Summary of Doctoral Dissertation

Towards sustainable manufacturing in the PBF-LB industrial process: assessment of opportunities and challenges

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Introduction

In recent years, global concerns about the environmental impacts of industry have grown. This has coincided with an increasing interest among companies in sustainability and sustainable development, which has led to a search for more eco-friendly technologies. Manufacturing processes that enable improvements in resource consumption, reductions in waste and emissions generation, and shorter supply chains could permit firms to achieve some of their sustainable development goals. Additive manufacturing (AM), due to its intrinsic nature, could represent a promising solution and understanding its characteristics and constraints is essential to better exploit its potential.

Sustainability

Sustainability is built on a simple and long-acknowledged assumption: all people's needs for their well-being and survival derive directly or indirectly from the natural environment. A high-quality environment is required for human health, well-being, economy, and security.

Conceptually, the origin of Sustainability and Sustainable Development comes from significant concerns about the social, economic, and environmental effects of the fast-growing world population, overproduction in current economies to meet consumer desires, and the ever-increasing consumption of natural resources. At the end of World War II, international agreements and institutions focused on two pillars, economic development and social development or human rights, were established. If on the one hand, the development worked well leading to a stronger global economy and higher living standards with a longer life perspective, on the other hand, in the 1970s and 1980s it was clear that to address issues like environmental degradation and pollution in the world, a change in development model was needed [1]. As a result, the World Commission on

Environmental and Development (known as the Brundtland Commission from its chair, Gro Harlem Brundtland) introduced in its fundamental 1987 report, *Our Common Future*, the emblematic definition of sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [2]. Furthermore, the Commission encouraged the United Union (UN) General Assembly to convert its report into a global action plan for sustainable development: at the 1992 "Earth Summit" conference in Rio de Janeiro, an international sustainable development action plan, known as *Agenda 21*, and 27 principles to guide sustainable development, called *Rio Declaration*, were approved. Thereby, the definition of development changed by adding a third pillar, environmental protection and restoration, to the social and economic pillars of development leading to the well-established "Three Pillars" model, also known as the "Triple Bottom Line" (TBL) approach: "Social", "Economic" and "Environmental" dimensions of sustainability constitute one of the most widely adopted models for assessing and capturing sustainability performance in business sector [1] (**Errore. L'origine riferimento non è stata trovata.**).

Figure 1. Triple Bottom Line (TBL) model.

The 2015 "United Nations Summit" in New York represented another fundamental achievement in global sustainable development: the document *Transforming our world: the 2030 Agenda for Sustainable Development* was adopted, which contains 17 Sustainable Development Goals (SDGs) and 169 associated targets, integrated and indivisible and that balance the three dimensions of sustainability [3,4]. Among the SDGs, five are strongly pertinent to the manufacturing sector: affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9), responsible consumption and production (SDG 12), and climate action (SDG 13). Given its broad scope and wide range of stakeholders, the manufacturing industry has played and is still playing a central role in driving the development, economic growth and prosperity of the countries, which is why it is considered one of the main sectors where significant changes toward sustainability are needed. Indeed, it is well known that manufacturing has a huge impact on environmental deterioration leading to several issues such as pollution, waste and effluents, exploitation of natural resources, and overconsumption of energy [5–7]. Therefore, the manufacturing industry is required to implement sustainable strategies and practices to mitigate, measure and control the environmental performance of the production processes. In this context, regulations on environmental and social impacts have been introduced, intergovernmental agreements and cooperation have been established, and an increasingly proactive way of working is being implemented by anticipating negative impacts during the design and planning stages of production. In this way, enterprises are motivated to transform their business structure into a sustainability-oriented business by improving their competitiveness [8–10].

According to TBL theory, the sustainable manufacturing (SM) concept has emerged as a key factor in helping companies face sustainability-related challenges. Different approaches to the problem were found in the literature. Previous studies were based on the sustainable manufacturing definition presented by the U.S. Department of Commerce as "*the creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and resources, are safe for employees, communities, and consumers and are economically sound*". Their focus was mainly on the ecological dimension in which only the environmental impacts of manufacturing operations were measured and assessed. However, based on the "Three Pillars" concept, all three dimensions of sustainability have equal weight and importance and no one of them is negligible. Based on the above, sustainable manufacturing practices (SMP) are defined as "*the actions, initiatives, and techniques that positively affect the environmental, social or economic performance of a manufacturing company,* *helping to control or mitigate the impacts of the manufacturing operations on the triple bottom line*" [8,11,12]. From sustainable manufacturing and development concepts, several sustainable manufacturing practices can be deducted which involve different production system stages such as processes, products and services. Some researchers have defined SMP by analyzing five distinct aspects: eco-design, process design, energy management, waste management, and supply chain management [13]. In addition, in sustainable manufacturing lean and six sigma practices are used to address the economic issues, 6Rs practices, i.e. reduce, reuse, recycle, recover, remanufacture, and redesign, are aimed at achieving environmental benefits, and, according to the ISO 26000 standard [14], operational and labor practices, human rights, organizational governance, consumer issues, and community involvement and development contribute to social benefits. The company has to implement all these practices with strategic planning to create a sustainable business model [15].

Additive manufacturing

Business models and manufacturing processes are ever-changing due to the radical paradigm shift towards a smart industry with advanced, autonomous, and interconnected manufacturing technologies, the so-called Industry 4.0. The goal of Industry 4.0 is to make firms more efficient, intelligent and cost-effective, optimize production and transform materials and processes management through nine enabling technologies (i.e. Industry 4.0 technological pillars). Therefore, due to the huge changes led by these emerging technologies, an advanced manufacturing process requires strategic planning and in-depth knowledge of its mechanism and characteristics from an early stage. In addition, technological progress can diversify companies and enhance their competition in the market [9,16,17]. In this context, additive manufacturing (AM) has emerged and attracted the attention of the industry: many companies are learning to adapt to AM processes through research and development and thinking about how they can change the production chain and exploit AM potential [18,19].

The American Society for Testing and Materials (ASTM) has defined additive manufacturing as the "*process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and* *formative manufacturing methodologies*” (according to ISO/ASTM 52900:2021, [20]). Various AM technologies, which differ in raw material, material state and adhesion mechanism between the layers, have been developed to meet industrial demand. Consequently, the classification of AM processes has been a highly discussed topic that has led several researchers to propose interesting alternatives. The ASTM has classified AM processes into seven standard categories: binder jetting (BJT), directed energy deposition (DED), material extrusion (MEX), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL), and vat photopolymerization (VPP). However, this classification provides a general distinction between AM categories based on basic process principles and characteristics and often a more detailed specification may be needed to distinguish different technologies within each process category; for instance, the powder bed fusion process can be for polymers as well as for metals, or powder bed fusion for metals can use a laser beam or an electron beam. Therefore, identifying a certain AM process is carried out through the process category, material processed and distinctive peculiarities of the AM process [20].

The best AM application is where conventional manufacturing shows limitations: AM, as a digital manufacturing technology, allows for direct production, immediate action to improve parts and process design, and for management of process parameters to control and ensure a high accuracy level, its nature enables design freedom and complexity that is impossible to obtain with subtractive or formative technologies, and its automated nature results in less manual and lower-skilled labor [18].

Although AM has attracted many industries mainly due to its technical and technological benefits, it also offers environmental advantages that enable companies to meet the increasingly stringent requirements for sustainable production in the manufacturing industry. AM processes, for their layer-by-layer nature, use only the material needed to make a part minimizing waste production, some specific additive processes, by allowing the remanufacturing and refurbishing of damaged or critical tools, have the potential to shorten the supply chain by removing processes for tooling fabrication, and, in terms of carbon footprint reduction, they lead to less use of energy-intensive processes and cutting fluids [18,19,21]. Consequently, several contributions of AM to sustainable manufacturing have been recognized by industrial stakeholders and, in order to assess how additive systems could promote sustainable industrial development, a triple bottom line approach has been used to explore environmental, economic and social aspects.

Sustainable additive manufacturing

The field of sustainability in additive manufacturing (SAM) represents a developing area of research. Although it is experiencing growth, it has not yet reached a point of maturity. In the literature, two distinct research fields have been identified: the sustainability of the manufacturing process itself and the added value in terms of the sustainability of 3D-printed products. In order to evaluate the sustainable implications of AM, it is necessary to go beyond the process parameters of the manufacturing phase itself and consider the whole product life cycle. Furthermore, the sustainability analysis of the products remains qualitative. Further studies could be more challenging. Nevertheless, the most frequently occurring aspects of sustainability potential associated with AM have been identified and detailed as follows [19,21,22].

- Product life extension: products can be discarded for two main reasons, technical or psychological issues. On the one hand, if a component is damaged or broken, technical approaches such as repair, remanufacturing or refurbishment could be adopted to extend its operational lifespan. As a digital technology, AM enables the repair and reproduction of failure parts and the digital storage and on-demand production of spare parts, thereby reducing inventory and storage costs significantly. In addition, certain additive techniques permit direct action on existing damaged surfaces. On the other hand, AM facilitates the customization and personalization of parts, which may foster product attachment and strengthen the bond between consumers and products, potentially extending the product lifetime.
- Resource efficiency improvement: improvements can be achieved in both the manufacturing and use phases. AM enables the reduction of material usage and energy consumption, facilitating the consolidation of components into a monolithic part with complex geometry. Furthermore,

it allows for the simplification of assembly lines and the enhancement of product functionality. These benefits can be achieved through different methods, such as topology optimization, or implementing design for additive manufacturing (DfAM) guidelines.

- Value chain reconfiguration: AM supports decentralized manufacturing, which is a network of local production centers that are designed to be closer to the needs of consumers through small-scale and flexible production. Distributed AM has the potential to be a more sustainable alternative to mass production due to the shorter supply networks, reduced transportation time and costs and shorter lead times.

The contribution of AM to sustainable industrial development can be enhanced by integrating circular design strategies into the construction of AM machines, the design of processes, the development of new materials, and the planning of supply chains.

Chapter 1

Laser-based powder bed fusion

Laser-based powder bed fusion (PBF-LB) is an advanced manufacturing technology that enables the production of complex near-net-shape products with less waste material and high resolution and accuracy. As with any production process, it presents environmental and economic impacts throughout the entire process chain, ranging from the extraction and processing of raw materials to the disposal of final products. These issues can be addressed through the implementation of sustainability practices.

1.1 The manufacturing process

Powder bed fusion (PBF) represents one of the AM process categories with the widest industrial application. All PBF processes possess common fundamental features, including an energy source employed to melt powder particles, a method to control the selective fusion of specific regions of the powder bed, and mechanisms to spread the powder. In addition, a wide variety of materials can be processed, such as metals, polymers, ceramics, and composites [23]. According to the type of thermal energy used, a distinction between laser-based PBF (PBF-LB) and electron beam-based PBF (PBF-EB) can be made [20]. This thesis will examine the PBF-LB process, previously known also as selective laser sintering, selective laser melting, direct metal laser sintering, direct metal laser melting, laser CUSING, etc.

The first PBF-LB system was developed for polymers and commercialized by the DTM Corporation, USA, in 1992. In 1994, EOS GmbH, a German company, launched its first system for the production of polymeric prototypes, and, in 1995, the company developed its first commercial machine for metallic parts. The building process of products is performed within a closed chamber that is filled with an inert gas, such as nitrogen or argon, to prevent undesirable reactions between the molten material and the surrounding environment. Furthermore, it facilitates removing impurities from the working area and other undesirable phenomena, such as spattering, which refers to the ejection of process by-products from the melt pool during the interaction between the laser and the material [24]. The process begins with spreading a thin layer of powdered material over the building platform by a recoating system (Figure 2). The powder dispenser supplies a greater amount of powder than is necessary, thereby ensuring that the recoating system spreads an even layer on the building platform. The excess powder is conveyed to a powder collector for future reuse [25]. Then, a laser beam is directed and moved onto the powder bed through a mirror-based system, consisting of a focusing lens and galvanometers, to selectively fuse the designated area of the cross-section. Once the melting of the layer has been completed, the building platform is lowered by one layer thickness, a new layer of powder is spread over the platform, and the laser scans the involved area in the following cross-section. This process is repeated until the building of the components has been finished [23].

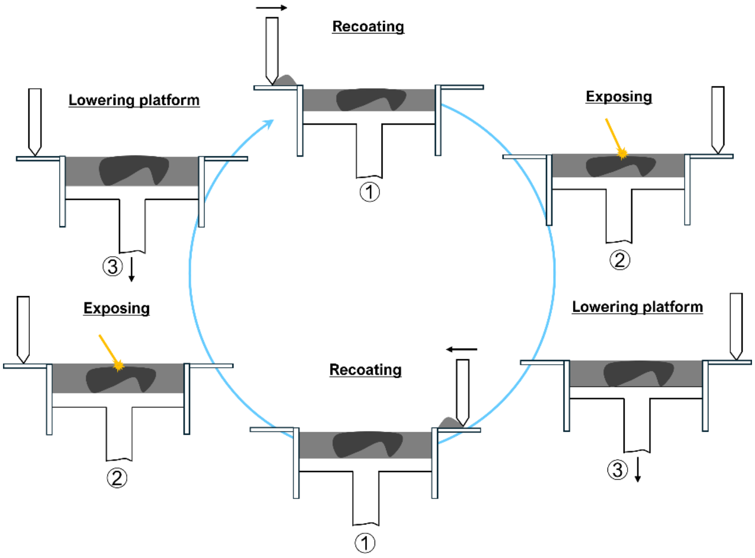

Figure 2. Schematic representation of the main phases in the PBF-LB process.

The PBF-LB process has demonstrated several beneficial characteristics typical of AM technologies, as reported below:

- It is possible to produce ready-assembled parts in a single manufacturing process with a near-net shape (i.e. close to the final shape and dimensions).
- A broad range of complex geometries can be produced, including lattice structures and topologically optimized shapes.
- The level of complexity is not a determining factor in manufacturing costs.
- It is possible to modify the properties of the parts by making local adjustments to the process parameters.

On the other hand, some limitations related to the manufacturing process must be considered:

- Due to the thermal gradients, several effects may occur, such as distortion of the parts, internal residual stresses or shrinkage phenomenon.
- The variety of materials available for this process is lower than for traditional manufacturing techniques.
- The properties of materials are strongly affected by the setting of process parameters.
- During the process, more powder is used than is required for the parts. Therefore, depowdering operations must be planned.

Although the basic process mechanisms are the same, there are significant differences between the PBF-LB systems designed for polymers and those designed for metals [26,27].

1.2 The PBF-LB process chain

PBF-LB technology is not merely a laser-based fusion and, thus, production process; it also encompasses pre- and post-processing operations that are necessary to provide customers with a ready-to-use product. The entire process chain is characterized by machines, equipment and supplementary apparatus, which must be considered for a comprehensive assessment of the sustainability aspects related to this manufacturing process [28].

The PBF-LB process chain starts with the pre-processing phase, which encompasses a series of operations. These include data preparation with software tools, in which specialized engineers manipulate a 3D CAD file to ensure the printability requirements of the process are met. Additionally, powders are sieved to separate impurities and particles that are too large from the rest. Finally, the machine is set up to prepare for the next build cycle. The set-up of machines for polymers encompasses the feeding of the powders, pre-heating of the chamber and powder bed, spreading of the first powder layers on the platform, and a low flow of inert gas into the working chamber. On the other hand, set-up for PBF-LB/M machines involves the feeding of powders, mounting of a suitable recoater blade according to the material to be processed, pre-heating and aligning of the building platform, spreading of the first powder layer on the platform, and flow of inert gas in the building chamber to reach low-content oxygen atmosphere.

The main phase of the process chain is the manufacturing process itself. This process is characterized by two distinct times: the exposure time, during which the laser is switched on and scans selectively the powder bed, and the recoating time, during which the laser is switched off, the axes of the machine move, and a new powder layer is deposited on the platform. In the processing of polymers, the recoating time involves also the preheating of the powder layer before the laser scanning. The main phase concludes upon the completion of the construction of the parts.

The post-processing phase includes all those operations that, starting from the as-built state, lead to ready-to-use products. Typically, these include depowdering, stress-relieving treatment, detachment of the parts from the platform, potential additional heat treatments, and surface finishing processes.

1.2.1 Opportunities for sustainable PBF-LB

The PBF-LB process, as a production technology, has a considerable impact on the environment, offering the potential for the implementation of sustainable practices throughout the entire production chain. These practices may be applied at any stage of the process, from the extraction and processing of the powders to the disposal or recycling of finished parts.

The sustainability implications of the pre-processing phase are mainly related to the production of the powders, the choice of the orientation of the parts on the building platform and the consequent generation of support structures, and the recycling of the powders.

The production processes for PBF-LB powders require high energy consumption to obtain a powder that meets the flowability and size requirements suitable for printing. Typically, metal powders are produced by gas or plasma atomization, a highly expensive process that may produce significant material loss. Using processes with a reduced energy impact may enhance their environmental effects. Nevertheless, alternative solutions may be considered, including the enhancement of the sustainability of alloys in terms of composition with more readily extractable and less refined materials, or the use of powders recycled from secondary materials, such as industrial waste or end-of-life products. In addition, bio-based or compostable materials may be used mainly to produce polymer powders, although, to date, their behavior remains poorly understood and difficult to control during the melting process [29].

During the data preparation phase, the engineers may optimize the orientation of the parts and the position within the building volume to minimize the necessity for support structures and subsequent post-processing operations. This aspect impacts mainly PBF-LB for metals, where the presence of supports significantly reduces the productivity of the building process and, if they are incorrectly designed, may induce the failure of the building. Furthermore, the post-process operations may increase both the lead time and the cost of the finished products. In this context, software tools that enable the simulation of the printing process and propose different orientation solutions to identify the most efficient configuration, such as the commercial software solution *Amphyon* by Oqton, are being developed to assist engineers in data preparation [30].

It is well known that PBF-LB facilitates the reuse of unmelted powders in subsequent build cycles, thereby improving the sustainability of the process. Initially, the powders are subjected to a sieving process to remove any impurities or large particles. Subsequently, to maintain the original powder size distribution and ensure the quality of the final parts, a certain amount of new powder is added to the sieved powder. After a certain number of build cycles, metallic powders can undergo several phenomena, including oxidation and contamination, which may limit their further use. The number of reuse cycles may vary according to the specific materials, initial quality of the powders, process parameters used during the building, machine set-up, and handling and storage conditions of the powders. Some sustainable solutions have been proposed to address this issue, such as the implementation of closed-loop systems, to minimize human intervention and potential contamination, and the reusing of the powders for other manufacturing processes with different powder requirements [31]. For polymeric powders, reusing is more challenging due to thermal degradation during the building process. Even polymeric powders can be regenerated by mixing recycled and virgin powders; however, recycled powders may lead to severe issues of accuracy and surface finish in the printed parts [32,33].

The manufacturing process is the most energy-intensive phase of the entire process chain. The utilization of a laser source to melt the powder bed necessitates a considerable input of energy, which has an adverse impact on the environment. The geometry, orientation and position of the parts within the build volume, the laser and scanning parameters, and the machine setup strongly influence the overall build time and, consequently, the energy consumption of the process. Machine manufacturers are equipping systems with ever-increasing automated solutions and more lasers to enhance process productivity. Additionally, advanced monitoring systems for real-time control and manipulation of process parameters are being implemented in PBF-LB systems, which could be also useful to reduce the risk of failure of the printing process. Furthermore, the optimization of process parameters to increase efficiency without compromising mechanical performance, and geometrical and dimensional accuracy of the parts could make PBF-LB more sustainable. In PBF-LB/P systems, the energy consumption related to the laser source is lower than that for metals, and the thermal control of the chamber has a more significant impact in terms of energy. Consequently, the recycling of chamber heat through energy recovery systems may reduce overall energy consumption [31,33,34].

The sustainability assessment of the post-processing phase mainly refers to the waste management, energy consumption and environmental impacts of potential heat treatments and surface finish operations.

Support structures or failed parts during a build cycle represent a source of material waste in the PBF-LB process. Recycling and recovery techniques are necessary to address the waste management issue. Additionally, the development of more sustainable post-processing techniques, such as low-energy surface finishing or heat treatments at lower temperatures, can also help to reduce the overall environmental impact of the process chain [31].

1.2.2 Limitations for sustainable PBF-LB

Despite the numerous enhancements and proposals for sustainable practices within the PBF-LB process chain, many constraints limit the extensive implementation of these innovations in the industrial sector.

Materials with low energy impacts are not yet fully optimized for the PBF-LB process, requiring extensive experimentation to develop appropriate process parameters and enhance their stability throughout the building process. Additionally, the lack of standardization strongly limits the adoption of these materials, especially in sectors with rigorous quality requirements, such as aerospace, automotive, and medical.

The recycling of unmelted powders may necessitate the implementation of supplementary processing operations, which could lead to an increase in production costs and a reduction in the sustainable advantage on a larger scale. Moreover, the use of recycled powders is currently permitted for applications with less restrictive quality requirements for the final products.

The use of simulations to optimize the orientation of the parts and generation of support structures requires the employment of sophisticated software and significant computational resources. This may result in elevated investment costs beyond the financial capabilities of small and medium-sized enterprises.

In addition, all the improvements that the machine manufacturers are implementing in their systems to enhance process efficiency, increase automation, and improve the handling and management of the powders are leading to a significant increase in investment costs that could outweigh the economic benefits mentioned above.

Recycling support structures, failed parts, and end-of-life PBF-LB products can be very challenging and expensive. In addition, the lack of studies highlighting the prospects for the reuse of waste products greatly limits the development and dissemination of recycling techniques.

In conclusion, the adoption of sustainable practices in the PBF-LB process chain implies several limitations related to the costs, product quality requirements, process complexity and materials management. Overcoming these limitations would require investment in advanced technologies, the development of more sustainable materials, standardized sustainable methodologies, and deep analysis of the end-of-life stage of products.

In light of the challenges presented in this chapter, the following sections will focus on examining potential solutions to enhance the sustainability of the PBF-LB/M process. Firstly, a detailed analysis of the process productivity and the factors on which it depends will be presented. Subsequently, strategies to increase productivity by optimizing process parameters, to develop more sustainable post-processing solutions, and to reuse unmelted metallic powders in a novel manufacturing process will be discussed.

Chapter 2

Research activities and results

2.1 Actual productivity of PBF-LB/M

One of the most challenging aspects of the widespread industrial use of PBF-LB/M is represented by its low productivity, which is related to its long building time and, consequently, high manufacturing costs [35,36].

In the literature, the most widely used metric for assessing the productivity of AM processes is the build volume rate ($\dot{V}$), which represents the volume of material processed in the time unit and can be defined as follows [35,37,38]:

$$\dot{V} = v_s \, h_d \, t \tag{2.1}$$

expressed in mm^3/s or cm^3/h and directly proportional to the scanning speed (v_s), hatch distance (h_d), and layer thickness (t). Generally, this equation is employed to evaluate the building speed of a certain set of process parameters or to compare the productivity of different AM technologies. However, the expression of the build volume rate refers only to the exposure phase and does not take into account all the mechanisms and parameters involved in the building process. For instance, it does not account for the differences between the in-skin, up-skin and down-skin areas. These regions can be processed with different laser and scanning parameters, according to the quality targets to be achieved, and their extension can vary with the orientation of the parts. Consequently, $\dot{V}$ provides a highly simplified estimation of the effective construction speed and is therefore not representative of the actual productivity of the process. Within this work, it has been compared with the effective build volume rate ($\dot{V}_{eff}$) which has been estimated as the ratio between the volume of the part (V) and T_{exp}:

$$\dot{V}_{eff} = \frac{V}{T_{exp}} \tag{2.2}$$

expressed in cm^3/h, where T_{exp} has been estimated using commercial software of a PBF-LB/M machine. T_{exp}, as a laser melting time, is also significantly affected by the volume of support structures, which can lead to a notable reduction in the productivity of the parts. In general, these structures are melted with laser and scanning parameters that differ from those used for the part volume, resulting in a different construction speed. In this study, the influence of support structures has been neglected.

To investigate the effect of the orientation and process parameters on the manufacturing time, samples with a simple geometry have been designed (Figure 3). The results are summarized in Table 1.

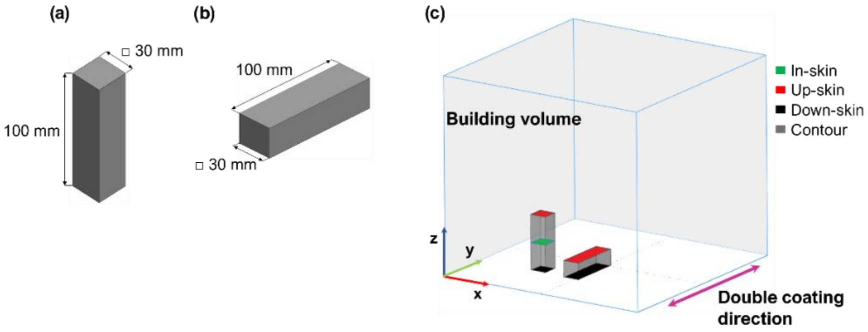

Figure 3. Parallelepiped in (a) vertical and (b) horizontal printing orientation. (c) Samples in the building volume.

Table 1. Building times of a simple geometry manufactured in different orientations, with the effect of coating directions.

Sample orientation	**No. layers**	**Single coating direction**			**Double coating direction**		
		T_{exp} [h]	T_{rec} [h]	T_{Build} [h]	T_{exp} [h]	T_{rec} [h]	T_{Build} [h]
Vertical	3333	4.05	13.75	17.80	4.05	6.45	10.50
Horizontal	1000	3.95	4.12	8.07	3.95	1.93	5.88

To investigate the effect of geometrical complexity on the effective building speed of the PBF-LB/M process, several samples with different geometries and degrees of complexity have been designed (Figure 4).

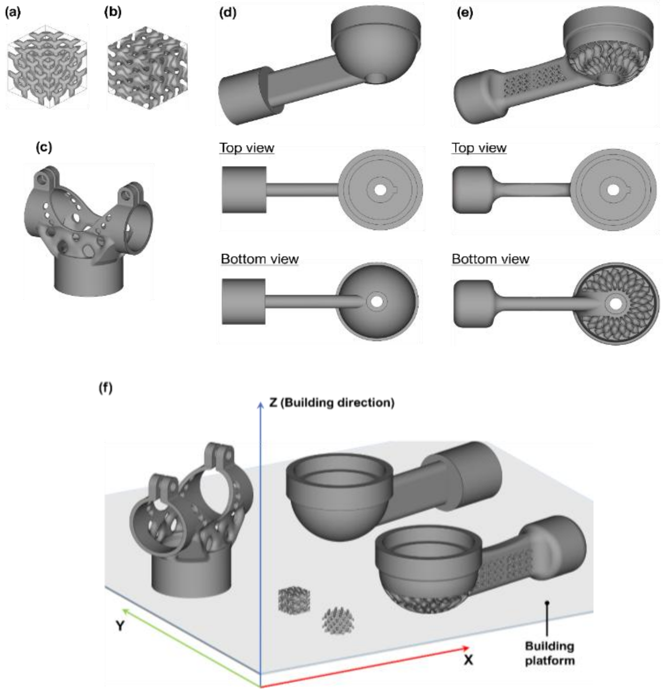

Figure 4. Samples with different degrees of complexity. (a) Diamond and (b) gyroid cubic samples, (c) bracket, lathe knob (d) replicated with AM and (e) optimized for AM. (f) Orientation of the samples on the building platform.

Table 2 summarizes the results. Firstly, it can be stated that all manufactured samples have shown $\dot{V}_{eff}$ value lower than the theoretical one. This is due to the process parameters and more complex geometries. In particular, it is often thought that the lightening of a component by introducing lattice structures into its geometry can result in a reduction of the building time. However, the complex geometrical nature of lattice structures leads to many up-skin, down-skin and contour areas during the printing process, and this reduces the overall speed of the process. Indeed, the results demonstrate that the effective exposure time of the two lattice structures analyzed, diamond and gyroid, increases and this has a significant impact on the build rate. Furthermore, by comparing the lathe knob with a traditional geometry and its variant optimized for AM, it can be observed that the introduction of TPMSs in the original design results in a reduced build rate. In addition, by comparing the hypothetical costs of the samples, it can be observed that the cost computed based on $\dot{V}$ ($Cost_{th}$) results lower than the cost based on $\dot{V}_{eff}$ ($Cost_{eff}$), due to the underestimation of exposure times.

Table 2. Effect of the geometrical complexity on the build volume rate and costs.

Sample	V [cm^3]	T_{rec} [h]	T_{exp_th} [h]	T_{exp_eff} [h]	$\dot{V}$ [cm^3/h]	$\dot{V}_{eff}$ [cm^3/h]	$Cost_{th}$ [€]	$Cost_{eff}$ [€]
Diamond	0.26	0.63	0.01	0.03	26.68	7.71	29	30
Gyroid	0.49	0.63	0.02	0.07		7.33	29	32
Replicated with AM	46.19	2.37	1.73	2.30		20.08	185	210
Optimized for AM	40.77	2.37	1.53	2.37		17.23	176	213
Bracket	13.90	4.93	0.52	0.98		14.14	245	266

2.2 Increasing productivity

The layer thickness represents one of the most significant parameters affecting the energy required for proper melting of the powder bed and the final properties of the parts. The use of thicker layer thicknesses may result in a significant *staircase effect*, which could compromise the accuracy of the final products. The staircase effect (also referred to as the ‘stair stepping’ effect) derives from the slicing of the STL files and is strongly related to the size of layer thickness and surface inclination [39]. The use of thinner layer thicknesses may reduce this effect, but it may also lead to a reduction in the overall productivity of the process. In this context, suitable scanning strategies can be employed to improve the accuracy of the parts without decreasing the building speed. ‘Fill-contour’ strategy is used in PBF-LB/M parts, in which the fill parameters are optimized for density and productivity, while the contour parameters are adjusted for accuracy. Therefore, an optimization of laser and scanning parameters with thicker layer thicknesses is required to improve building efficiency and obtain high-quality final parts. In the present study, the layer thickness was fixed at 90 μm. Table 3 summarizes the process parameters used in this study.

Table 3. Process parameters and DoE definition. Number of replications: 3.

	Fixed parameter	**Variable parameter**	**Value**
	Layer thickness [µm]		90
	Laser beam diameter [µm]		100
	Platform temperature [°C]		100
In-skin / Up-skin / Down-skin	Laser power [W]		370
	Scanning strategy		Stripes, rotated by 67°
		Scanning speed [mm/s]	800, 900, 1300, 1400
		Hatch distance [mm]	0.09, 0.11, 0.12, 0.13
Contour		Laser power [W]	290, 340
		Scanning speed [mm/s]	700, 750, 1200, 1300
		Build volume rate [mm^3/s]	6.48–16.38

To investigate the results of the Archimedes test, a comprehensive characterization using CT scanning was performed on the samples that have shown the optimal trade-off between the density and build rate values (Figure 5).

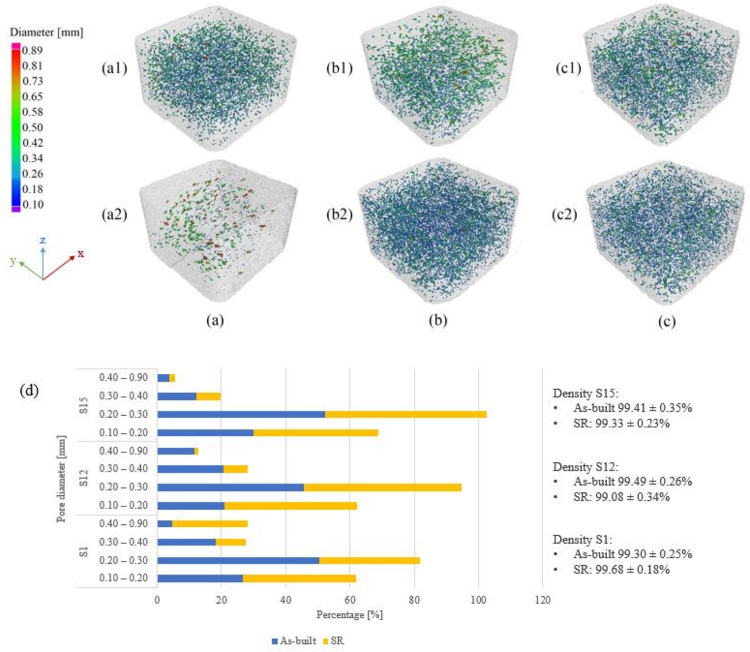

Figure 5. CT scan images of the samples showed the best results from Archimedes test [40].

Table 4 shows the tensile results compared with reference values of mechanical performances of the same die-cast alloy. The mechanical properties of specimens are comparable with specimens produced by conventional techniques, as already noted in the literature.

Table 4. Tensile test results in z-direction. *For the high pressure die casting AlSi10Mg parts, the properties for as-cast (F) as well as for the aged (T6) condition are given [40].

	Yield strength [MPa]	*Ultimate tensile strength* [MPa]	*Elongation at break* [%]
S1 as-built_zone 1	178 ± 6.36	298 ± 0.71	2.5 ± 0.07
S1 as-built_zone 2	189 ± 6.36	306 ± 4.24	2.5 ± 0.14
S1 as-built_zone 3	170 ± 7.78	282 ± 0.71	2.1 ± 0.14
S1 SR_zone 1	149 ± 7.00	235 ± 7.00	4.2 ± 0.39
S1 SR_zone 2	151 ± 4.74	241 ± 8.45	4.2 ± 0.15
S1 SR_zone 3	141 ± 0.18	216 ± 4.01	3.5 ± 0.84
Conventional cast and Aged [41]	170	300-317	3.6
High pressure die casting F*		300-350	3-5
High pressure die casting T6*		330-365	3-5

2.3 Reusing waste powder in a novel manufacturing process

The novel production process MAPS, Metal Additive using Powder Sheets, patented by Trinity College Dublin [44], was employed to test the reusability of the PBF-LB/M waste powders. Particularly, waste and reused AlSi10Mg powders were used to produce an AlSi10Mg sheet (Figure 6).

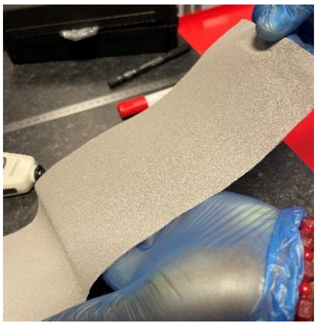

Figure 6. AlSi10Mg powder sheet.

It was analyzed by FESEM and stereomicroscope images to evaluate its packing density. Then, it was used for the printing process (Figure 7).

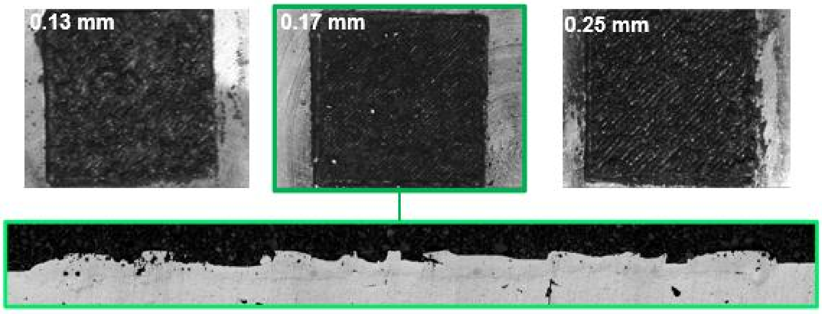

Figure 7. Printed parts with AlSi10Mg powder sheet.

The results have shown good printability, with some problems of porosity and carbon content to be addressed in the future. Furthermore, this process could be used for coating metals to protect them from environmental corrosion.

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