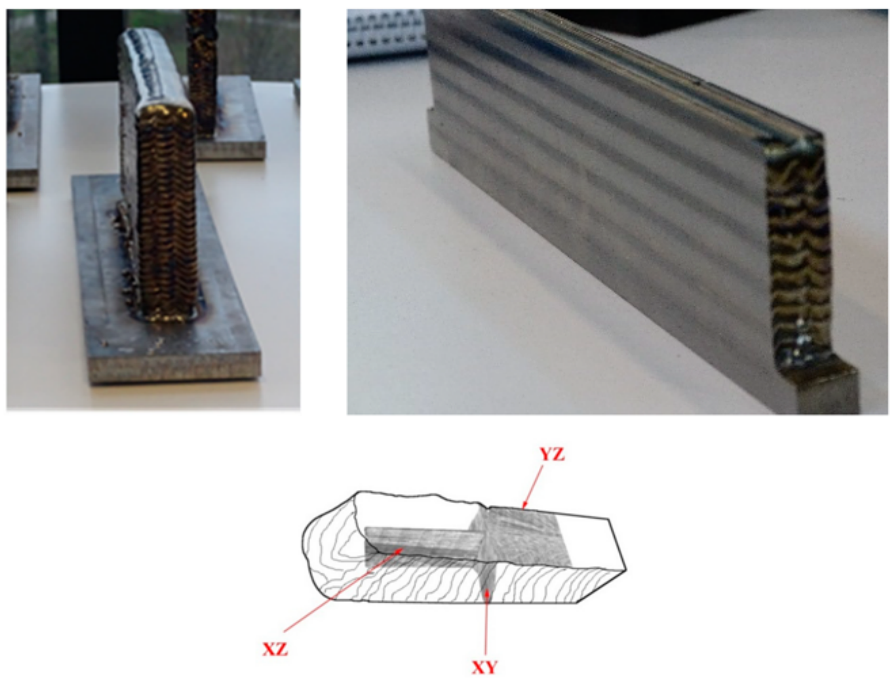
Materials

As can be analyzed based on the graphs, most studies use metal as their base material, followed by using multiple material combinations whether metal-metal, metal-polymer, etc. Several studies combined two or more materials, effectively producing a multimaterial part [49], [50], [51], [6], [52], [34]. However, most of these studies consist of the combination of a powder material with similar characteristics compared to the substrate material (such as the combination of two alloys). Only a few studies combined materials with considerably different chemical compositions [22], [27], [7], [29], [10]. In particular, silver paste may be combined with a PTFE substrate, with a focus on electronic systems [22]. Injection molding inserts were produced by aggregating steel with a copper alloy. In particular C5 (XC48) steel, Ampcoloy 83 copper alloy and X3NiCoMoTi maraging steel were combined to produce these parts [27]. Carvalho and Faria et al. combined zirconia and hap with the intent to biofunctionalize dental implants for better osseointegration [7], [29]. Finally, 13-8 PH stainless steel, ceramic ink, and silver and platinum particles were amalgamated to produce smart parts that contained electronic components between layers [10].

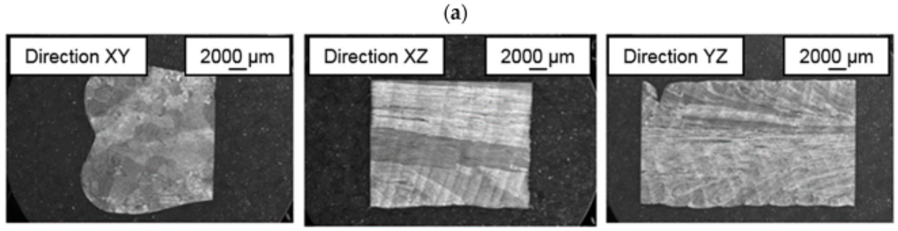
Only three studies utilized polymeric materials: Study [43] which used PLA (Polylactic Acid) deposited with a Fused Deposition Modeling (FDM) head; Study [33] used PEGDA which was crossed linked by a femtosecond laser (FS laser), modulated using a digital micromirror device (DMD) to crosslink only the desired regions; Study [22] used a PTFE fluoropolymer substrate and dispensed silver paste on it with a 3D dispenser printer.

A colossal amount of studies utilized 316L stainless steel which is a medical and marine grade material [19], [4], [9], [31], [49], [53]. Moreover, Ti-6Al-4V titanium alloy is also fairly popular and it is often deployed in the aerospace and biomedical industry owing to its low density and high corrosion resistance [36], [23]. Li et al. [43] used PLA as the base material, which was deposited via a FDM head that can be switched with a laser cladding head.

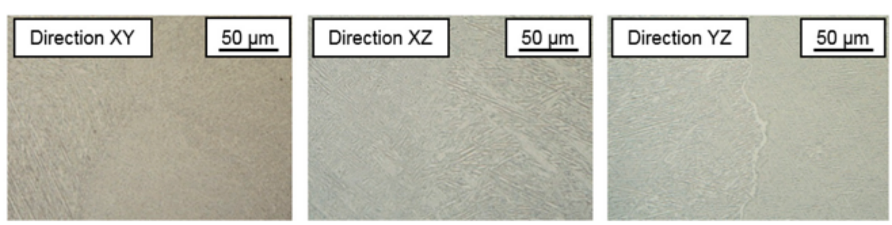
An example of study that used a single material for the HM process, namely Ti-6Al-4V, was [54]:



(a)



(b) (c) (d)



(e) (f) (g)

Only a few studies deposited material along curved surfaces [43], [9], [55]. The remaining studies built the components either from a powder bed (case o SLS and SLM processes) or from scratch using a simple plate as the base, also referred as substrate. Some of the laser cladding studies shown that the inclination of the base plate negatively influences the deposition of the material Therefore, it is convenient to program the system in such a way that the DED head deposition axis is as perpendicular as possible to the part's surface. This way the melt pool does not "slip" as much to the side and therefore maintains its integrity [56]. Note however, that some of the DED systems have the part fixed to the base table, meaning the DED head may deposit the material at non-ideal angles in some regions. By having a movable table that can position the part at proper angles with respect to the DED head, the designer can produce parts whose geometry is more faithful (closer) to the original CAD model. Having two systems, one that moves the part and the other that moves the laser head, also has the benefit of allowing the head to deposit material in "hidden" regions of the part (e.g. the bottom region of the part). By moving or tilting the part it is possible to expose those regions and thus customize the part.

In terms of material properties, study [49] manufactured 316L parts using ASHM with different laser energy densities, in particular an energies ranging from 159 J/mm3 up to 370 J/mm3. In the former the specimens obtained a Yield Strength (YS) of ~380 MPa and a Ultimate Tensile Strength (UTS) of ~563 MPa. In the latter the YS was of ~405 MPa and a UTS of ~570.5 MPa. In terms of hardness (Vickers microhardness, HV) the former had 201 HV and the latter 212 HV. The higher the energy the higher the density (less pores).

Hybrid manufacturing can produce materials containing hard surfaces. In [51] the hardness of the ASHMed top and side surfaces is 12.5% to 14.1% higher than that of the SLMed sample. The cutting forces experiment, between the wrought samples and SLMed samples showed that the latter can present a higher cutting force up to ~30% due to a finer microstructure which relates to a higher yielding strength.

It is possible to create stronger parts using powder and LMD compared to traditional ingot parts. The authors [52] used 316L-Si and observed that compared to the 316L-Si ingot, the LMDed sample had higher strength due to using small powder grains. The ingot sample had a YS of ~170 MPa and a tensile strength of ~485 MPa, compared to a YS of 451 MPa and 693 MPa.

In some cases machining a part and then adding features on top may decrease the part overall strength. The study [29] showed that the mean flexural strength of ASHMed samples of Zirconia + HAp laser textured samples was 503 $\pm$ 24 MPa, lower than those reported in literature for (692 $\pm$ 41 MPa) without the AMed part (HAp).

The bonding strength of printed patterns to substrates can be higher than the fill material itself. For instance, in [19] EDM was used to produce 17-4PH surfaces with a roughness of 2.5, 1.4, 0.8 and 0.4 μm, onto which 316L was printed on top and a bonding strength of ~600 MPa was observed.

There are also studies that use hybrid manufacturing and multimaterial approaches for education purposes as shown by [57] based on Resin and Medical grade silicone GSM50. Others include [58] and [59].

Processes

DED truly dominates most AM processes, even SLS regarding part repair or customization. SLS is tailored to only manufacture parts from scratch, which is a considerable shortfall. Not coincidentally, a myriad of hybrid machines are based on DED. The advantage of DED is that not only it is capable of manufacturing a part from a build platform, but it is also capable of adding material on top of existing surfaces or parts. Therefore, DED bears some crucial advantages, such as part coatings, repair, and modification. Other advantages include production of larger parts and greater mechanical properties compared to SLS. The DED machine firmware needs to be diligently programmed using the inverse kinematics of the machine and the distance between the tool and the part. Moreover, DED machines provide a wide range of feedstock material. The machine's feeder, which contains the material, can be replaced or combined to produce multimaterial parts (e.g. metal-ceramic composites) [60].

In contrast, the advantage of using SLS over DED processes is the higher control of the layer thickness since the powder is uniformly spread by the machine and the process is always performed in a flat region. Despite of DED allowing to manufacture in curved regions, it still lacks the fine control of the layer's thickness even if performed in a flat surface, because of the variable bead height from the melt pool. This limitation can be somewhat overcome using a milling machine which is a process that is also beneficial to SLS to improve the surface quality. SLS also leverages on higher dimensional resolution and powder recyclability. Furthermore, shrinkage and residual stress are possible issues when using DED

[60]. Surface finish in DED is traditionally lower compared to SLS. As an example, using 316L as the basis for comparison, the laser sintering (SLS) study [61] achieved a surface roughness (Ra) lower than 10 μm. On the other hand, the laser cladding (DED) study [62] produced a surface roughness Ra $\sim$ 15 μm. Either way, both SLS and DED usually require a surface finishing to produce high fidelity parts [13]. Furthermore, the DED systems are usually more expensive than SLS system. This is specially true for hybrid DED machines. One disadvantage of DED is also the lack or complexity of support structures that traditional FDM systems offer. SLS cleverly uses the unsintered powder as the support for the next layer. Dissolvable support structures or complex slicing algorithms for overhangs are solutions for the aforementioned DED support structure crisis [63] [64].

From the analyzed articles most used conventional machining (such as milling or turning), whereas just a few used high speed milling (HSM) [65], [23],[66], Electrical discharge machining (EDM) [19], [56], [67], [52], [32], [28], [68], [53] or laser machining [22], [7], [26], [29], [30], [33]. Additionally, it should be emphasized that alternative methods were used for machining, such as micro milling [69], cryogenic milling [18] and JECM [34].

Compared to traditional machining, HSM allows to remove material at higher rates, meaning it improves manufacturing/ finishing efficiency and thus lowers costs. Furthermore, since the spindle's tool is working at a higher speed, the generated forces are lower and less heat is generated. This is useful to avoid distortion of the part and deflection of the tool. However, by working with the tool at higher speeds, more precisely at higher acceleration/ deceleration rates, a HSM machine will have higher wear of guideways and spindle bearings. Substitution of the milling tool is often required. Furthermore, HSM machines require a specialized spindle, fixtures, controllers and materials to handle delicate tasks. All these factors lead to higher maintenance costs [70].

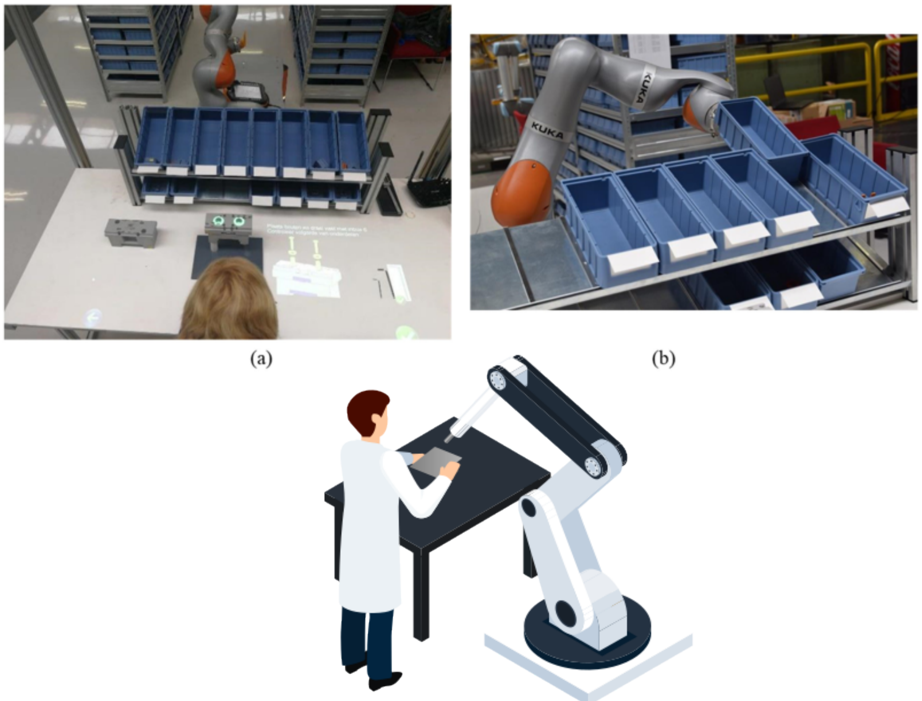
One advantage of using EDM is the fact that the wire (or electrode in the case of μ-EDM) actually does not touch the workpiece. Therefore, the machinist is able to generate slots, grooves and other features without applying stress to the part. Furthermore, in contrast to conventionally drilled surfaces, a EDM surface will be smooth without any burrs. Some limitations of EDM include the inability to machine non-conductive materials, 3D curved surfaces, impenetrable surfaces and the low metal removal rate [67].

Some advantages of using laser machining compared to traditional machining is the speed and precision which one can scan a surface. It allows for automation and application of patterns onto the surface. Some studies such as [30] and [33] used ultrashort pulse laser micromachining with a duration in the femtosecond scale. This has the advantage of using a "cold" and "contactless" processing [71]. The disadvantage is that usually laser processing is focused in surface modification whereas conventional milling allows to cut larger portions of material.

In the age of AI breakthroughs, especially with developments accelerated by

OpenAI, the manufacturing paradigm will inevitably change to a situation where intelligent machines will cooperate with humans to develop bleeding edge parts efficiently and safely. This shall establish the eventual shift towards industry 5.0 that builds upon the IoT processes of industry 4.0 combined with AI to maximize the cooperation between humans and robots. The following articles present HHRM-specific research contributions to the field: [72], focuses on Industry 4.0, IoT and Cloud, emphasizing significant advancements in manufacturing efficiency and capability. [73] studies the integration of human expertise with flexible robots. [74] also aligns with Industry 4.0 trends, focusing on smart manufacturing solutions. [75] focuses on the Teaching by Demonstration (TbD) method in robotic systems. This suggests a focus on improving robot learning capabilities through human interaction, potentially leading to more intuitive and efficient human-robot collaborations.

Contrasting these HHRM-based studies with other machine types (like HM, HAM, etc.) reveals key differences. In HM, HAM and HSM processes, the emphasis is more on technological integration for material processing rather than on the human-robot collaboration aspect seen in HHRM studies. HHRM systems, with their emphasis on human-robot interaction, fill a unique niche in the field of hybrid manufacturing. These can be particularly helpful in an assembly context and may also be important for outsourcing heavy loads from the user to the robot, improving the operators well-being and reducing health risks. Combining all these systems under the same roof will pave the way for smart warehouses that will become highly efficient and provide the end customers with services or products at lightning speeds for a fraction of the typical cost.



(a) (b)

(c)

Conclusion

Modern hybrid machines provide an exciting future in the manufacturing world, however they still lack features such as real-time adaptive manufacturing combined with artificial intelligence (AI). Hybrid manufacturing is a revolutionary technology that incentivizes the incorporation of sensing elements such as stereo vision cameras, displacement sensors, Resistance Temperature Detectors (RTDs), strain gauges, accelerometers and more than meets the eye [24]. Based on all this stimuli and data, the machine adapts, corrects and guides itself according to optimal parameters. This opens the door to engineer, create, modify, or repair groundbreaking components. Furthermore, most of the hybrid systems in the literature do not incorporate industry 4.0 processes. These include internet-of-things (IoT), data automation, cloud computing and AI. Therefore, there is tremendous potential and market opportunity to develop “4D printing” hybrid machines that can produce smart materials, multimaterial components and functional parts.

Table – Reviewed Hybrid Manufacturing Studies. The terms SLM, SLS and DMLS all refer to PBF processes. Laser cladding processes are DED, LMD, DLD, LPC and WAAM (most are powder based, excluding e.g. WAAM which is wire based).

Appendix I (Search Query)

"hybrid manufacturing"

Bibliography

[1] T. Christiansen *et al.*, "Insights into the composition of ancient Egyptian red and black inks on papyri achieved by synchrotron-based microanalyses," *Proceedings of the National Academy of Sciences*, vol. 117, no. 45, pp. 27825–27835, Nov. 2020, doi: 10.1073/pnas.2004534117.

[2] A. Mitchell, U. Lafont, M. Hołyńska, and C. Semprimoschnig, "Additive manufacturing — A review of 4D printing and future applications," *Additive Manufacturing*, vol. 24, pp. 606–626, Dec. 2018, doi: 10.1016/j.addma.2018.10.038.

[3] W. E. Frazier, "Metal Additive Manufacturing: A Review," *Journal of Materials Engineering and Performance*, vol. 23, no. 6, pp. 1917–1928, Jun. 2014, doi: 10.1007/s11665-014-0958-z.

[4] J. Liu, X. Wang, and Y. Wang, "A complete study on satellite thruster structure (STS) manufactured by a hybrid manufacturing (HM) process with integration of additive and subtractive manufacture," *International Journal of Advanced Manufacturing Technology*, vol. 92, no. 9–12, pp. 4367–4377, Oct. 2017, doi: 10.1007/s00170-017-0540-6.

[5] F. Marin, A. F. de Souza, C. H. Ahrens, and L. N. L. de Lacalle, "A new hybrid process combining machining and selective laser melting to manufacture an advanced concept of conformal cooling channels for plastic injection molds," *International Journal of Advanced Manufacturing Technology*, vol. 113, no. 5–6, pp. 1561–1576, Mar. 2021, doi: 10.1007/s00170-021-06720-4.

[6] R. J. Urbanic, R. W. Hedrick, S. Saquib, and N. Nazemi, "Material bead deposition with 2+2 A1/2 multi-axis machining process planning strategies with virtual verification for extruded geometry," *The International Journal of Advanced Manufacturing Technology*, vol. 95, no. 9–12, pp. 3167–3184, Apr. 2018, doi: 10.1007/s00170-017-1376-9.

[7] O. Carvalho, F. Sousa, S. Madeira, F. S. Silva, and G. Miranda, "HAp-functionalized zirconia surfaces via hybrid laser process for dental applications," *Optics & Laser Technology*, vol. 106, pp. 157–167, Oct. 2018, doi: 10.1016/j.optlastec.2018.03.017.

[8] W. Zhang, M. Soshi, and K. Yamazaki, "Development of an additive and subtractive hybrid manufacturing process planning strategy of planar surface for productivity and geometric accuracy," *The International Journal of Advanced Manufacturing Technology*, vol. 109, no. 5–6, pp. 1479–1491, Jul. 2020, doi: 10.1007/s00170-020-05733-9.

[9] M. Perini, P. Bosetti, and N. Balc, "Additive manufacturing for repairing: From damage identification and modeling to DLD," *Rapid Prototyping Journal*, vol. 26, no. 5, pp. 929–940, 2020, doi: 10.1108/RPJ-03-2019-0090.

[10] M. Juhasz *et al.*, "Hybrid directed energy deposition for fabricating metal structures with embedded sensors," *Additive Manufacturing*, vol. 35, p. 101397, Oct. 2020, doi: 10.1016/j.addma.2020.101397.

[11] Z. Zhu, V. G. Dhokia, A. Nassehi, and S. T. Newman, "A review of hybrid manufacturing processes – state of the art and future perspectives," *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 7, pp. 596–615, Jul. 2013, doi: 10.1080/0951192X.2012.749530.

[12] H. Wu *et al.*, "Recent developments in polymers/polymer nanocomposites for additive manufacturing," *Progress in Materials Science*, vol. 111, p. 100638, Jun. 2020, doi: 10.1016/j.pmatsci.2020.100638.

[13] D. Dev Singh, T. Mahender, and A. Raji Reddy, "Powder bed fusion process: A brief review," *Materials Today: Proceedings*, vol. 46, pp. 350–355, 2021, doi: 10.1016/j.matpr.2020.08.415.

[14] A. Saboori, A. Aversa, G. Marchese, S. Biamino, M. Lombardi, and P. Fino, "Application of Directed Energy Deposition-Based Additive Manufacturing in Repair," *Applied Sciences*, vol. 9, no. 16, p. 3316, Jan. 2019, doi: 10.3390/app9163316.

[15] R. Sureban, V. N. Kulkarni, and V. N. Gaitonde, "Modern Optimization Techniques for Advanced Machining Processes – A Review," *Materials Today: Proceedings*, vol. 18, pp. 3034–3042, Jan. 2019, doi: 10.1016/j.matpr.2019.07.175.

[16] F.-C. Iliescu, I.-D. Deaconu, C. G. Fartinescu, A.-S. Deaconu, and A.-I. Chirilă, "Computer numerically controlled device," in *2015 9th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, May 2015, pp. 162–165. doi: 10.1109/ATEE.2015.7133774.

[17] Y. Koren, "Control of Machine Tools," *Journal of Manufacturing Science and Engineering*, vol. 119, no. 4B, pp. 749–755, Nov. 1997, doi: 10.1115/1.2836820.

[18] J. Moritz *et al.*, "Hybrid manufacturing of titanium Ti-6Al-4V combining laser metal deposition and cryogenic milling," *INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY*, vol. 107, no. 7–8, pp. 2995–3009, Apr. 2020, doi: 10.1007/s00170-020-05212-1.

[19] N. Zhang, J. Liu, H. Zhang, N. J. Kent, D. Diamond, and M. D. Gilchrist, "3D Printing of Metallic Microstructured Mould Using Selective Laser Melting for Injection Moulding of Plastic Microfluidic Devices," *Micromachines*, vol. 10, no. 9, p. 595, Sep. 2019, doi: 10.3390/mi10090595.

[20] T. Ostra, U. Alonso, F. Veiga, M. Ortiz, P. Ramiro, and A. Alberdi, "Analysis of the Machining Process of Inconel 718 Parts Manufactured by Laser Metal Deposition." *Materials (Basel, Switzerland)*, vol. 12, no. 13, p. 2159, Jul. 2019, doi: 10.3390/ma12132159.

[21] F. Liou, K. Slattery, M. Kinsella, J. Newkirk, H.-N. Chou, and R. Landers, "Applications of a hybrid manufacturing process for fabrication of metallic structures," *Rapid Prototyping Journal*, vol. 13, no. 4, pp. 236–244, 2007, doi: 10.1108/13552540710776188.

[22] E. A. Rojas-Nastrucci *et al.*, "Characterization and Modeling of K-Band Coplanar Waveguides Digitally Manufactured Using Pulsed Picosecond Laser Machining of Thick-Film Conductive Paste," *Ieee Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp. 3180–3187, Sep. 2017, doi: 10.1109/TMTT.2017.2677447.

[23] W. Du, Q. Bai, Y. Wang, and B. Zhang, "Eddy current detection of subsurface defects for additive/subtractive hybrid manufacturing," *The International Journal of Advanced Manufacturing Technology*, vol. 95, no. 9–12, pp. 3185–3195, Apr. 2018, doi: 10.1007/s00170-017-1354-2.

[24] R. Liu, Z. Wang, T. Sparks, F. Liou, and C. Nedic, "Stereo vision-based repair of metallic components," *Rapid Prototyping Journal*, vol. 23, no. 1, pp. 65–73, Jan. 2017, doi: 10.1108/RPJ-09-2015-0118.

[25] S. Li, B. Zhang, and Q. Bai, "Effect of temperature buildup on milling forces in additive/subtractive hybrid manufacturing of Ti-6Al-4V," *INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY*, vol. 107, no. 9–10, pp. 4191–4200, Apr. 2020, doi: 10.1007/s00170-020-05309-7.

[26] W.-S. Woo, E.-J. Kim, H.-I. Jeong, and C.-M. Lee, "Laser-Assisted Machining of Ti-6Al-4V Fabricated by DED Additive Manufacturing," *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 7, no. 3, pp. 559–572, May 2020, doi: 10.1007/s40684-020-00221-7.

[27] B. Abbès, F. Abbes, H. Abdessalam, and A. Upganlawar, "Finite element cooling simulations of conformal cooling hybrid injection molding tools manufactured by selective laser melting," *The International Journal of Advanced Manufacturing Technology*, vol. 103, Aug. 2019, doi: 10.1007/s00170-019-03721-2.

[28] S. Bose and T. Nandi, "Statistical and experimental investigation using a novel multi-objective optimization algorithm on a novel titanium hybrid composite developed by lens process," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 235, no. 16, pp. 2911–2933, Aug. 2021, doi: 10.1177/0954406220959101.

[29] D. Faria, B. Henriques, A. C. Souza, F. S. Silva, and O. Carvalho, “Laser-assisted production of HAp-coated zirconia structured surfaces for biomedical applications,” *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 112, p. 104049, Dec. 2020, doi: 10.1016/j.jmbbm.2020.104049.

[30] G. Bouet *et al.*, “Laser-Based Hybrid Manufacturing of Endosseous Implants: Optimized Titanium Surfaces for Enhancing Osteogenic Differentiation of Human Mesenchymal Stem Cells.” *ACS Biomaterials Science and Engineering*, vol. 5, no. 9, pp. 4376–4385, Sep. 2019, doi: 10.1021/ACSBIOMATERIALS.9B00769.

[31] N. Tapoglou and J. Clulow, “Investigation of hybrid manufacturing of stainless steel 316L components using direct energy deposition,” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 235, no. 10, pp. 1633–1643, Aug. 2021, doi: 10.1177/0954405420949360.

[32] T. Feldhausen, N. Raghavan, K. Saleeby, L. Love, and T. Kurfess, “Mechanical properties and microstructure of 316L stainless steel produced by hybrid manufacturing,” *Journal of Materials Processing Technology*, vol. 290, p. 116970, Apr. 2021, doi: 10.1016/j.jmatprotec.2020.116970.

[33] P. Kunwar, Z. Xiong, S. T. Mcloughlin, and P. Soman, “Oxygen-Permeable Films for Continuous Additive, Subtractive, and Hybrid Additive/Subtractive Manufacturing,” *3D Printing and Additive Manufacturing*, vol. 7, no. 5, pp. 216–221, Oct. 2020, doi: 10.1089/3dp.2019.0166.

[34] L. Junzhi, C. Gao, L. Shen, H. Cheng, X. Gao, and X. Han, “Microstructure and Surface Morphology of Inconel 625 Alloy Prepared by Laser Melting Deposition using Abrasive-Assisted Jet Electrochemical Machining,” *International Journal of Electrochemical Science*, vol. 13, pp. 10654–10668, Nov. 2018, doi: 10.20964/2018.11.25.

[35] N. Kolsch *et al.*, “Novel local shielding approach for the laser welding based additive manufacturing of large structural space components from titanium,” *Journal of Laser Applications*, vol. 32, no. 2, p. 022075, May 2020, doi: 10.2351/7.0000114.

[36] P. J. T. Conradie, D. Dimitrov, G. A. Oosthuizen, P. Hugo, and M. Saxer, “Comparative assessment of process combination for Ti6Al4V components,” *Rapid Prototyping Journal*, vol. 23, no. 3, pp. 624–632, 2017, doi: 10.1108/RPJ-10-2015-0153.

[37] D. Bhaduri *et al.*, “Evaluation of surface / interface quality, microstructure and mechanical properties of hybrid additive-subtractive aluminium parts,” *CIRP Annals - Manufacturing Technology*, Apr. 2019, doi: 10.1016/j.cirp.2019.04.116.

[38] A. Stournaras, P. Stavropoulos, K. Salonitis, and G. Chryssolouris, “An investigation of quality in CO2 laser cutting of aluminum,” *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 1, pp. 61–69, Jan. 2009, doi: 10.1016/j.cirpj.2009.08.005.

[39] P. Didier *et al.*, “Consideration of additive manufacturing supports for post-processing by end milling: A hybrid analytical-numerical model and experimental validation,” *Progress in Additive Manufacturing*, vol. 7, no. 1, pp. 15–27, Feb. 2022, doi: 10.1007/s40964-021-00211-4.

[40] Z. C. Chen, Z. Dong, and G. W. Vickers, “Automated surface subdivision and tool path generation for 31212-axis CNC machining of sculptured parts,” *Computers in Industry*, vol. 50, no. 3, pp. 319–331, Apr. 2003, doi: 10.1016/S0166-3615(03)00019-8.

[41] J. Fontes, J. Santos, and M. Silva, “Torque Optimization of Parallel Manipulators by The Application of Kinematic Redundancy,” Aug. 2014.

[42] P. Masek, T. Fornusek, P. Zeman, M. Bucko, J. Smolik, and P. Heinrich, “MACHINABILITY THE AISI 316 STAINLESS STEEL AFTER PROCESSING BY VARIOUS METHODS OF 3D PRINTING,” *MM SCIENCE JOURNAL*, vol. 2019, no. November, pp. 3338–3346, Nov. 2019, doi: 10.17973/MMSJ.2019_11_2019091.

[43] L. Li, A. Haghighi, and Y. Yang, “A novel 6-axis hybrid additive-subtractive manufacturing process: Design and case studies,” *Journal of Manufacturing Processes*, vol. 33, pp. 150–160, Jun. 2018, doi: 10.1016/j.jmapro.2018.05.008.

[44] Y. Yang, Y. Gong, S. Qu, Y. Rong, Y. Sun, and M. Cai, “Densification, surface morphology, microstructure and mechanical properties of 316L fabricated by hybrid manufacturing,” *International Journal of Advanced Manufacturing Technology*, vol. 97, no. 5–8, pp. 2687–2696, Jul. 2018, doi: 10.1007/s00170-018-2144-1.

[45] X. Zhang, W. Cui, W. Li, and F. Liou, “A Hybrid Process Integrating Reverse Engineering, Pre-Repair Processing, Additive Manufacturing, and Material Testing for Component Remanufacturing,” *Materials*, vol. 12, no. 12, p. 1961, Jun. 2019, doi: 10.3390/ma12121961.

[46] A. du Plessis *et al.*, “Beautiful and Functional: A Review of Biomimetic Design in Additive Manufacturing,” *Additive Manufacturing*, vol. 27, pp. 408–427, May 2019, doi: 10.1016/j.addma.2019.03.033.

[47] T. Furumoto, S. Abe, M. Yamaguchi, and A. Hosokawa, “Improving surface quality using laser scanning and machining strategy combining powder bed fusion and machining processes,” *International Journal of Advanced Manufacturing Technology*, vol. 117, no. 11–12, pp. 3405–3413, Dec. 2021, doi: 10.1007/s00170-021-07880-z.

[48] J. P. M. Pragana, R. F. V. Sampaio, I. M. F. Bragança, C. M. A. Silva, and P. A. F. Martins, “Hybrid metal additive manufacturing: A state–of–the-art review,” *Advances in Industrial and Manufacturing Engineering*, vol. 2, p. 100032, May 2021, doi: 10.1016/j.aime.2021.100032.

[49] Y. Gong, Y. Yang, S. Qu, P. Li, C. Liang, and H. Zhang, “Laser energy density dependence of performance in additive/subtractive hybrid manufacturing of 316L stainless steel,” *The International Journal of Advanced Manufacturing Technology*, vol. 105, no. 1–4, pp. 1585–1596, Nov. 2019, doi: 10.1007/s00170-019-04372-z.

[50] J. Näsström, F. Brueckner, and A. F. H. Kaplan, “Laser enhancement of wire arc additive manufacturing,” *Journal of Laser Applications*, vol. 31, no. 2, p. 022307, May 2019, doi: 10.2351/1.5096111.

[51] W. Du, Q. Bai, and B. Zhang, “Machining characteristics of 18Ni-300 steel in additive/subtractive hybrid manufacturing,” *INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY*, vol. 95, no. 5–8, pp. 2509–2519, Mar. 2018, doi: 10.1007/s00170-017-1364-0.

[52] M. Riede *et al.*, “Material Characterization of AISI 316L Flexure Pivot Bearings Fabricated by Additive Manufacturing,” *Materials*, vol. 12, no. 15, p. 2426, Jan. 2019, doi: 10.3390/ma12152426.

[53] J. P. M. Pragana, S. Rosenthal, I. M. F. Bragança, C. M. A. Silva, A. E. Tekkaya, and P. A. F. Martins, “Hybrid Additive Manufacturing of Collector Coins,” *Journal of Manufacturing and Materials Processing*, vol. 4, no. 115, p. 115, Dec. 2020, doi: 10.3390/jmmp4040115.

[54] F. Veiga, A. G. D. Val, A. Suárez, and U. Alonso, “Analysis of the Machining Process of Titanium Ti6Al-4V Parts Manufactured by Wire Arc Additive Manufacturing (WAAM).” *Materials (Basel, Switzerland)*, vol. 13, no. 3, p. 766, Feb. 2020, doi: 10.3390/ma13030766.

[55] A. Calleja, G. Urbikain, H. Gonzalez, I. Cerrillo, R. Polvorosa, and A. Lamikiz, “InconelA (R) 718 superalloy machinability evaluation after laser cladding additive manufacturing process,” *INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY*, vol. 97, no. 5–8, pp. 2873–2885, Jul. 2018, doi: 10.1007/s00170-018-2169-5.

[56] Y. He, J. Wei, J. Liu, X. Wang, Y. Wang, and L. He, “Experimental study on the fabrication profile and mechanical properties by substrate-inclined angle using laser melting deposition (LMD) integrating with the substrate of stainless steel,” *OPTICS AND LASER TECHNOLOGY*, vol. 125, p. 106038, May 2020, doi: 10.1016/j.optlastec.2019.106038.

[57] K. Fitzgerald *et al.*, “A human-centred design approach to hybrid manufacturing of a scapholunate interosseous ligament medical practice rig,” *Annals of 3D Printed Medicine*, vol. 9, p. 100084, Feb. 2023, doi: 10.1016/j.stlm.2022.100084.

[58] A. Tejo-Otero *et al.*, “3D printed prototype of a complex neuroblastoma for preoperative surgical planning,” *Annals of 3D Printed Medicine*, vol. 2, p. 100014, Jun. 2021, doi: 10.1016/j.stlm.2021.100014.

[59] A. D. Weatherall, M. D. Rogerson, M. R. Quayle, M. G. Cooper, P. G. McMenamin, and J. W. Adams, "A Novel 3-Dimensional Printing Fabrication Approach for the Production of Pediatric Airway Models." *ANESTHESIA AND ANALGESIA*, vol. 133, no. 5, pp. 1251–1259, Nov. 2021, doi: 10.1213/ANE.0000000000005260.

[60] D. Svetlizky *et al.*, "Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications," *Materials Today*, vol. 49, pp. 271–295, Oct. 2021, doi: 10.1016/j.mattod.2021.03.020.

[61] D. Wang, Y. Liu, Y. Yang, and D. Xiao, "Theoretical and experimental study on surface roughness of 316L stainless steel metal parts obtained through selective laser melting," *Rapid Prototyping Journal*, vol. 22, no. 4, pp. 706–716, Jan. 2016, doi: 10.1108/RPJ-06-2015-0078.

[62] S. K. Moheimani, L. Iuliano, and A. Saboori, "The role of substrate preheating on the microstructure, roughness, and mechanical performance of AISI 316L produced by directed energy deposition additive manufacturing," *The International Journal of Advanced Manufacturing Technology*, vol. 119, no. 11, pp. 7159–7174, Apr. 2022, doi: 10.1007/s00170-021-08564-4.

[63] C. S. Lefky, B. Zucker, A. R. Nassar, T. W. Simpson, and O. J. Hildreth, "Impact of compositional gradients on selectivity of dissolvable support structures for directed energy deposited metals," *Acta Materialia*, vol. 153, pp. 1–7, Jul. 2018, doi: 10.1016/j.actamat.2018.04.009.

[64] K. Lee and H. Jee, "Slicing algorithms for multi-axis 3-D metal printing of overhangs," *Journal of Mechanical Science and Technology*, vol. 29, no. 12, pp. 5139–5144, Dec. 2015, doi: 10.1007/s12206-015-1113-y.

[65] P. Mognol, M. Rivette, L. Jegou, and T. Lesprier, "A first approach to choose between HSM, EDM and DMLS processes in hybrid rapid tooling," *Rapid Prototyping Journal*, vol. 13, no. 1, pp. 7–16, 2007, doi: 10.1108/13552540710719163.

[66] Z. Ye, Z. Zhang, X. Jin, M.-Z. Xiao, and J. Su, "Study of hybrid additive manufacturing based on pulse laser wire depositing and milling," *The International Journal of Advanced Manufacturing Technology*, vol. 88, no. 5, pp. 2237–2248, Feb. 2017, doi: 10.1007/s00170-016-8894-8.

[67] H. Hassanin, F. Modica, M. A. El-Sayed, J. Liu, and K. Essa, "Manufacturing of Ti–6Al–4V Micro-Implantable Parts Using Hybrid Selective Laser Melting and Micro-Electrical Discharge Machining," *Advanced Engineering Materials*, vol. 18, no. 9, pp. 1544–1549, 2016, doi: 10.1002/adem.201600172.

[68] A. H. Seltzman and S. J. Wukitch, "Surface roughness and finishing techniques in selective laser melted GRCop-84 copper for an additive manufactured lower hybrid current drive launcher," *Fusion Engineering and Design*, vol. 160, p. 111801, Nov. 2020, doi: 10.1016/j.fusengdes.2020.111801.

[69] C. L. F. de Assis, G. R. Mecelis, and R. T. Coelho, “An investigation of stainless steel 316L parts produced by powder bed fusion submitted to micro-endmilling operations,” *International Journal of Advanced Manufacturing Technology*, vol. 109, no. 7–8, pp. 1867–1880, Aug. 2020, doi: 10.1007/s00170-020-05710-2.

[70] R. C. Dewes and D. K. Aspinwall, “A review of ultra high speed milling of hardened steels,” *Journal of Materials Processing Technology*, vol. 69, no. 1, pp. 1–17, Sep. 1997, doi: 10.1016/S0924-0136(96)00042-8.

[71] W. Zhao, L. Wang, Z. Yu, J. Chen, and J. Yang, “A processing technology of grooves by picosecond ultrashort pulse laser in Ni alloy: Enhancing efficiency and quality,” *Optics & Laser Technology*, vol. 111, pp. 214–221, Apr. 2019, doi: 10.1016/j.optlastec.2018.09.056.

[72] J. Erasmus, P. Grefen, I. Vanderfeesten, and K. Traganos, “Smart Hybrid Manufacturing Control Using Cloud Computing and the Internet-of-Things,” *Machines*, vol. 6, no. 4, p. 62, Dec. 2018, doi: 10.3390/machines6040062.

[73] B. Sadrfaridpour and Y. Wang, “Collaborative Assembly in Hybrid Manufacturing Cells: An Integrated Framework for Human-Robot Interaction,” *IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING*, vol. 15, no. 3, pp. 1178–1192, Jul. 2018, doi: 10.1109/TASE.2017.2748386.

[74] K. Traganos, P. Grefen, I. Vanderfeesten, J. Erasmus, G. Boultadakis, and P. Bouklis, “The HORSE framework: A reference architecture for cyber-physical systems in hybrid smart manufacturing,” *JOURNAL OF MANUFACTURING SYSTEMS*, vol. 61, pp. 461–494, Oct. 2021, doi: 10.1016/j.jmsy.2021.09.003.

[75] C. Zeng, C. Yang, Z. Chen, and S. Dai, “Robot learning human stiffness regulation for hybrid manufacture,” *ASSEMBLY AUTOMATION*, vol. 38, no. 5, pp. 539–547, 2018, doi: 10.1108/AA-02-2018-019.