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Overview of Selective Laser Melting for Industry 5.0: Toward Customizable, Sustainable, and Human-Centric Technologies

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Abstract: Industry 5.0 combines automation/digitalization with human capabilities to create a more intuitive, interactive, and sustainable working environment. Additive manufacturing, widely known as 3D printing, is a key technology used to increase customization and efficiency and reduce waste in manufacturing. Industry 5.0 enables manufacturers to create environmentally sustainable and consumer-centric products. However, there is a lack of studies on the introduction of AM technologies to Industry 5.0. The present study investigates the use of additive manufacturing for the fabrication of metallic parts/assemblies and the correlation between human-centric technologies, additive manufacturing, and environmental sustainability. Effective communication between these components is the key to achieving the goals of Industry 5.0, and the important parameters are shown in this article. The present work is focused on an overview and the impact of the futuristic subdivision of additive manufacturing applied to the fabrication of metallic parts/assemblies, more specifically, the 3D printing of challenging alloys or composites (such as copper alloys and/or composites with hard particles).

Keywords: Industry 5.0; human-centric technologies; additive manufacturing; environmental sustainability; autonomy; human–machine interface

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1. Introduction

Industry 5.0 is the current stage of industrial development, which aims to complement the current Industry 4.0 model by emphasizing the importance of research and innovation in driving the transition toward a sustainable, resilient, and human-centered industry. This transition stage is expected to continue for another decade and emphasizes the integration of cutting-edge technologies and digitalization with a focus on sustainability, human-centricity, and customization. In contrast with Industry 4.0, which is distinguished by the extensive application of automation and data exchange in manufacturing, Industry 5.0 will be value-driven, whereas Industry 4.0 is technology-driven [1]. The vital, key features of Industry 5.0 are human centricity, system resiliency, and social sustainability [2]. Industry 5.0, known as the human-centric industry, complements the existing Industry 4.0 approach by specifically combining the benefits of automation/digitalization with human capabilities. Human-centric technologies are being used to create a more intuitive, interactive, and sustainable working environment to enhance the satisfaction of both workers and consumers.

Human-centric technologies (HCT) refer to technologies that are designed to enhance the relationship between humans and machines, making them easier to use and more intuitive [3,4]. This includes technologies such as augmented and virtual reality (VR), wearable devices, collaborative robots (CR), collaborative software (CS), haptic mechanisms, digital twins, and human–machine interfaces (HMIs). Additive manufacturing (AM), widely known as 3D printing, is a process of creating 3D objects by adding materials (liquids, powders, or solids) layer by layer based on a computer-aided design (CAD). This advanced technology allows for more flexible and efficient manufacturing processes, with less waste and a greater ability to customize products. These technologies enable the on-demand production of customized products (prototyping), thereby reducing the need for mass production (individualization) and reducing the environmental impact of the manufacturing processes (autonomy). Based on the sketched framework, the present study introduces the most futuristic subdivision of additive manufacturing applied to the fabrication of metallic parts/assemblies. Additive manufacturing can be used to produce challenging alloys (such as copper alloys or composites with hard particles) for 3D printing parts, which can then be used in specific applications.

Environmental sustainability (ES) is the practice of designing and manufacturing products in a way that minimizes negative environmental impacts, conserves natural resources, and promotes social responsibility. Environmental sustainability is another pivotal key focus of Industry 5.0 in the creation of a more sustainable future and pollution prevention. This includes using renewable energy sources, reducing waste, and minimizing pollution. The appropriate design of components in AM can lead to the creation of a sustainable environment free of pollutants compared with subtractive manufacturing [5–7]. Through the widespread use of human-centered approaches and additive manufacturing, Industry 5.0 is enabling manufacturers to create products that are both environmentally sustainable and consumer-centric.

For example, in a 3D metal printing case, these components encompass part designs (porous instead of bulk), device designs (quadruple lasers instead of single-fiber lasers), application-based designs (hybrid composites or cermets instead of metallic alloys), etc. [8,9]. The AM of copper and its alloys (important for the electronics industry, thermal heatsinks, and digitalization) can offer several benefits, which are outlined below: design flexibility (complex shapes), reduced material waste (build-to-order process), time efficiency (rapid prototyping), customizability (easy-to-change parameters tailored to the needs of the end-user), and improved material properties (particle size selection and alloying for strength and ductility). On the other hand, the main disadvantages are the high initial investment (the cost of AM equipment), limited material availability (Fe-, Ti-, and Al-based metals are wider than Cu), post-processing requirements (especially for metals and laser-based processes), and quality control (a lack of standardization and testing) [10–12].

In Industry 5.0, AM is expected to play a significant role in achieving environmental sustainability goals. The integration of additive manufacturing with digital technologies such as artificial intelligence and cloud computing can enable a more sustainable, flexible, and efficient manufacturing process. This, in turn, can help reduce the environmental impact of manufacturing while improving the quality, rate of waste reduction, and affordability of products. In the present study, HCT, AM, and ES correlations are investigated, and a perspective on metal/composite 3D printing is discussed in detail.

2. Industry 5.0: HCT, AM, and ES

HCT, AM, and ES are three important components of manufacturing in Industry 5.0 and can be thought of as the vertices of a triangle, with communication and integration being crucial to the success of Industry 5.0. This configuration is illustrated in Figure 1, where, together, these three components form a triangle in which each element supports, communicates with, and enhances the others. In this regard, HCT can improve operator efficiency and safety [13]. AM technologies can reduce raw material waste, significantly reduce the cost of customization and complexity, and save time (rapid production, user-friendly devices/software) [14]. Finally, ES can reduce energy consumption and carbon emissions [15].

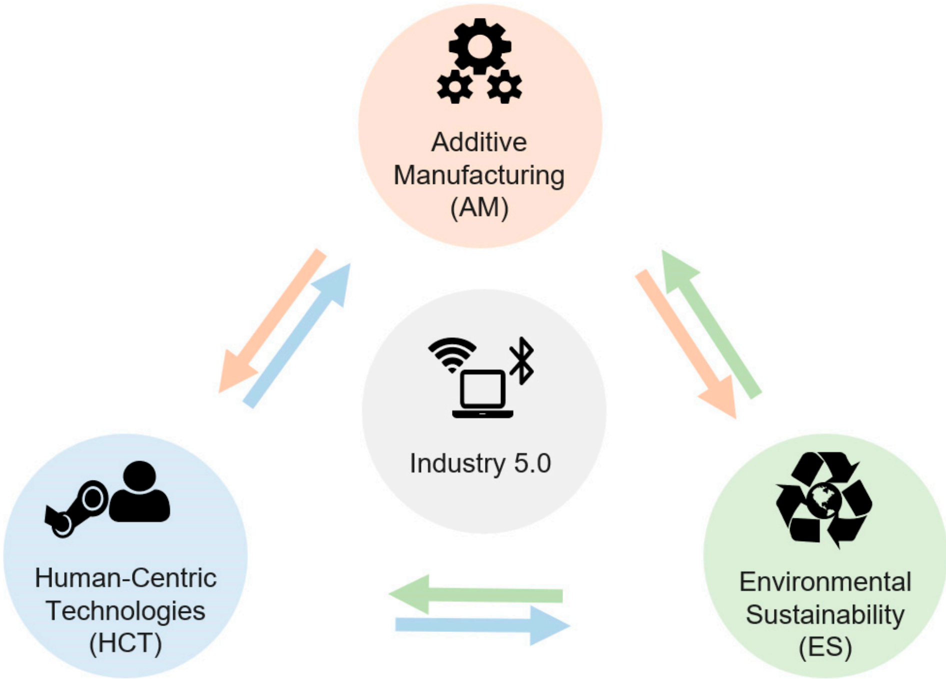

Figure 1. Human-centric technologies, additive manufacturing, and environmental sustainability as three important components and communication vertices of the triangle of Industry 5.0.

Figure 2 shows six effective parameters of HCT. First, HCT is a problem-solving approach where experienced humans are at the center of the loop, and it is a skill-based production process based on the knowledge of the operator [16]. We are trying to decrease dependency on machines among humans (reductions in error) and move toward more autonomy. Human rights, dignity, regional/global culture, and domination need to be considered. Second, connecting workflows in the cloud using computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided engineering (CAE) enables working teams to follow and track designs and manufacturing through the whole process, and IT-based networks are on-demand platforms that provide teams with private and/or public access.

In the current and 6.0 iterations of industries, interdisciplinary software (IS) and artificial intelligence (AI) have a pivotal role [17,18]. The powder bed fusion (PBF) software can read the CAD file for complex shapes in AM and control the details during the process. Usually, in PBF, a CAD file is utilized to define the geometry of a part. Increased complexity in the object's geometry necessitates greater control over parameters [19,20]. Advancements in AM technology over the last ten years have led to the development of software, which can now be used for preliminary modeling independent of CAD software and hardware (smaller devices, faster processes, and more efficient energy consumption), resulting in the fifth or sixth industrial revolution. Nowadays, most SLM devices come equipped with their own specialized software, in addition to popular design software such as AutoCAD and SolidWorks. Once a .stl or .step file is imported into the device, the software analyzes it and applies the correct laser power, scanning strategy, support structures, etc., based on either predefined settings or user-defined parameters. The development of both devices and software happens in parallel. Similar to other technologies, SLM operations are becoming increasingly automated, reducing the reliance on operators. This is advantageous, as it minimizes the risk of failure and enhances production speed. The initial versions of SLM software were simple and had limited control over complex geometries, requiring manual support structures. However, current device software has greater control over laser power based on the geometry of the object, as well as the sequencing of powder spreading and melting. The latest software packages for SLM devices are tailored to specific metal alloys, such as Al, Cu, and Ti, eliminating the need for users to optimize parameters separately for each alloy. Operators can choose the appropriate package provided by the device manufacturer (e.g., SLM Solution, Trumpf, Renishaw, or EOS) and modify only the necessary parameters and support structures, rather than creating them from scratch. However, in this case, futuristic software has the capability of 3D scanning an available part, analyzing the printing conditions, transferring data to the CAM model, and restarting the device in failed situations (autonomous mass production). Cloud ecosystems and collaborative robots/software are a way to fully automate the future phase of the industrial revolution [21]. A good example of this robot–software collaboration is the Zero-G Printer [22], developed by the National Aeronautics and Space Administration (NASA) and capable of operating in microgravity environments, such as the International Space Station (ISS).

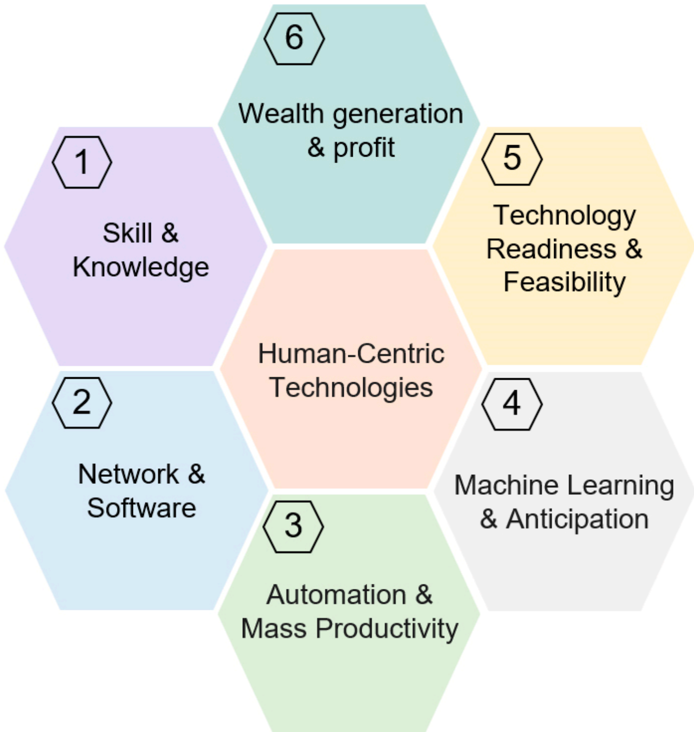

Figure 2. Honeycomb of human-centric technologies, showing the six effective parameters.

The third important parameter is the automation and mass production that has developed up to the present era (including the fourth and fifth industrial revolutions), which is nicknamed digitalization, as shown in Figure 2. During this epoch, devices are becoming smaller (or miniaturizing) and production has increased. For a recent example, compare the size and capabilities of selective laser melting (SLM) machines over the last decade, from the single-laser, small platform and a weak fiber laser to double/quadruple-laser sources and the fast implementation of platforms. The size and dimensions of the device are only relevant when dealing with materials that must maintain equivalent or superior performance at the same volume. The fourth parameter, machine learning (ML), anticipates the requirements of humans, and sensor/smart robotic manufacturing (SRM) (which can serve as an overview of the sixth industrial revolution in terms of the future) is a subset of AI and capable of imitating human mannerisms, skills, and tasks intelligently [23]. AI machines copy human behavior to modify, perform, and implement sophisticated tasks to solve problems, answer questions, and accelerate processes/products/services.

The next parameter is the technology readiness level (TRL) and the feasibility of applying new updates to either the hardware or software of a device, combining methods, communication with machines, ML, AI, importing/exporting/interpreting data, creativity, and novelty [24]. The last side of the HCT honeycomb is wealth generation and return of capital (ROC). Nowadays, the number of billionaires is increasing drastically due to their domination of social media and virtual industries [25,26]. Accordingly, one can expect abrupt wealth growth and high income from one's initial investment. Based on this, AM is an important technology, of which numerous German and American companies are already investing in its materials and methods.

In Industry 5.0, the integration of HCT with advanced AM methods such as SLM can enable the production of highly personalized and customized products while also providing opportunities for increased efficiency and productivity. In this way, HMI plays a more prominent role not only in production but also in process monitoring and failure detection [27,28]. SLM in particular offers advantages such as the ability to produce complex geometric parts with high accuracy, making it an attractive option for various industries. As for the future of SLM, it is expected to continue to grow as a key player in the AM industry. Advancements in SLM technology, such as improved materials, faster printing speeds, and larger build rates/volumes, are likely to expand its potential applications and make it a more accessible option for a wide range of industries. Additionally, the integration of SLM with other manufacturing technologies (hybrid approach), such as robotics and AI, may further enhance its capabilities and efficiency [29,30].

The most remarkable processes in AM technology and their subdivisions are shown in Figure 3. In PBF, a layer of powder material is spread onto a build platform, and then, a laser or electron beam selectively melts the powder to build up, layer by layer, the desired 3D object. SLM is the main branch of AM and PBF for metallic alloys and uses a high-power laser to selectively melt and fuse metal powders together. The complete term for it is the laser-based powder bed fusion (PBF-LB) of metals. In one study, the authors considered the SLM process for metal 3D printing and, more specifically, copper and its alloys for electro-thermal application [31,32]. Direct Energy Deposition (DED) processes encompass a range of 3D printing technologies and can fabricate large parts with moderate complexity, and these processes have a higher build-up rate and lower costs compared with PBF processes [33,34]. As one of its main subsections, wire arc additive manufacturing (WAAM) specifically uses a wire that is melted and deposited onto a substrate to build up a 3D object [35,36]. While WAAM is not a newly introduced technology, it has seen increased interest and development in recent years as a potential alternative to other DED processes such as laser- or electron-beam-based processes. We believe that WAAM could have a promising future due to its ability to create large, complex metal parts relatively quickly and cost-effectively compared with other DED processes. WAAM is able to install collaborative robots (Cobots), which are equipped with various sensors and safety features that enable them to work alongside humans [37,38]. Such a WAAM–Cobot interface can drive multi-tasks for surface strengthening, fabrication, and modification/repair for all kinds of surfaces (not only flat or cylindrical ones). Cobot development is in progress; they are a type of robot designed to work safely alongside humans in a shared workspace.

Vat polymerization processes (fluid-based 3D printing) involve the use of a liquid photopolymer resin that is cured layer by layer, using a light source to create a solid 3D object. In vat polymerization and, more specifically, stereolithography (SLA), the light source is typically a laser or a UV lamp that cures the resin. Fused deposition modeling (FDM), also known as fused filament fabrication (FFF), is a solid-based material extrusion that is a versatile and relatively low-cost 3D printing technology that can be used for a wide range of applications, from prototyping and hobbyist projects to small-scale manufacturing and production. The technology has seen significant adoption in both home and industrial settings. It has the ability to quickly iterate designs and fabrications, but it has lower resolution and accuracy compared with other 3D printing technologies, and thus needs to be improved.

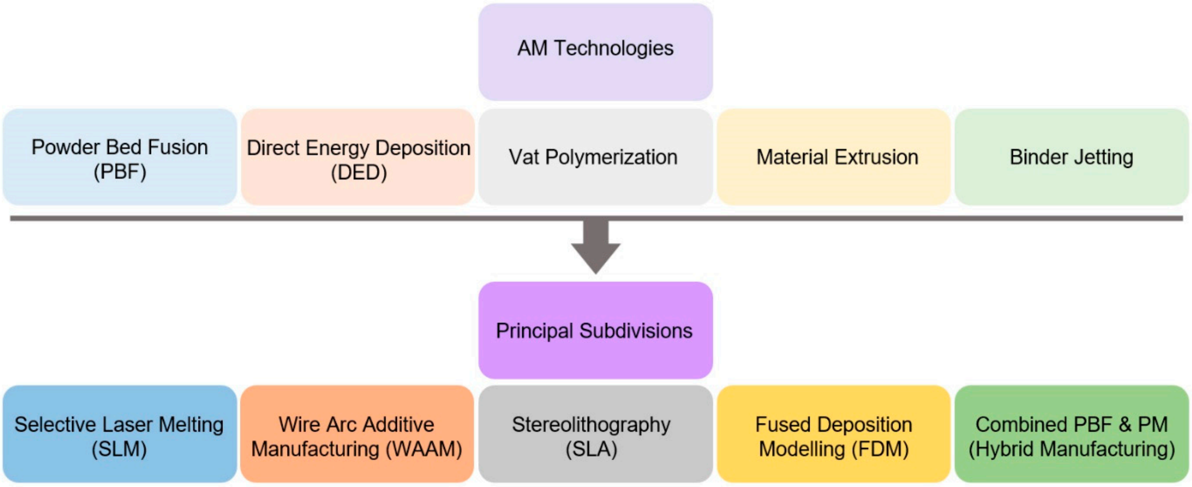

Figure 3. Revolutionizing manufacturing: promising additive processes and their subdivisions for a sustainable future.

Binder jetting (BJ) is a modern combination of PBF and PM that has an impact on the future of AM. Whereas other AM processes are in development, researchers believe BJ is ready for industrial mass production. In summary, while binder jetting uses some principles of powder metallurgy (PM) and a similar process to PBF, it is a distinct 3D printing technology that offers unique advantages and applications. BJ can be used with a variety of metals, ceramics, and composites and has advantages such as fast printing speeds, low costs, and the ability to produce complex geometries. *DigitalMetal* and *ExOne* are companies that are known to be developing BJ technology in the EU and USA [39,40]. According to Figure 3, the integration of PBF and PM technologies has led to the creation of BJ, which may also be used for other, similar AM techniques in future industrial advancements [41,42]. For instance, during the COVID-19 pandemic, PBF–PM integration was employed to produce an antiviral metal–ceramic (cermet) composite that demonstrated strong virucidal capabilities for in vitro use. As a result, combining various methods using a hybrid approach can result in hybrid composites comprising a blend of materials [43,44].

Environmental sustainability is one of the most important factors in the Industry 5.0 revolution; it is closely related to additive manufacturing, and it is depicted in Figure 4. Renewable resources (RR) [45] enable the sieving of metal/material powders, which can then be reused numerous times for 3D printing (easy recycling). In addition, transportation emissions can be considered here because the parts will be produced at the location (local fabrication). Argon is an inert gas and does not react with other chemicals or contribute to air pollution. As noted in an overview on pollution prevention (PP) [46], releasing this gas into the open atmosphere/environment is not hazardous, and its usage in LPBF/SLM is not significant.

AM technologies have the potential to revolutionize manufacturing processes by integrating with digital technologies such as AI, the Internet of Things (IoT), and cloud computing (CC), which can enable a more sustainable and efficient process in working toward Industry 6.0 [47,48]. Note that AM is applied for complex shapes, and it does not need to make molds or use multiple processes (either prototyping or mass production). Quality/durability is controllable by defining parameters such as layer thickness, alloying powders for new materials, finishing/polishing, etc. The total time and cost of AM technologies are lower compared with traditional/subtractive manufacturing.

Electronic Stewardship Management (ESM) refers to the responsible management of electronic devices throughout their lifecycle to minimize the environmental impact. It includes reducing the use of hazardous materials in the manufacturing process, promoting the reuse and recycling of electronics (cost efficiency), and properly disposing of e-waste. This approach promotes environmental sustainability by reducing pollution and conserving natural resources. The 3D printing of copper and its alloys has been investigated since AM was developed, but this process is still in progress regarding the promotion of production via the optimization of laser power, alloying pure copper, successive remelting, and using green laser sources [49–51].

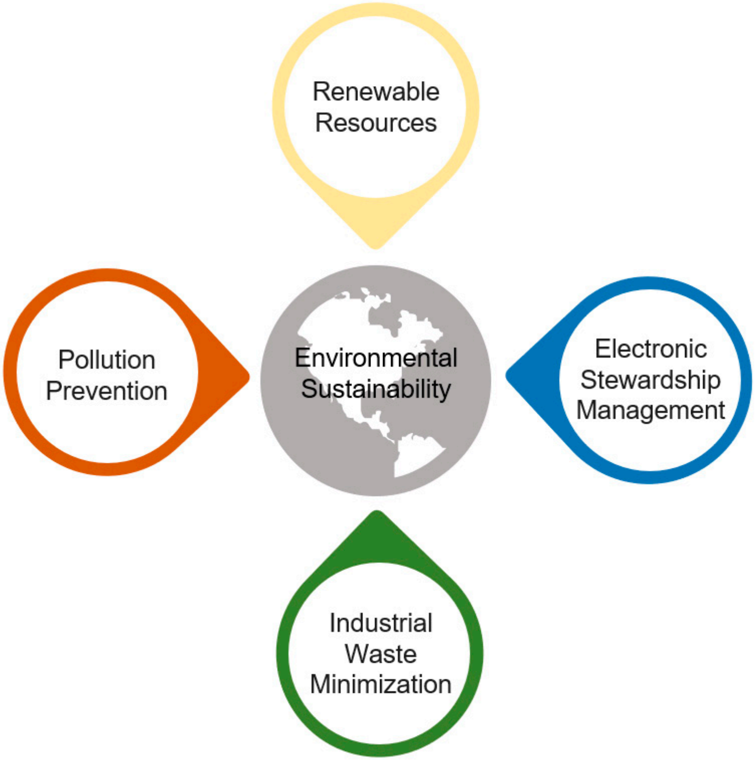

Figure 4. Breaking down environmental sustainability: an exploration of key subsections.

In terms of environmental sustainability, AM can help reduce the environmental impact of traditional manufacturing processes. Traditional manufacturing processes are often resource-intensive, produce a large amount of waste, and rely on the transportation of goods across long distances. Additive manufacturing, on the other hand, can produce goods locally, reduce transportation emissions, and can use only the exact amount of material needed, reducing waste. As a key subsection in Figure 4, industrial waste minimization (IWM) is integrated mainly with AM in four aspects:

1. The fabrication of lightweight structures (material minimizing);
2. Reductions in fabrication time (energy minimizing);
3. Using double- or quadruple-laser sources to enhance production rates (time efficiency);
4. Standardizing the process (cost efficiency).

Standardizing AM processes (as with other new technologies) is a pathway to reducing industrial waste, streamlined supply chains, consistent production, and reductions in human errors. These are the results of standardization. This pathway is shown in Figure 5 and divided as follows:

1. Modeling: The 3D scanning of a (present) part or the CAD modeling of a new model; design software and portable scanners are important for CC.
2. Fabrication: Material properties and specifications for all kinds of AM processes.
3. Characterization: Macro- or microstructure investigations, density measurements, etc.
4. Testing: This includes defining testing protocols, mechanical properties, and inspection criteria and certifying parts for their application.

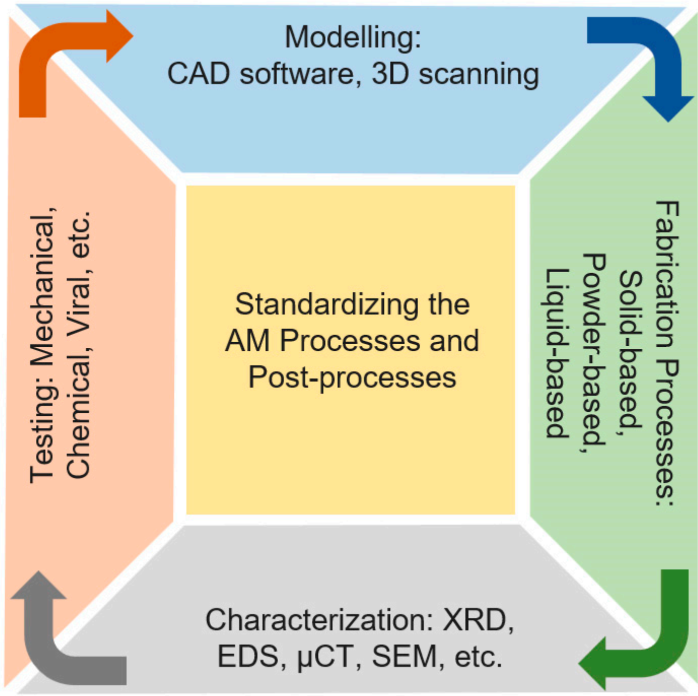

Figure 5. Standardization in AM processes for waste minimization and sustainability.

3. Industry 5.0: Fabrication of Multi-Material AM Objects with Complex Geometries

The fifth industrial revolution seeks digitalization and a smarter definition of HMI. The challenges of the present stage are rapid prototyping and reliable human–robot connections. New high-tech materials have been introduced via AM processes (such as PBF/SLM) and spark plasma sintering (PM/SPS) techniques [52–54]. In fact, this is the method used to combine subtractive and additive approaches regarding hybrid manufacturing. Spherical copper alloy powders (CuNi2SiCr or Cu15Ni8Sn), along with doped Ag/TiO_2, are 3D printed through the SLM process for the antiviral keyboards of ESP32 chipset controllers. This state of the art is sketched out in Figure 6.

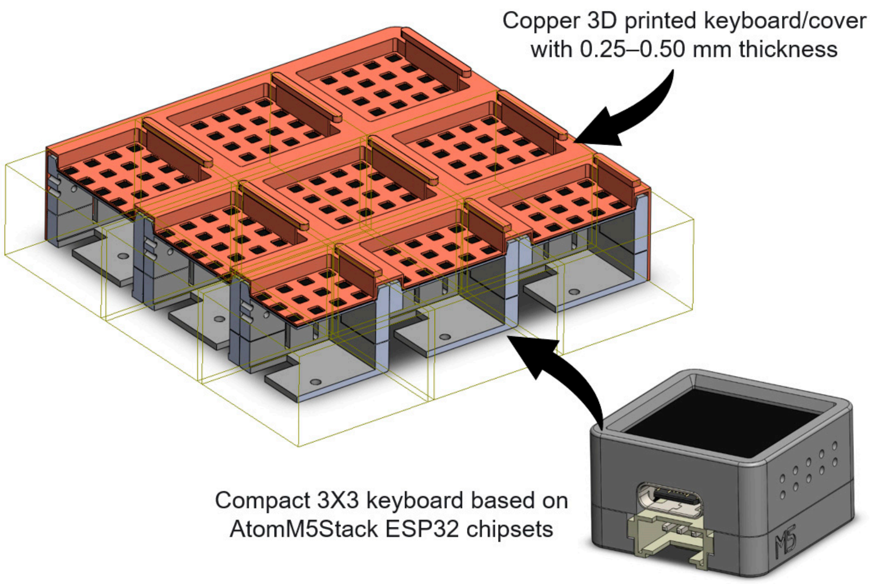

Figure 6. Schematic of 3D-printed CuNi2SiCr in a selective laser melting process for an antiviral keyboard of a controller.

AM and, particularly, the SLM of copper alloys (or other similar reflective/precious metals such as silver and gold) face a few challenges. For example,

- High thermal conductivity: Copper alloys have high thermal conductivity, which can lead to heat dissipation and insufficient energy input during the SLM process. This can result in poor fusion, porosity, and a lack of adhesion between layers.
- Oxidation: Copper alloys are prone to oxidation, which can occur during the SLM process due to exposure to oxygen in the atmosphere. This can lead to the formation of oxides and porosity in the final product.
- Residual stresses: The SLM process can introduce residual stresses into the part due to the rapid heating and cooling cycles. In copper alloys, these residual stresses can lead to distortion and cracking in the final product.

The solution to the aforementioned problems is addressed in the new generation of SLM devices by using the green wavelength range of lasers to heat platforms, alloy copper, etc. Furthermore, Industry 5.0 can potentially solve some of these problems by leveraging advancements in sensors, artificial intelligence, and automation. For example,

- Real-time monitoring: Sensors can be used to monitor the temperature and energy input during the SLM process to ensure that the parameters are optimized for copper alloys. This can help prevent heat dissipation and insufficient energy input.
- Inert gas environment: Industry 5.0 can enable the use of an inert gas environment during the SLM process to prevent oxidation and reduce porosity in the final product.
- Automated post-processing: Industry 5.0 can enable the automated post-processing of parts to reduce residual stresses and distortion. This can include heat treatment, machining, and surface finishing.

AM technologies provide the possibility of fabricating components with complex geometries from a wide range of materials. However, there are limitations in manufacturing 3D components with two or more materials, such as printability, required post-processing, size, and material compatibility. Recently, many works have investigated the fabrication of AM components using multi-materials via WAAM, SLM, DED, LENS, etc., and multi-material additive manufacturing (MMAM) could help to further improve performance, technological readiness, buy-to-fly ratio, reliability, and mechanical properties. In addition, AM components from two or more materials (multi-materials) could be used in various industries that need multi-component functionalities, including soft robotics, medicine, energy, and aerospace. Multi-material AM components could be fabricated from two or more materials that have different physical and mechanical properties. The fabrication of complex components from multi-materials [55,56] can lead to overcoming the limitation of these technologies, which is the long-standing issue of single materials. For instance, a component with complex geometry can be fabricated from three different particles that have different corrosion and tribological behaviors and thermal and electrical behaviors, as shown in Figure 7. Material A may show good mechanical and tribological properties, such as a mixture of 316L and diamond. Material C may be an alloy that has excellent thermal conductivity, such as a mixture of copper and graphite, and Material B could be an alloy that is compatible with the mentioned alloys or an alloy to achieve the desired properties.

On the other hand, recently developed LPBF/SLM machines employ multi-beam laser systems to fabricate 3D parts, and this technique can reduce fabrication time and improve efficiency. Multi-lasers can improve the properties of fabricated parts, such as surface roughness, density, process speed, and micro-/macrostructural properties in the SLM process. Although single lasers are the most commonly used in SLM processing, their productivity is much lower compared with multiple lasers. Analytical and experimental results have shown that the number of lasers used significantly affects residual stress, with an increase observed as the number of lasers increases. Therefore, it is necessary to define the influence of the scan strategy on residual stresses and its relationship with the number of lasers used. Additionally, the transient temperature field in the molten pool, the overlap/boundary areas of laser scanning, and the preheating of the platform need to be thoroughly investigated to ensure that the resulting object meets the desired properties and dimensional accuracy. [57–60]. In addition, multi-beam lasers could be used for different purposes, such as tailoring the microstructure and/or adjusting the cooling rate of the molten materials. Moreover, the AM of copper and its alloys, integrated into the fourth industrial revolution, can support the trend toward localized manufacturing (on-site) and on-demand mass production. As the manufacturing process is automated, customized, and sustained, it can be easily installed and run in small batches or even as a one-off production, which can lead to saving time and reducing inventory costs and waste.

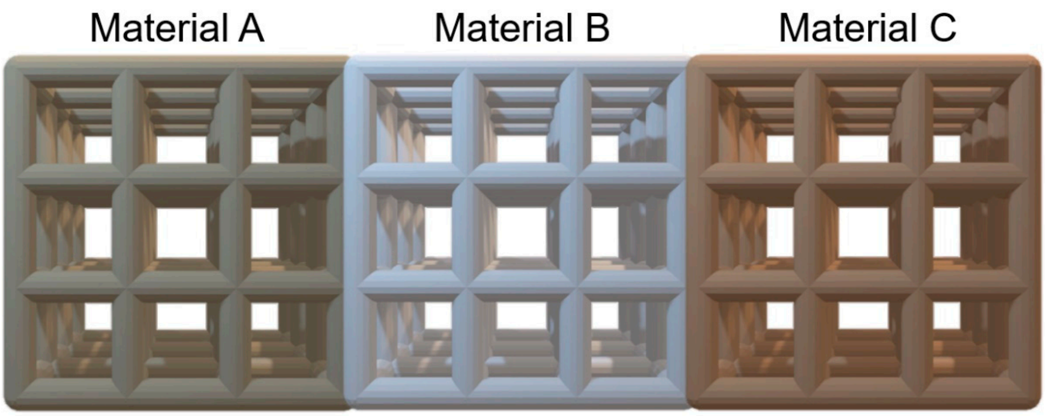

Figure 7. A representative schematic of an AM multi-material component, showing a component with complex geometry from three materials.

Figure 8 illustrates the projected improvements in the next generations of SLM devices, more specifically, for copper alloy structures. With advancements in technology, the precision of SLM machines is likely to improve, allowing for the production of more complex geometries with higher accuracy [61]. This implies that lattice and bulk structures (particularly those with intricate geometries) can be fabricated with satisfactory mechanical properties and densification, suitable for use in specific applications, with approval according to standard testing procedures and without requiring post-processing [62]. The primary intended applications for gold are in jewelry; for silver, they are in electronics; and for copper, they are in heatsinks, and SLM processes can be applied to fabricate parts for these industries. However, the high reflectivity/conductivity of some metals has been a challenge since the development of the SLM process [63]. Nevertheless, the ultrashort pulse laser is attracting growing attention as a means of surmounting these constraints [64]. The laser source can either be integrated within the device or provided as a standalone unit [65].

Industry 5.0 is expected to bring about faster rates and more precise and more efficient SLM processes, enabling manufacturers to produce parts with poor printability, such as copper structures. This encompasses multiple laser sources and multiple scanning processes (an optimized scanning strategy) [66,67]. Dual scanning is a type of remelting in the SLM process, but it involves using two lasers instead of one to achieve a higher level of control over the microstructure of the printed material. As the technology matures, the cost of SLM machines and raw materials is likely to decrease, making it more affordable for manufacturers to produce metallic structures. Two main changes that are anticipated include the development of comprehensive software (a combination of CR–CS) by device suppliers and the effective sizing of building chambers. Users/operators are expected to become more independent by utilizing a single program to create designs, set up printing parameters/platforms, and even refabricate existing parts, leading to savings in materials, time, and costs and minimizing nitrogen/argon consumption gas [68]. In addition to optimizing parameters, software, and chambers, it is also possible to customize the support structure and platform for specific applications [69,70]. For instance, in tissue engineering [71,72] and dental prostheses [73], where rapid production is required for patients, the ability to quickly install and remove modified software modules and individualized platforms is crucial. Recent advancements in the AM/SLM process have also been focused on the use of different powders. There is now a wide selection of alloyed materials available to address the challenges of printing reflective materials and cater to specific applications. Copper-balanced alloys such as pre-alloyed, gas-atomized, and spherical-shaped CuCr1Zr, CuNi2SiCr, CuSn10, CuAl10, and CuZn10 can now be effectively subjected to SLM with a high level of densification [74,75]. These powders can be recycled and sieved multiple times.

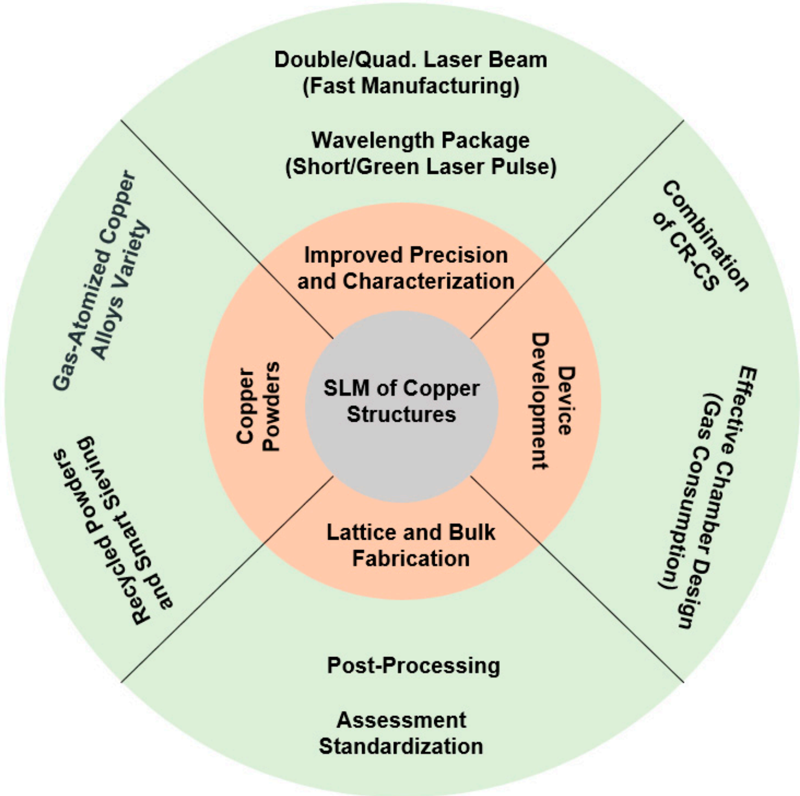

Figure 8. Anticipation of advances in copper alloy structures.

To enhance the visual appeal and ease of comprehension, the present article's storyline has been meticulously divided into figures to help the reader quickly grasp and recall the main concepts. Figure 1 depicts the primary components of Industry 5.0, highlighting the interactions between additive manufacturing and other variables. The vertices of the Industry 5.0 triangle are illustrated separately in Figure 2 for human-centric technologies, in Figure 3 for promising additive subdivisions, and in Figure 4 for environmental sustainability elements. Following the introduction of these main components, the discussion continued in Figure 5, which focuses on standardization in AM processes using LPBF/SLM technology. This is a significant challenge in the development of SLM devices; this is covered within the text and is revealed in Figure 6 as a format for Cu/Ag/Au 3D printing. Additionally, the upgrade to multi-materials and multi-lasers is another challenge that is illustrated in Figure 7. Finally, Figure 8 demonstrates the advancements in this field.

4. Conclusions

To achieve the goals of Industry 5.0, effective communication between human-centric technologies, additive manufacturing, and environmental sustainability is crucial. This approach combines automation and digitalization with human capability and controllability and prioritizes sustainable production, advanced technologies, and human demands for a more resilient and equitable future. Additive manufacturing is a futuristic technology used in Industry 5.0 to increase production efficiency, reduce waste, and enable the on-demand production of customized products. These technologies enable the on-demand production of customized products (prototyping), thereby reducing the need for mass production (personalizing) and reducing the environmental impact of manufacturing processes (autonomy). Some subsections of AM technologies have more potential for starting the fifth industrial revolution, e.g., selective laser melting, wire arc additive manufacturing, and binder jetting. Industry 5.0 integrates human-centric technologies with advanced AM methods such as SLM to produce highly personalized and customized products while also improving efficiency and productivity. The significance of SLM is emphasized particularly when it comes to 3D printing reflective and precious metals such as copper, silver, and gold. As a result, combining various methods of powder bed fusion and powder metallurgy using a hybrid approach can result in hybrid composites comprising a blend of materials, e.g., metals, ceramics, and polymers. The present work, more specifically, focused on SLM as a futuristic subdivision of additive manufacturing applied to the fabrication of metallic parts/assemblies and 3D-printed copper alloys.

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Nomenclature

Abbreviation	Name
AI	Artificial Intelligence
AM	Additive Manufacturing
BJ	Binder Jetting
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CC	Cloud Computing
CR	Collaborative Robots
CS	Collaborative Software
DED	Direct Energy Deposition
EDS	Energy Dispersive Spectroscopy
EMS	Electronic Stewardship Management
ES	Environmental Sustainability
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication

HCT	Human-Centric Technologies
HMI	Human–Machine Interface
IoT	Internet of Things
IS	Interdisciplinary Software
ISS	International Space Station
IWM	Industrial Waste Minimization
LPBF	Laser Powder Bed Fusion
MMAM	Multi-Material Additive Manufacturing
ML	Machine Learning
NASA	National Aeronautics and Space Administration
PBF-LB	Laser-Based Powder Bed Fusion
PBF	Powder Bed Fusion
PM	Powder Metallurgy
PP	Pollution Prevention
ROC	Return of Capital
RR	Renewable Resources
SEM	Scanning Electron Microscope
SLA	Stereolithography
SLM	Selective Laser Melting
SPS	Spark Plasma Sintering
SRM	Sensor Robotic Manufacturing
VR	Virtual Reality
WAAM	Wire Arc Additive Manufacturing
XRD	X-Ray Diffraction
μCT	Micro-Computed Tomography

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