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Review

Study of the Environmental Implications of Using Metal Powder in Additive Manufacturing and Its Handling

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Abstract: Additive Manufacturing, AM, is considered to be environmentally friendly when compared to conventional manufacturing processes. Most researchers focus on resource consumption when performing the corresponding Life Cycle Analysis, LCA, of AM. To that end, the sustainability of AM is compared to processes like milling. Nevertheless, factors such as resource use, pollution, and the effects of AM on human health and society should be also taken into account before determining its environmental impact. In addition, in powder-based AM, handling the powder becomes an issue to be addressed, considering both the operator´s health and the subsequent management of the powder used. In view of these requirements, the fundamentals of the different powder-based AM processes were studied and special attention paid to the health risks derived from the high concentrations of certain chemical compounds existing in the typically employed materials. A review of previous work related to the environmental impact of AM is presented, highlighting the gaps found and the areas where deeper research is required. Finally, the implications of the reuse of metallic powder and the procedures to be followed for the disposal of waste are studied.

Keywords: AM; sustainability; metal powder; powder handling; waste material

1. Introduction

Additive manufacturing (AM) is a technology that has the potential of generating a change in the way manufacturing is conceived as well as in the world economy. Initially, it emerged as an alternative that allowed rapid prototyping (RP) of complex parts in the design or early manufacturing stages. Nevertheless, today AM allows the manufacture of complex parts that otherwise would be impossible or too expensive to achieve, as well as a large number of advantages that can reduce manufacturing costs. Based on a survey conducted in 2018, more than 30% of the components manufactured using AM technology are functional parts [1]. Besides, AM offers the possibility to redesign the entire value chain [2].

However, AM is at an early stage. Although the number of parts manufactured using this technology is growing at a rate of 25% per year, they still comprise a small fraction of the total worldwide production. According to the analysis presented by Wholers Associates in 2017, AM represented less than 0.1% of total world manufacturing [1]. However, the Digital Transformation Monitor of the European Commission states that by 2021 the AM market will reach 9.65 billion € [3]. Among AM technologies, one of the processes that is gaining relevance based on its capability to manufacture functional parts is metal AM. In fact, the number of equipment dedicated to metal AM sold in 2016 was 983, whereas, in the year 2017 this value rose to 1768 units, which implies an 80% increase [1].

As far as economy and sustainability are concerned, AM offers several advantages over conventional manufacturing techniques, which confers many potential applications to AM in diverse industrial sectors, such as automotive, aerospace, biomedical, energy, and consumer goods [4]. In the aerospace industry, for example, AM enables aerospace motorists to create blades with much more complex internal cooling channels, allowing engines to run at higher temperatures and thus increase their performance [5]. In the report presented by the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce, it is stated that in aerospace engines titanium parts are machined down to size from large initial blocks, which leads to more than 90% waste material, material waste that could be reduced by using AM [6]. The European Commission in the Digital Transformation Monitor of 2017 presented similar numbers, where the disruptive nature of 3D printing was studied. It was estimated that by 2050, AM could save up to 90% of the raw material needed for manufacturing [3].

Nonetheless, the possibilities of AM are not only limited to a reduction of raw material usage. The possibility of manufacturing lighter components could lead to energy savings, estimated between 5% and 25% by 2050, as well as a reduction in manufacturing costs of around 4–21% for the same period [7]. This trend is applicable to different industrial sectors. For example, SmarTech expects the overall market for AM in automotive to reach 5.3 billion USD in revenues by 2023 and to achieve 12.4 billion USD by 2028 [8].

The lack of European and international standardization related to AM is proving to be an impediment to the implementation of this technology on a large scale [3]. To meet this challenge, in 2013 the European project for Support Action for Standardization in Additive Manufacturing (SASAM) developed a roadmap for the standardization of this technology [9]. In that work, several standard categories were distinguished, including design, industry-specific requirements, quality of manufactured parts, materials, information processing, safety regulations, and education.

Nevertheless, further work is required in the AM field, especially when metallic powder is used during the manufacturing process. In view of this need, hereafter the main metal AM processes are detailed. Also, the advantages and disadvantages that AM offers regarding the sustainability of the process are discussed. Finally, the handling of the used powder in metal AM is studied, focusing on the issues regarding the hazards in the workplace and the treatment of the waste material.

2. Methodology Applied for the Literature Review

Systematic Literature Review (SLR) was used for determining the review field [10], see Figure 1. This is an objective, systematic, and replicable method, which makes the revision of the state of the art clearer and more concise [11]. SLR makes it possible to determine the necessary criteria to determine the relevant research within the field of additive manufacturing, specifically with regard to the sustainability of the process.

In addition, the snowball approach was used, which allows a wider range of searches based on the reference list of a paper or the citations to identify relevant publications [12,13].

First, the main questions were established: "What is the environmental impact of additive manufacturing?" "How is the waste generated in the process managed?" Keywords were also defined: AM (Additive Manufacturing), LCA (Life Cycle Assessment), Sustainability, Recycle, and Reuse. The search was performed in databases such as Scopus and ScienceDirect, both belonging to Elsevier, and different combinations of the keyword strings were used. The results obtained for the different keyword combinations are shown in Table 1.

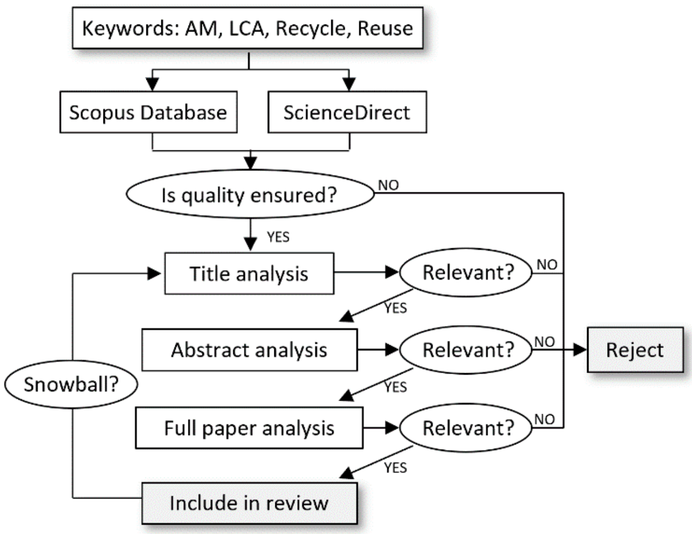

Figure 1. Flow chart for Systematic Literature Review (SLR) (Additive Manufacturing (AM) and Life Cycle Assessment (LCA)).

Table 1. Keyword strings used in the SLR and the corresponding number of matches.

Keyword strings	Science Direct	Scopus	Used for
Laser Metal + AM	792	811	Introduction
Metal AM + LCA	17	19	Sustainability study
Metal AM + Sustainability	34	20	Sustainability study
AM + Recycle	23	8	Handling of powder
AM + Reuse	37	35	Handling of powder
Metal AM + Hazard	2	5	Handling of powder

The search was limited to books and journals, where both review and research articles were considered. Only manuscripts in English were included and, to guarantee the quality of the search, publications corresponding to national or international conference papers that were not published in International JCR (Journal Citation Reports) Journals were automatically discarded. In addition, in the first approach, references prior to the year 2010 were not considered. Nevertheless, those relevant references obtained using the snowball approach were included in the review despite not fulfilling some of the criteria explained above. Among the manuscripts found with the keywords Laser, Metal, and Additive Manufacturing, those that focused on process modeling and metallographic study were eliminated.

3. Metal AM processes

According to the American Society for Testing and Materials (ASTM) group "ASTM F42-Additive Manufacturing," AM technologies are classified into seven categories [14]. More specifically, according to Hopkinson et al., AM technologies can be subdivided into 18 technologies, where they are divided according to the material type [15]:

(1) Liquid-based processes: Stereolithography, Jetting Systems, Direct Light processing^{TM} technologies, High-Viscosity Jetting, and Maple process.
(2) Powder-based processes: Selective Laser Sintering (polymers), Selective Laser Sintering (Ceramics and Metals), Direct Metal Laser Sintering, Three-Dimensional Printing, Fused Metal Deposition Systems, Electron Beam Melting, Selective Laser Melting, Selective Masking Sintering, Selective Inhibition Sintering, Electrophotographic Layered Manufacturing, and High-Speed Sintering.
(3) Solid-based processes: Fused Deposition Modelling and Sheet Stacking Technologies.

Among the different technologies, those capable of manufacturing fully dense and functional metallic parts are the Electron Beam Melting (EBM), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), and Fused Metal Deposition (FMD) methods. Nevertheless, since Selective Laser Melting (SLM) and DMLS were developed, metal materials are manufactured by these processes rather than by SLS.

EBM technology was developed and patented by Arcam, and uses an electron beam source for melting the metallic powder layers in a vacuum chamber [16]. DMLS was first developed by EOS in the 1990s [17], whereas the SLM was first patented by the ILT Fraunhofer in 1995, patent number DE 19649865 [18]. Both processes are similar and based on the same working principle, with the main difference being that in SLM the powder-shaped material is completely melted, whereas in DMLS powder is partially melted and sintered [19]. From their inception, variations of the above-mentioned initial technologies have arisen and all of them grouped within the name Powder Bed Fusion (PBF), see Table 2.

The first Fused Metal Deposition system was developed in 1997 under the name LENS (Laser Engineering Net Shaping) after an agreement between the Sandia National Laboratory [20] and Pratt and Whitney (United Technologies Corporation). Similar technologies have been launched to the market under different names ever since, such as Laser Metal Deposition (LMD) and Selective Laser Cladding (SLC). Still, the working principle is similar in all of them. In all of them, powder-shaped metal is directed toward the melt pool generated by a laser beam, and all can be included under the name of Directed Energy Deposition (DED), see Table 2.

Table 2. Overview of the metal AM processes [21].

AM Process Type	Brief Description	Technologies
Powder Bed Fusion (PBF)	Thermal energy selectively fuses regions of a powder bed	Electron Beam Melting (EBM) Selective Laser Sintering (SLS) Direct Metal Laser Sintering (DMLS) Selective Laser Melting (SLM)
Directed Energy Deposition (DED)	Focused thermal energy is used to fuse material by melting as it is being deposited	Fused Metal Deposition Systems (FMD) Laser Metal Deposition (LMD) Selective Laser Cladding (SLC)

3.1. Fundamentals of the DED Process

The DED is mainly applied to build fully dense functional parts, coat damaged parts, or enhance the surface properties in certain regions [22]. In DED, a melt pool is generated in the surface of the substrate by an energy source, see Figure 2. Meanwhile, filler material is injected simultaneously through a nozzle [23]. The filler material is usually powder or wire-shaped [24], and melted by the energy source and adhered to the substrate. Therefore, by properly overlapping the generated clads, subsequent layers are overlaid until the required geometry is obtained [25]. The nozzle has a double function, it directs the filler material towards the melt pool and it is also responsible for avoiding material oxidation by generating a protective atmosphere.

One of the main advantages of the DED technology when compared to other additive processes, such as arc welding or plasma spraying, is the comparatively low total amount of energy introduced into the substrate, which leads to minimum geometrical distortions [26]. Consequently, the dilution between layers is minimized and a fine microstructure is generated [27]. Thanks to these characteristics, final parts with good mechanical properties and reduced imperfections are achieved.

The DED process is used with different materials and research related to tool steels [28], stainless steels [29], titanium alloys [30], nickel alloys [31], and copper alloys [32] have been already published. Besides, the DED also enables enhancing the surface properties and adapting gradually to the final requirements by means of Functionally Graded Materials [33,34]. One of the main advantages of DED is the capability to produce near-net-shape parts, which results in a reduction of the waste material generated and an environmentally friendlier process [35]. For example, buy-to-fly material ratios of 4:1 are commonly achieved in traditional five-axis milling processes, with some components having ratios up to 20:1 [36]. Nevertheless, LMD is capable of reducing these buy-to-fly ratios to below 1.5:1 [37].

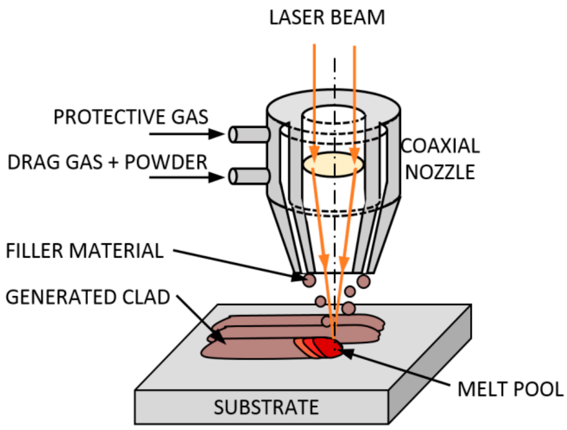

Figure 2. Basis of the LMD process.

The DED is mainly applied to the remanufacturing, coating, and repair of existing parts [38], as well as to push the design limits of processes such as machining, allowing the development of innovative geometries [39,40]. For example, DED is used for the manufacture and repair of high-added-value parts of aerospace engine components [41,42], die and molds [43], and high-resistance coatings [44], among others.

Nevertheless, DED technology presents several limiting factors that restrict its applications, for example, the relatively low accuracy of the final parts and the resulting high surface roughness [45]. Therefore, it is necessary to include postprocessing operations to match the final requirements. In addition, the directional nature of the additive process results in anisotropic properties. Consequently, corrective measures are required during the DED process to avoid cracking of the material, reduce geometrical distortions [46], and manufacture near-net-shape functional parts with close tolerances and acceptable residual stress [47].

An alternative to the use of a laser source is the WAAM (Wire Arc Additive Manufacturing), which enables processing of a wide range of materials and higher deposition rates [48]. However, WAAM uses wire as feedstock material, instead of powder-shaped particles, which reduces the health issues and environmental impact of this technology. Therefore, this technology is left out of the present study, which is focused on the handling of the powder particles used in additive processes.

3.2. Fundamentals of the PBF Process

Powder Bed Fusion is a two-step process. First, a thin layer of material is predeposited and then determined regions are selectively melted using a heat source, which is typically a laser beam. Constant layer height is ensured by means of a recoater or powder leveling system, see Figure 3, which feeds the powder-shaped material to the build chamber. This process is repeated successively until the desired final part is obtained. Once the process is completed and the part finished, the metal powder that remains unmelted can be sieved and reused [49].

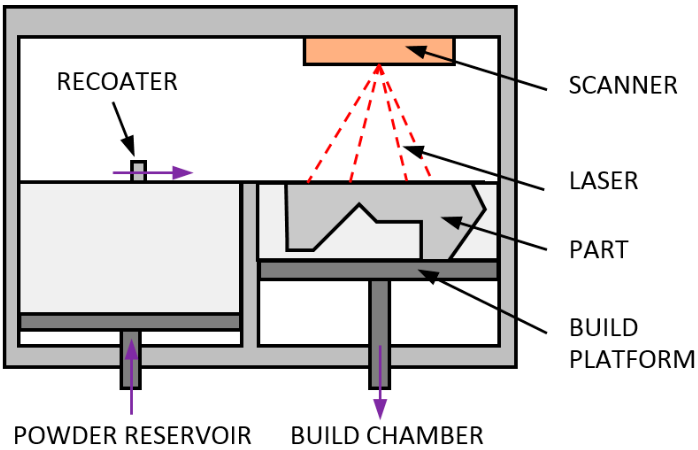

Figure 3. Basis of the PBF processes.

The process takes place inside a closed chamber, which is filled with inert gas in the case of PBF. Also, support structures are usually employed to build overhanging regions and improve heat dissipation [50]. Consequently, the proper orientation of the part and the location of the supports are factors to keep in mind in PBF.

One of the main applications of the PBF technologies is the full manufacture of 3D parts that include complex geometrical details, where good accuracy and resolution are attained. Furthermore, they offer the opportunity to work with a wide range of materials, including metals, ceramics, polymers, and composites. Therefore, PBF is becoming a relevant tool for aerospace and biomedical applications [51]. Examples of PBF technology applications are the manufacture of functional parts for medical implants [52,53] and turbine blades with embedded cooling channels [54].

The parts produced by means of PBF are limited by the size of the build chamber and the deposition rate is lower than that of DED, see Table 3. Nevertheless, PBF enables higher complexity and better surface finish.

Table 3. Overview of the metal additive manufacturing processes.

AM Process Type	Powder Particle Size (µm)	Deposition Rate (g/min)	Dimensional Accuracy (µm)	Surface Roughness (µm)	References
Powder Bed Fusion (PBF)	45–150	2–3	±0.05	9–16	[55–58]
Direct Energy Deposition (DED)	10–30	5–30	±0.13	≈40	[55,56,59,60]

3.3. Powder Employed in Metal AM and Its Health Issues

In this section, some of the most typical powders employed in metal AM are analyzed. Powders with various characteristics and used in the different industrial sectors are studied, which are detailed in Table 4. The main characteristics of the different powders as well as the applications were obtained from the information provided by the different metal powder manufacturers.

The use of small powder particles, see Figure 4b, involves serious hazards to human health and the environment. Every powder container must be properly labeled, and the corresponding hazard classification must be indicated. CLP hazard pictograms are found on all powder bottles, see Figure 4a.

Table 4. Studied metal powders and their main applications [61–65].

Material	Main Characteristics	Main Application
Inconel 718	• Excellent corrosion resistance in a wide range of environments. • High-temperature oxidation resistance. • Resistance to stress corrosion cracking. • Good wear resistance and high ductility.	Turbine blades, heavy industry, etc.
Titanium Ti6Al4V	• High strength-to-weight ratio. • Excellent corrosion resistance.	Aerospace industry and biomechanical applications (implants and prostheses)
AISI H13	• Good resistance to abrasion at both low and high temperatures. • High level of toughness and ductility. • Good high-temperature strength and resistance to thermal fatigue.	Injection molds, wear-resisting parts, hot stamping dies, etc.
AISI 316L	• Resistant to corrosion, pitting and intercrystalline corrosion up to temperatures of 400 °C. • Scale resistant up to 800 °C.	Corrosion-resistant applications, naval industry, intermediate soft layers, etc.
Stellite 6	• Excellent resistance to chemical corrosion and mechanical wear over a wide temperature range. • Good resistance to impact and cavitation. • Keeps hardness up to 500 °C.	Crankshaft, bearing tracks, stamping dies, extrusion screws, etc.

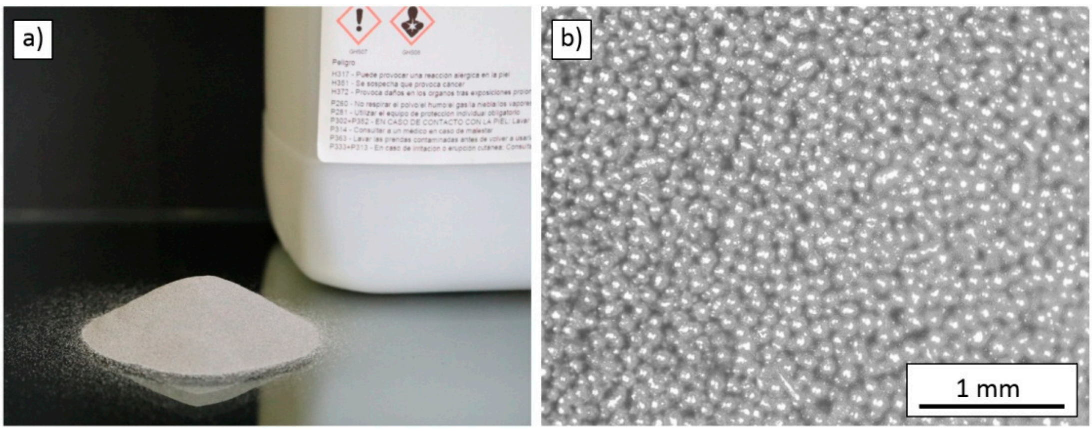

Figure 4. (**a**) AISI 316L powder and container with the hazard details, (**b**) AISI 316L.

The powders analyzed are composed of 45–150 µm diameter particles, which is a typical value for DED applications, and therefore, the analyzed hazards are applied to that particle size. Smaller diameter particles may generate other health and environmental issues not studied in the present case.

The hazardous nature of each material depends mainly on its composition, which determines the exposure limits. In Table 6, the CAS and EC numbers of each element of the alloys defined in Table 5 are detailed.

Table 5. Powder provider, composition, and hazard classification.

Material	Manufacturer	Main Composition (wt.%)	Classification
Inconel 718	Oerlikon Metco [66]	Ni: 53, Cr: 20, Fe: 17.4, Nb: 5.1, Mo: 3.1, Ti: 0.9, Al: 0.5	H317 H351 H372 H412
Titanium Ti6Al4V	LPW Technology [67]	Ti: 89.09, Al: 6.4, V: 3.9, Fe: 0.22, O: 0.07, C: 0.01	H315 H319 H334
AISI H13	FST [68]	Fe: 90.41, Cr: 5.12, Mo: 1.33, V: 1.13, Si: 0.8, C: 0.41, Mn: 0.5	H317 H351 H372 H412
AISI 316L	Eramet [69]	Fe: 67.5, Cr: 18.2, Ni: 11.8, Mo: 2.3, Si: 0.34, C: 0.03, Mn: 0.08	H317 H351 H372 H412
Stellite 6	Oerlikon Metco [66]	Co: 60.4, Cr: 28.5, W: 4.5, Si: 1.5, Fe: 1.5, C: 1, Mo: 1	H319 H334 H317 H361 H400 H410

For each material, the corresponding hazard classification is shown and the limit values according to the Spanish Law 1/2014 of the Environmental Limit Value (EVL) for a Daily Exposure (DE) are specified. Information not provided by the suppliers regarding the classification of the materials is complemented with the European Chemicals Agency database [70], whereas the EVL-DE in Spain has been completed with information from the Spanish National Institute for Occupational Safety and Health [71].

The TWA (Time Weighted Average) is also shown, with units in mg/m^3 for an 8 h exposure. The missing data are completed with information from the Occupational Safety and Health Administration of the United States Department of Labor [72] and the NIOSH Pocket Guide to Chemical Hazards from the Centers for Disease Control and Prevention (CDC)[73].

The explanation of the hazard codes employed in Tables 5 and 6 are detailed in Table 7, where the hazard category and the corresponding statement are detailed. Information is obtained from the "Guidance on the Application of the CLP Criteria" published by the European Chemicals Agency in 2017 [74].

Table 6. Classification and limit exposure values of different metal elements.

Material	CAS Number	EC Number	Classification [70]	Limit Values According to Spanish Law 1/2014 ELV-DE [71]	8 h Exposure Control TWA in mg/m^3
Titanium	7440-32-6	231.142-3	H228 H315 H335	1 mg/m^3 in 8 h	10 [73]
Aluminum	7429-90-5	231-072-3	H261 H228	10	10
Vanadium	7440-62-2	231-171-1	H228 H315 H319 H335 H413	3 mg/m^3 in 8 h (breathing)	0.05 mg V_2O_5 [73]
Chromium	7440-02-0	231-157-5	H350	2 mg/m^3 in 8 h	0.5
Nickel	7440-02-0	231-111-4	H317 H351 H372 H412	1 mg/m^3 in 8 h	1
Niobium	7440-03-1	231-113-5	H228 H332 H250	-	-
Molybdenum	7439-98-7	231-107-2	H225 H228 H361	3 mg/m^3 in 8 h (breathing)	10 [73]
Iron	7439-89-6	231-096-4	H228 H251	-	1
Cobalt	7440-48-4	231-157-5	H332 H319 H317 H350i H361f H400 H410	-	0.1
Tungsten	7440-33-7	231-143-9	H228 H252	10 mg/m^3 in 15 min 5 mg/m^3 in 8 h	3 mg/m^3 [72]
Manganese	7439-96-5	231-105-1	H319 H412	0.2	1 [73]

Table 7. Hazard statement corresponding to the classification code and category [74].

Code	Classification (Category)	Hazard Statement
H228	1	Flammable solid
H252	2	Self-heating in large quantities; may catch fire
H261	2	In contact with water releases flammable gases
H315	2	Causes skin irritation
H317	1	Warning: May cause an allergic skin reaction
H319	2	Causes serious eye irritation
H332	4	Harmful if inhaled
H334	1	May cause allergy or asthma symptoms or breathing difficulties if inhaled
H340	1	May cause genetic defects
H341	2	Suspected of causing genetic defects
H350	1	May cause cancer
H350i	1	May cause cancer by inhalation
H351	2	Suspected of causing cancer
H361	2	Suspected of damaging fertility or the unborn child
H361f	2	Suspected of damaging fertility
H372	1	Causes damage to organs (state all organs affected, if known) through prolonged or repeated exposure (state route of exposure if it is conclusively proven that no other routes of exposure cause the hazard)
H400	Aquatic Acute 1	Very toxic to aquatic life
H410	Aquatic Chronic 1	Very toxic to aquatic life with long-lasting effects
H412	Aquatic Chronic 3	Harmful to aquatic life with long-lasting effects

4. AM—A Sustainable Manufacturing Process

The transformation of raw material into consumer products is an important source of environmental pollution and as a result of the process, waste is generated [75]. This issue has been amplified by the rapid technological development that has taken place in recent decades; together with the population growth, massive exploitation of resources, and pollution, waste generation has produced severe environmental issues [76]. Thus, in the last decades, efficient use of resources and environmental awareness have increased.

In this direction, Bourhis et al. studied greenhouse gas emissions and concluded that over 19% were due to industrial activity associated with manufacturing, where machining processes are the main activity [77]. Therefore, industrial processes need to balance the demand for natural resources with the capacity of the environment to respond to those demands in a sustainable manner [78].

Until the end of the 20th century, productivity was a priority and the main goal was to obtain the required quality at the lowest price, regardless of the resulting environmental impact. The concept of sustainable manufacturing did not begin until almost a decade after the United Nations environmental declaration in 1972 [79]. Since that date, sustainable manufacturing has attracted increasing attention, and nowadays, manufacturing processes not only have to guarantee products that meet the specified requirements, with a competitive price and quality, but also must ensure a minimum environmental impact.

4.1. Life Cycle Analysis

In order to quantify the environmental impact of a process, it is necessary to analyze the footprint at each stage of the product life cycle: from the extraction of the raw material to the disposal at the end of the product's life, which is known as Life Cycle Analysis (LCA). This procedure allows an evaluation of the environmental impact from a comprehensive and objective manner [80], and makes it possible to analyze and quantify the environmental aspects of a product, process, or service along its life cycle [78,81].

In 1997, the International Organization for Standardization (ISO) established the principles and the frame of reference for LCA through ISO 14040:2006, and afterward the details to perform an LCA as detailed in ISO 14044:2006 [82]. According to ISO 14040:2006, the environmental impacts can be sorted into three main categories: (a) damage to the natural environment, (b) damage to human health, and (c) resources consumption [83]. In order to carry out an LCA in accordance with the methodology proposed by ISO 14040:2006, four interrelated and iterative phases of work must be considered, which follow a more or less defined sequence, although sometimes it is possible to carry out a study in which some phases are ignored: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation [84].

To gain accuracy, the LCA must be as thorough as possible and it is necessary to consider each step of the product life cycle, from extraction of the raw material to the end of life, including the manufacturing step. However, there are few methods for accurately assessing the environmental impact of a manufacturing process. Also, it is necessary to consider that not all manufacturing processes have the same environmental impact [77].

In general, AM processes are considered to be cleaner processes than traditional subtractive manufacturing (SM) processes, because the produced waste material is reduced, the design is optimized, and the resultant pieces are lighter. However, it is necessary to continue working to assess the carbon footprint of the AM processes globally [77]. In addition, the high flexibility of AM enables the redefinition of new supply-chain distributions. However, these configurations may have an additional sustainability impact that should be addressed in the LCA [85]. As Rejeski et al. stated, AM generates unique challenges and uncertainties regarding economic and social issues, and a safe and responsible use must be ensured [86].

Nevertheless, nowadays there is no AM process capable of creating ready-to-use parts. In most cases postprocessing is required, such as assembling, SM, or heat treatment, and the LCA must consider all of them in order to provide reliable information [87]. From the point of view of LCA, manufacturing processes are divided into five steps, see Figure 5 [79].

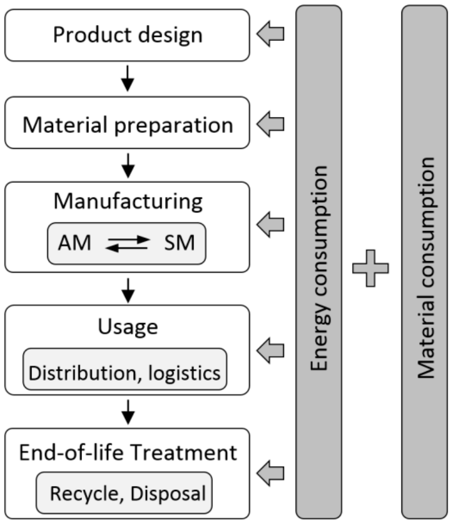

Figure 5. A life cycle perspective on metal AM and Subtractive Manufacturing (SM).

Although AM is considered an environmentally friendlier process than traditional manufacturing systems, there are not enough LCA studies to prove it. Therefore, more large-scale AM LCA analysis is necessary to support the statement that AM is environmentally friendly [88]. To be more sustainable, among others, the AM process should provide a raw materials´ efficient usage, extend product life to the maximum, consider lean supply chain (just-in-time), eliminate stock that becomes obsolete, and improve the health and safety of workers. However, some of these aspects are neither measurable nor generalizable to all contexts [89].

In contrast with the literature explaining the huge sustainability benefits, according to Niaki et al. the decision to manufacture a part using AM is not determined by its environmental benefits [90]. Instead, decisions are made based on economic aspects and the capability of AM for producing almost any complex geometry.

Therefore, despite the spreading use of AM, it is observed that both industry and academia are not well prepared to face the potential environmental and health issues, and the associated negative economic impact related to them [91]. Consequently, when referring to the sustainability of AM, the three dimensions of sustainability should be considered: economy, environment, and society, see Figure 6, with their corresponding aspects.

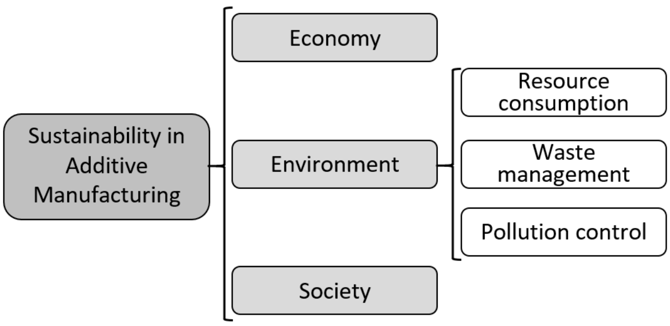

Figure 6. Aspects to consider in the environmental impact of AM.

Due to the complexity of performing a complete LCA of AM, most of the research works have focused on the resource consumption as the main environmental issue. Baumers et al. compared two SLS commercial machines from an electric-consumption point of view [92]. Authors applied a novel classification for the energy used in AM, which can be job-, time-, geometry-, and height-dependent. They published another research work focused on the effect of the part geometry complexity on the process energy consumption [93] and concluded that the energy consumption is almost independent of the part complexity. However, the part complexity does affect the energy consumption of other traditional manufacturing processes, such as milling. Therefore, it is a key factor when determining the manufacturing process from a sustainable point of view [94]. Similarly, Nagaran and Haapala studied the DMLS process efficiency from an energetic point of view and concluded that only 10% of the total process inputs become part of the final piece, whereas the rest is lost as heat, material waste, and work [95]. The authors employed the ReCiPe impact assessment method [96]. Minetola and Eyers also studied the efficiency of AM and compared it with traditional manufacturing processes [97]. AM was concluded to be a less efficient process; however, it enables on-demand manufacturing and avoids overproduction issues.Other authors have presented broader investigations and included factors such as pollution and the impact on human health. Drizo and Pegna presented a review of the problems associated with the Environmental Impact Assessment of AM and the most relevant issues at the year 2006 [98]. In 2017, Bours et al. presented a study that highlighted the fact that the LCA does not provide enough information to make decisions based on hazard exposure [99]. They proposed a framework that analyzes the human health and environmental impact in AM and complements the LCA. Similarly, Yang and Li studied the volatile emissions produced in AM and proposed a model that was experimentally validated [100].

A common research topic is to compare AM and traditional machining operations. Faludi et al. compared two AM processes with a traditional milling machine and focused on the environmental impact of AM [101]. Other authors such as Gao et al. performed an LCA of newly manufactured and remanufactured turbochargers and compared obtained results [102]. They concluded that remanufacturing reduces energy consumption and pollutant emissions. Similarly, Böckin and Tillman presented an LCA that compares traditional manufacturing techniques with AM for the case of manufacturing a truck engine [103].

However, any investigation that wants to analyze sustainability in AM should not forget its social impact, which should be an essential part in decision making [104]. In the year 2013, Huang et al. presented a review of the social impact that produces AM. The main social benefits of AM were classified as the capability to produce customized healthcare products and the simplification of the supply chain [105].

Furthermore, in the life cycle of a product, three stages can be distinguished: design, production, use, and end-of-life [89]. Ma et al. concluded that AM has the highest social impact in the end-of-life stage [91].

Consequently, AM is especially oriented to the manufacture of spare parts, ease of disassembly, integration of components, choice of material, reduction of material waste, and postprocessing. Nevertheless, to be able to quantify the potential environmental consequences of these processes, more studies about the possible benefits and drawbacks should be performed from a localized production and a shortened lead time points of view [103]. Despite a few works that were found related to the analysis of the indirect impacts of AM [106], deeper work is still required in this field.

4.2. Ecodesign and Circular Economy

Ecodesign or Design for Environment, which are the terms used in Europe and in the U.S., respectively, is the new way for developing products where the environmental aspects are given the same status as functionality, durability, costs, time-to-market, aesthetics, ergonomics, and quality [107]. In Figure 7, the closed-loop of product life in AM processes is shown, adapted from [107].

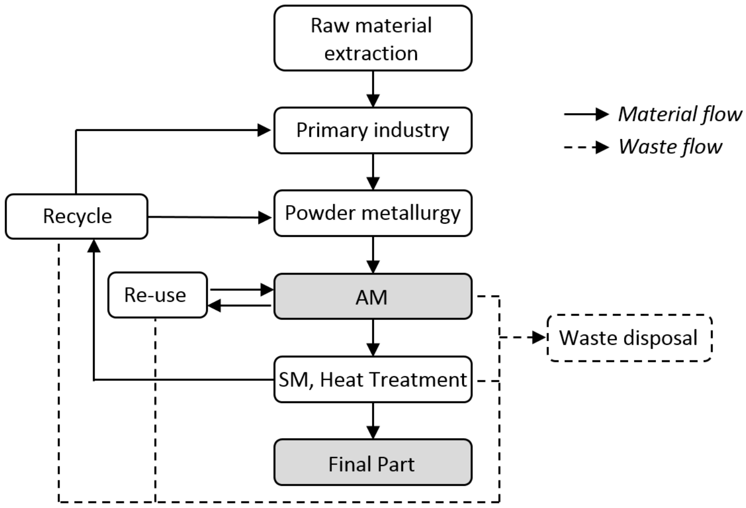

Figure 7. Material product life cycle in AM. Adapted from [107].

A growing number of products and consumer goods are in demand every day, and new paradigms have emerged as a response to the need for reducing waste and limiting the consumption of natural resources. One of these new concepts is the circular economy [108].

The European Commission defines the circular economy as a production model, where the value of products, materials, and resources is maintained as long as possible, and the generation of waste is minimized [40]. The circular economy model promotes high-value material cycles along with more traditional recycling. In addition, it promotes cooperation between producers, consumers, and other social actors to increase sustainability [109].

However, it is still unclear whether reconfiguring the value chain will actually allow a more circular use of resources [110]. That is why, before implementing any circular economy strategy, it is necessary to be careful and assess it with regard to its potential sustainability [111].

Generally, AM allows extending the lifespan of the product, by repairing or updating it. Hence this technology can be integrated into the concept of the circular economy. The capabilities of AM within the circular economy have been already addressed. For instance, Sauerwein et al. studied different opportunities that AM offers in this regard [112].

In conclusion, AM has consolidated its position as a technology capable of repairing damaged parts, thus increasing its useful life. Nevertheless, during AM a series of wastes are generated that also need to be considered from a circular economy point of view, and must be reused or recycled. In view of this deficiency, the following section focuses on the handling of metallic powder used in AM.

5. Handling of Powder in Metal AM

5.1. Risks in the Workplace

AM technology offers several advantages to industrial applications, such as the capability of building spare parts on-demand or even the ability to repair worn areas by adding new features on an existing part, hence avoiding the replacement of the whole construction [113].

Although AM is gaining relevance in the industry, there is still relatively scarce information as far as health and safety issues for operators related to metal AM processes. Ljunggren et al. and Mellin et al. focused their research on the biomonitoring of metal exposure [113] and the nanoparticles generated during the AM process [114], respectively. Both of them emphasized that it is necessary to carry out further research to minimize the exposure risk to AM operators.

However, several studies have been published regarding the health effects of metal gas and particle exposure in other occupational settings. In welding, airborne nanoscale metal particles are known to be hazardous to human health, and in AM processes these particles may also be generated.

Authors like Llunggren et al. performed a gravimetric analysis and concluded that the total dust exposure is low and does not present inhalation problems in AM operators, but they also remarked that transient emission of smaller particles constitutes a risk to human health [113].

In metal AM, alloys containing heavy metals are employed, therefore studies that focus on specific materials have been performed. Rehfisch et al. studied the possible health issues in workers that inhale cobalt [115]. Moreover, special attention is posed on the nanosized particles generated during the AM process. At this particle size, handling or inhaling such small particles implies an extreme exposure risk and motivates precaution. In fact, compounds that were not considered harmful for human health turned out to be toxic in the nanometer scale [114]. Such particles can easily cross biological barriers and be absorbed by the skin hair follicles and lungs, which allows the particles to enter the human body.

Preventive Actions

There is a need for careful design and consistent regulation of AM environments, but until this situation is reached, the implementation of preventive actions by the company can reduce the workers' metal exposure. The most important safety measures are:

(1) Ventilation: The exposure can be considerably reduced by the implementation of good general ventilation which allows for the reduction of particles and fibers in the working environment [114]. It can be further improved by point ventilation placed at strategic emission sources. Furthermore, to protect the outdoor environment, particle/fiber collection filters should be installed.
(2) Protective mask: Machine operators should wear a personal protective mask in the working environment where emission occurs. The mask is considered the most effective personal protective equipment [114].
(3) Machine enclosure: A proper cabinet is required to prevent particles from spreading through the workshop [116].

In addition, Ljunggren et al. presented a gravimetric analysis of the airborne particles generated in AM and concluded that operators should wear exposure markers [113]. Graff et al. reached a similar conclusion and suggested that operators should wear personal protective equipment. Furthermore, they recommended regular urine analysis of the operators to detect possible metal particle inhalation at an early stage [117].

5.2. Treatment of Waste Material

AM provides the possibility to manufacture near-net-shape parts [4] and offers several environmental benefits, such as a reduction in the waste material generated [118], higher energy efficiency, and transportation impact reduction, thanks to the possibility of local manufacturing [86]. Nevertheless, wastes still exist in AM and in some cases, human and machine errors may lead to an increasing amount of residue [119].

Therefore, as a zero-waste process does not exist, in this section the main treatment procedures for the waste material are detailed. According to Article 4 of the "Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives" [120], the following procedures, described below, must be applied to the generated waste: (1) prevention, (2) preparing for the reuse, (3) recycling, (4) other recovery (e.g., energy recovery), and (5) disposal.

In the case of AM, waste generation is reduced by increasing the process efficiency, e.g., improving the nozzle efficiency in the DED process or adapting the building chamber geometry to the shape of the built-part in the case of PBF. Once the powder is used and waste is generated, the first choice in order to reduce the environmental impact of the process is the reuse of the powder after a preparing process, which usually consists of a sieving stage.

If the powder is heavily contaminated, it can no longer be reused due to its degradation and it must be recycled, where the powder can be remelted and after the corresponding composition adjustments, reatomized to obtain new powder. However, from the point of view of the AM-process user, this last option corresponds to discarding the powder and therefore, hereafter it will be referred to as disposal.

5.2.1. Reuse

The ecological impact of AM processes highly depends on the material recycle and reuse capability, therefore, practical methods to recycle unused material powder have been investigated [121]. Studies report that over 40% of waste material can be avoided using AM and 95% of unused material can be reused [122], but these statements have not yet been confirmed for all materials.

For PBF-based AM processes such as SLM and EBM, powders can be recycled but only up to a limited degree, since during the AM process powder-composition change has been reported [123]. Nevertheless, results depend on the employed material and recycling conditions. For example, in the case of parts built from reused Ti6Al4V powders, which require a rigorous recycling procedure, the number of reuse cycles had a strong impact on the quality of the final part [123]. Hereafter are detailed the most relevant works related to powder recycling in PBF.

Tang et al. studied the powder reuse issue in PBF and concluded that the affordability of AM parts depends on the recycling capability of the powders and the number of reuses [123]. As global trends, the oxygen content in the powder increases progressively with the number of reuses. Also, the particles became less spherical and satellites began to appear, see Figure 8. Nevertheless, the authors concluded that the reused powder had no effect on the tensile properties or on its behavior.

Similarly, Gorji et al. studied the mechanical properties of the printed parts when new and reused powders were employed [124]. Parts manufactured with powder which was reused over 10 times presented almost no differences with those manufactured with virgin powder; the authors concluded that the powder reuse reduces the metallic powder waste and printing time.

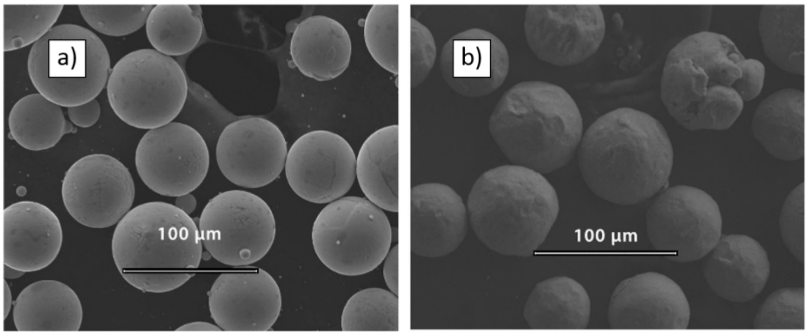

Figure 8. SEM images of (**a**) new Ti6Al4V powder, (**b**) strongly reused Ti6Al4V powder after the 69th cycle [125].

Petrovic et al. studied powder recyclability of EBM-produced Ti6Al4V parts for aerospace applications [126]. The authors concluded that the quality of the final parts was ensured after consecutive buildings employing reused powder. Nevertheless, diametrically opposed results were obtained by Popov et al. for the same material and process. These authors stated that recycling negatively affected the manufactured parts, which presented lower elongation in tensile tests and a higher resulting dispersion [125]. Popov et al. attributed these results to the loss of humidity and temperature control when recycling powder. In addition, a cooling control of the powder must be applied and powder should be cooled down to 80 °C once the manufacturing process is finished to prevent excessive oxidation of the powder in the machine once the door is opened and the protective atmosphere is lost.

Heiden et al. analyzed 13 different AISI 316L powders in their new and reused conditions and studied the properties of the metal particles [127]. They concluded that the multiple usages of the powder had no relevant impact on the resultant mechanical properties, but minor variations were detected in the process. The key properties of the metal particles that influence the AM process, and hence the final part, are detailed in Figure 9.

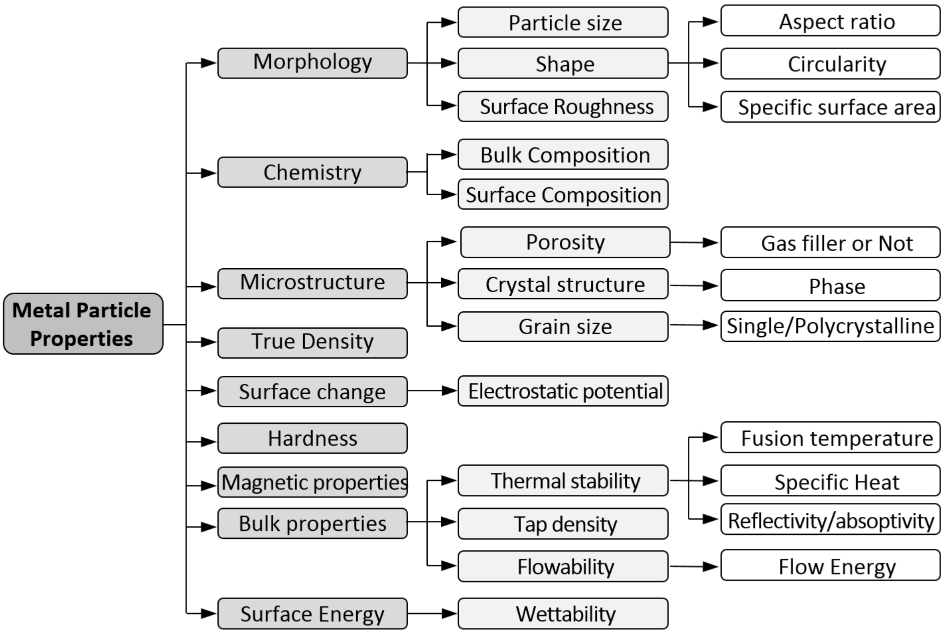

Figure 9. Classification of key metal particle properties that may influence AM part formation quality. Adapted from [127].

Working with the same material, AISI 316L stainless steel, Pinto et al. studied the phase transformation changes and their influence on the magnetic behavior of the powder [128]. The authors concluded that an increasing number of reuses affected the uniformity of the powder bed and generated defects such as porosity, delamination, warping, and lack of fusion. Similarly, Sutton et al. studied the effect of the reuse when depositing AISI 304L stainless steel in the PBF process [129]. The powder was reused up to seven times and the authors concluded that as the number of reuses increased, it also changed the oxygen concentration, which increased from 240 ppm in the new powder to nearly 325 ppm after seven reuses. Furthermore, microstructural and morphological changes were also detected.

In recycled powder, particle size distribution shifts slightly towards large diameters due to a reduction of the number of finer particles (<10 µm). Therefore, powder flowability is increased, whereas the packing capability is reduced since there are fewer fine particles to fill the voids between the coarser ones [130]. The authors concluded that the powder aspect ratio and circularity decreased only slightly with reuse, while the surface roughness increased for reused particles; this was a major source of the satellite creation through vapor condensation on unused particles. In addition, the authors noted particle discoloration due to its oxidation. This oxidation process also occurred in the powder that was not melted by the laser beam, due to the heating and cooling cycles that the powder undergoes. This same oxidation process entailed a slight decrease in the powder density when highly reused powder was used but had no influence on the UTS (Ultimate Tensile Strength) and yield strength, which remained almost constant. On the contrary, Maamoun et al. found that for $AlSi_{10}Mg$ there was no difference between the new and recycled powder particle size distribution for SLM [131].

Regarding DED AM processes, powder recycle is a more complex task, as the working environment is not as controlled as in the case of PBF. DED capture efficiencies can be as high as 80% [132], which means that more than 20% of the injected powder does not adhere to the substrate. According to ASTM, the capture efficiency defines the quantity of powder being part of the final part divided by the total amount of powder supplied to produce it. Several studies corresponding to various materials have been published in the last years.

Rousseau et al. studied the effect of the oxygen content in new and reused Ti_6Al_4V components for the DED process. After 10 runs they concluded that there was no oxygen pickup in the reused powder when compared to the original [133]. The main reason for this behavior of the powder was the argon protective atmosphere under which the tests were carried out, which protected the particles in their most reactive state. Therefore, the protective atmosphere played an important role in powder reuse.

Renderos et al. studied the microstructure on recycled Inconel 718 powder in DED [134] and concluded that powder particles maintained their morphological and chemical properties after crossing through the nozzle. The static mechanical properties of the recycled builds were found to be similar to those of the new powder builds for a limited recycling number (two times). Beyond this value, the breaking strain was found to decrease sharply. In the study, the authors applied a magnetic separation and a mechanical sieving process to rebuild the particle size distribution [135].

Finally, Saboori et al. studied the effect of recycled powder on microstructure and mechanical properties of AISI 316L produced by DED [136]. Parts built using recycled powder presented a 50% lower elongation at breakage, which was attributed to the appearance of Mn and Si oxides as the number of reuses increased (Figure 10).

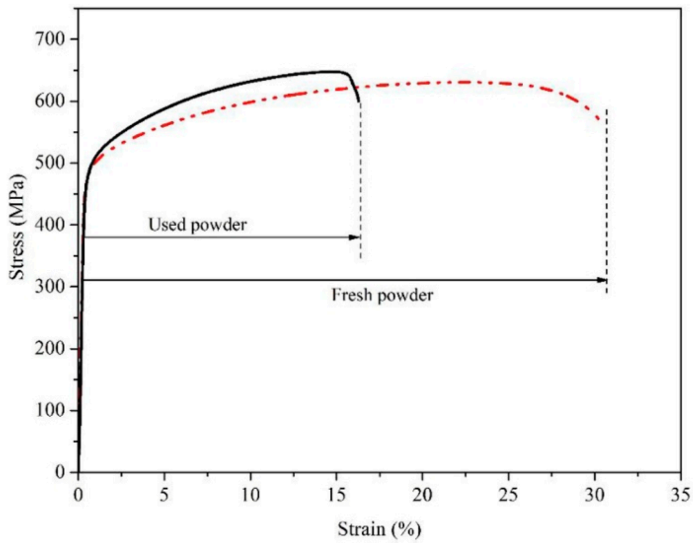

Figure 10. Stress-strain curves of AISI 316L produced by DED using fresh and recycled powders [136].

5.2.2. Waste Disposal

The residues generated during the AM process must be properly treated according to the EU Commission Decision 2000/532/EC [137]. Based on Point 1 in Article 15, "Member States shall take the necessary measures to ensure that any original waste producer or other holder carries out the treatment of waste himself or has the treatment handled by a dealer or an establishment or undertaking which carries out waste treatment operations or arranged by a private or public waste collector in accordance with Articles 4 and 13." Furthermore, a Member State may consider waste as hazardous when, even though it does not appear as such on the list of waste, it displays one or more of the properties listed in Annex III of the Directive 2008/98/EC [120].

Therefore, despite the common law in the EU, each Member State is responsible for the waste generation. In the case of Spain, this responsibility is transferred to certain regional governments, which is the case of the Basque Autonomous Community. The department of Environment, Spatial Planning, and Housing of the Basque Government defines the necessary requirements of individual agents and transporters, as well as the necessary characteristics of the facilities where the waste treatment operations are carried out, and the operators must be adequately qualified to do so [138].

In the case of DED, due to the size of the particles used, they do not represent a hazard for the transporter, and hence are classified according to their nature and independently of their format (size, shape, etc.). Therefore, AM wastes are treated as inorganic solids. The company that generates the waste must contact the Basque Government to detail their activity and the chemical composition of the generated wastes, so that it can authorize their treatment, as well as indicate the corresponding -List of Waste (LoW) code.

Once the waste has been assigned an LER code, it is the responsibility of the company to contact the corresponding waste manager, which at the same time has to be approved by the Basque Government [139]. Unless otherwise stated, AM powder is classified on the basis of the following nomenclature: 12 01 02—ferrous metal dust and particles, 12 01 04—non-ferrous metal dust and particles. However, if the powder was in contact with oil or coolant (in the case of hybrid machines), the waste is labeled as 12 01 18*—metal sludge (grinding, honing, and lapping sludge), which indicates that it contains oil and must be considered a hazardous substance.

6. Conclusions

AM processes are shown to reduce the environmental impact with regard to traditional processes, mainly due to the more efficient use of raw materials. Nevertheless, for AM to be considered a fully environmentally friendly technology, it is also necessary to make efficient use of energy, to perform adequate management of industrial waste, minimize emissions and toxic materials, and prevent occupational health and safety risks. Furthermore, it must favor the manufacture of repairable, reusable, and recyclable parts. Consequently, after the present review work, it is noticed that although AM is considered an environmentally friendly technology, further studies are required to make a definitive statement and the need to study certain aspects in more detail are identified:

(1) In order to consider the manufacturing impact, it is necessary to analyze the whole AM product supply-chain, from cradle to grave. So, more research work considering design, production, use, and end-of-life is needed.
(2) The prevailing environmental issue is resource consumption, and more specifically energy consumption. But there are other factors that should be considered such as resource use, pollution, impact on human health, and social impact. To assess the sustainability of the AM process and its environmental impact, all these aspects must be considered equally. The weighted quantification of the economic impact of each factor could be a possibility to consider all of them with the same relevance.
(3) Several authors focused their research efforts in studying the behavior of reused powder:
    (i) The protective atmosphere plays an important role in powder reuse. The correct design of the protective atmosphere allows the powder-shaped material to maintain its original properties and chemical composition. Therefore, the powder can be reused efficiently in AM.
    (ii) As a global trend, the oxygen content in the powder increases progressively as the number of reuses increases and the particles become less spherical. Consequently, this influences the powder flowability and the material oxidation in the final part.
    (iii) Most research states that the UTS and yield strength values of the reused powder do not vary with regard to the new powder. Nevertheless, it is widely accepted that parts manufactured with recycled powder present a more brittle nature. Nonetheless, uneven results were obtained even for the same material and AM process. This means that a proper procedure for evaluating the reusability of the powder in AM is needed to ensure reliable results.
    (iv) It is important to define a standardized particle recycling procedure. However, opposed conclusions were reached by different authors regarding powder recyclability. Results depended on the process and the employed powder, and therefore, it is not possible to make general statements.

(4) Once that powder cannot be longer reused, it has to be disposed of according to the law in force in each country. This last step is of great importance in minimizing the environmental impact of AM.
(5) The LCA and ecodesign concepts should be applied in the early stages of product development design to improve the viability of end-of-life strategies. In addition to the final price, the quality, production time, and factors such as human health and environmental impact need to be taken into account.

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