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Comparative Life Cycle Assessment and Cost Analysis of the Production of Ti6Al4V-TiC Metal–Matrix Composite Powder by High-Energy Ball Milling and Ti6Al4V Powder by Gas Atomization

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Abstract: Environmental awareness and the necessary reduction in costs in industrial processes has facilitated the development of novel techniques such as Additive Manufacturing, decreasing the amount of raw materials and energy needed. The longing for improved materials with different and enhanced properties has resulted in research efforts in the Metal Matrix Composites field. These two novelties combined minimise environmental impacts and costs without compromising technical properties. Two technologies can feed Additive Manufacturing techniques with metallic powder: Gas Atomization and High Energy Ball Milling. This study provides a comparative Life Cycle Assessment of these technologies to produce one kilogram of metallic powder for the Directed Energy Deposition technique: a Ti6Al4V alloy, and a Ti6Al4V-TiC Metal–Matrix Composite, respectively. The LCA methodology is according to ISO 14040:2006, and large amounts of information on the use of raw materials, energy consumption, and environmental impacts is provided. Different impact categories following the Environmental Footprint methodology were analysed, showing a big difference between both technologies, with an 87.8% reduction of kg CO_2 eq. emitted by High Energy Ball Milling in comparison with Gas Atomization. In addition, an economic analysis was performed, addressing the viability perspective and decision making and showing a 17.2% cost reduction in the conventional process.

Keywords: life cycle assessment; metal–matrix composite; additive manufacturing; titanium; gas atomization; high energy ball milling

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1. Introduction

Current regulation aiming for the reduction of environmental impacts is increasing. The Paris Agreement [1] was the first international agreement to fight against climate change with a reduction of emissions target at 55% below 1990 levels, and the European Union (EU) is addressing it through policy initiatives under the European Green Deal [2], seeking climate neutrality in the EU by 2050. Additionally, according to the Intergovernmental Panel on Climate Change, regulation on Greenhouse Gas emissions will be stricter and will come in the form of both penalties and incentives [3], highlighting the need for an environmentally friendly industry approach. This reduction can be reached by reducing the use of resources in manufacturing, but most importantly on the production of primary material process, where the greatest amount of energy is consumed [4]. In recent decades, due to the increasing complexity of industrial components, industries have started to use metal powders [5], leading to the implementation of Additive Manufacturing (AM) techniques, which are more convenient for this purpose. Therefore, the use of powder metallurgy is progressing as an opposition to subtractive manufacturing, allowing more design possibilities and reducing the use of feedstock and energy at the same time [6].

AM is defined as a "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" by ASTM and ISO standards [7]. It can provide many significant advantages over traditional processes such as: decreased production time; a reduction of operator intervention; the non-requirement of multiple tools; ability to design and manufacture complex geometries; improvement of cost-competitiveness using expensive materials; negligible production of scraps and waste by using only the exact amount of material; non-necessity of adjuvants, coolants and lubricants; and transformation of the supply chain, enabling local and proximity production [8–12]. All these advantages make AM a promising technology for Industry 4.0 and the transition to a Circular Economy by reducing the use of resources and extending products' service lives, for instance by increasing the capability to repair specific and complex components [13]. The interest from the industry in adopting AM technologies in their production processes is reflected in the markets. The global metal AM market is expected to grow around 24% annually until 2027 [14]. This means that the adoption of AM at a large scale will develop economies of scale, reducing costs for raw material and machinery investments and allowing firms to create cost-effective business models that can optimise the use of resources in production processes considering the whole supply chain, compared with conventional manufacturing methods [15].

This study compares the production of commercial Ti6Al4V titanium alloy powders by Gas Atomization, which is the conventional and more common process to obtain feedstock for Additive Manufacturing, with the production of a titanium metal matrix composite formed by Ti6Al4V (whose titanium comes in the form of irregular powder by Kroll process) and TiC nanoparticles under a High Energy Ball Milling process. A Life Cycle Assessment (LCA) and a cost analysis has been carried out, as the demand for this integration is increasing [16]. These two slightly different powders can be compared under the same LCA framework without compromising the consistency of the study because they have an identical function. Both powders can be used and are compared specifically for the Directed Energy Deposition technique, which is an AM process where the powder material is simultaneously fused by an energy source depositing material in a continuous way, forming a melt pool layer by layer [17]. To our knowledge, this type of evaluation on these technologies has not been performed to date in this research field. Thus, the present paper provides new primary data from the evaluated process and sets a basis for further evaluation of the technology.

Regarding the relevance of the manufacturing sector, a 7% annual expansion from 2020 to 2027 is expected for the powder metal subsector in particular [18], as titanium was the material with the highest revenue share in the AM metal market in 2020 [19]; thus, it is important to assess the environmental impacts of these manufacturing techniques, which can be performed applying the LCA standardised methodology, to create awareness and support decision-making towards a more sustainable and eco-friendly industry.

2. Literature Review

In order to provide more insights about the technologies evaluated and the cases under study, and to give proper reasoning for the further modelling steps, a broad review was carried out including the process description of both the methods and materials under scope.

Currently, Gas Atomization (GA) is the leading processing method to produce metal powders for AM [20]. During this process, liquid metal melted in a furnace is sprayed into droplets by a pulverisation of high-pressurised gas, which fall into a cooling chamber under inert gas protection to solidify, form, and obtain metal powder particles with fine sizes (<100 µm), high sphericity, and flowability [21–23]. In the route of nanostructured materials production, a better alternative to the aforementioned method is High Energy Ball Milling

(HEBM), a simple and powerful process to produce them [24]. This technique is greatly used for the production of nanocomposite powders, based on different processes taking place simultaneously, such as: cold welding, which increases the average particle size of the composite; fracturing, which causes fragmentation of the particles; and the re-welding of ceramic particles and metallic powders. All of this takes place in a highly activated milling media, where the impact of one ball with another and with the container wall in a repetitive way uniformly distributes the particles to achieve fine grained nanostructures [25–28]. This powder metallurgy technique can be used to produce matrix whole range reinforcement compositions, known as Metal Matrix Composites (MMCs), which are materials made up from two or more constituents, where normally one is a metal, called the matrix, and the other one a ceramic, which is the reinforcement material, whose combination produces a material with different and superior characteristics to the component constituents [29–31]. This process allows the creation of mechanically strong interfaces between the nanoparticles and the matrix, avoiding miscibility inconveniences [32]. Creating nanocomposite materials with a uniform reinforcement distribution is a difficult step, but the high collision rate and the bigger number of free surfaces produced under the HEBM process helps to achieve it [33]; this method is technically suitable for MMC powder production, in opposition to GA.

The production of nanostructured materials by HEBM, such as the MMCs, has received extraordinary attention over recent years, mainly because of their functional and structural characteristics, and most recently for their use in AM fabrication [34]. It has become an area of research given its easy application, which leads to the production of these advanced materials with enhanced physical and mechanical properties such as higher strength, stiffness, light weight, and wear resistance, whose potential applications generate a great interest in industry [26]. Habitually, these materials have been produced by casting techniques that obtain billet forms as a result, which have to be processed under subtractive methods, losing material and increasing the cost; thus, powder metallurgy methods offer advantages in this field [35]. In the present, MMCs are the best alternative to the conventional materials [36] and are preferred over the metals, non-metals, and alloys [37], replacing them in an exponential way in different industries (aerospace, automobile, defence, etc.) because of their superior mechanical properties and lesser cost to make them [38,39]. These materials play an important role in today's necessity of higher production and productivity in manufacturing, while having lower cost increases and reconciles these needs with environmental preservation by reducing the energy consumption, waste generation, and raw material consumption [40].

Regarding the material involved in this study, the increase in the demand of titanium and its alloys in new technologies (automotive, aerospace, biomedical . . .) has made the research in the development of new processes that consume less energy and require less material very relevant [41,42]. Titanium and its alloys have exceptional properties such as low density, a low elastic modulus, high-specific strength, good formability, reasonable ductility, high fracture toughness, the ability to withstand high temperatures, biocompatibility, and good corrosion resistance [42]. Specifically, titanium matrix composites have good performance in corrosion resistance, high specific strength, high specific modulus, and heat resistance [43]. In particular, the Ti6Al4V alloy (Ti, 6 wt.% Al, 4 wt.% V), the focus of this study and which is the most widely used titanium alloy [44], has good characteristics such as a high strength to weight ratio, corrosion resistance, biocompatibility, and low thermal expansion [45]. Additionally, the use of TiC ceramic particles as a reinforcement phase is interesting due to their high melting point, elastic modulus, high hardness, low density, high flexure strength, good thermal conductivity, high resistance to corrosion and oxidation, and high thermal shock resistance [46]. These improved characteristics have been recently demonstrated by several different works, where the combination with ceramic particles increases the wear resistance, corrosion, and strength of the fabricated part [47–50].

Previous studies also confirm the suitability of irregular and not spherical titanium feedstock powder for AM processing, using titanium sponge from conventional Kroll processes and starting from ilmenite ore mineral extraction converted to TiCl4, which is reduced by magnesium, obtaining a sponge that is sliced and crushed [51]; another option is hydrogenated-dehydrogenate (HDH) titanium, which can be produced by hydrogenation of nearly any source of titanium [52]. For instance, titanium sponge from the Kroll process was directly ball milled and then consolidated by Spark Plasma Sintering in a work by Zadra [53]. Arias-González et al. [54] studied the deposition by Laser Cladding of irregularly shaped Ti grade four powder, demonstrating its viability. A comparative work, using the Directed Energy Deposition (DED) technique, was performed by Amado et al. [55] between gas atomization Ti powders and sponge fines from the Kroll process, obtaining a harder printed layer from the sponge one at lower cost. In their work, Goso and Kale [56] stated that the main source of titanium powder to be blended with other elements to produce alloys, such as Ti6Al4V, is the sponge product of the Kroll process; they also prepared a laboratory-scale approach to hydrogenate and mill these products, making them suitable for metallurgical compacts. Sponge elemental titanium powder and HDH elemental titanium powder were sintered under same conditions by Bolzoni et al. [57] to compare their final mechanical characteristics. Dong et al. [58] transformed non-spherical hydrogenated-dehydrogenated (HDH) titanium powder into spheres and printable forms using a ball milling method, grounded it until its morphology was near-spherical to further blend it with elemental powders of aluminium and vanadium, and developed low-cost HDH Ti-6Al-4V, which was later printed using a Laser-Based Powder Bed Fusion machine. Electron Beam Powder Bed Fusion was used by Narra et al. [59] to successfully print parts from Ti6Al4V HDH powder compared with spherical atomized powder, obtaining similar qualities. In other work by X. Yang et al. [60], irregular HDH titanium was modified in an HEBM to fabricate parts by Selective Laser Melting, reducing in this way the cost of using high-purity spherical powder, similar to the results achieved by Hou et al. [61] manipulating HDH Ti by ball milling technology to produce printable Ti powders for the same AM technology. In addition, other kind of techniques, such as the disproportionation reaction in molten NaCl-KCl, have demonstrated the production of powders from titanium sponge [62].

The information retrieved from different sources shows the differences between both manufacturing techniques and the materials involved in the assessment. It also supports the utilisation of irregular powder in the HEBM process.

3. Materials and Methods

This study was conducted under the Environmental Life Cycle Assessment methodology, also known as simply Life Cycle Assessment (LCA), which is a management tool to evaluate the environmental performance of products, goods, and services [63]. The LCA methodology to be used is according to the ISO framework [64] and refers to the recommendations and requirements given by the European ILCD guidelines [65]. In addition, the instructions included in Life Cycle Assessment: Theory and Practice [66] were used as a background to complete the study and methodology explanation.

3.1. Case Study

The present study was carried out with the aim of knowing and comparing the environmental impact of two different processes, both capable of producing useful material for additive manufacturing techniques: (i) an MMC powder formed by Ti6Al4V and TiC nanoparticles with an HEBM process, and (ii) a Ti6Al4V alloy powder produced by GA was carried out under an LCA framework. These processes were developed by MBN Nanomateralia S.p.A within the framework of the European LightMe project (GA. 814552). The powder production started with the selection of commercially available raw materials at an industrial scale (Ti6Al4V and TiC) which were, in the first case, mechanically alloyed via High Energy Ball Milling under inert atmosphere (to prevent oxygen and nitrogen uptake). The powder output was then sieved, and coarser particle size fraction was re-processed to increase the overall process yield. Finally, in the range of 45–106 μm Ti6Al4V-TiC, powder suitable for AM was obtained. In the second case process, a high-velocity gas, argon in this case, disrupted the melting metal, producing spherical-shaped particles in the range of 50–150 µm, already proven used in AM.

Scanning Electron Microscope (SEM) images of powder morphology for both produced samples are shown in Figure 1, highlighting the differences between the products obtained through HEBM and GA. Despite the visible morphological differences, both products are suitable for use in the Directed Energy Deposition technique.

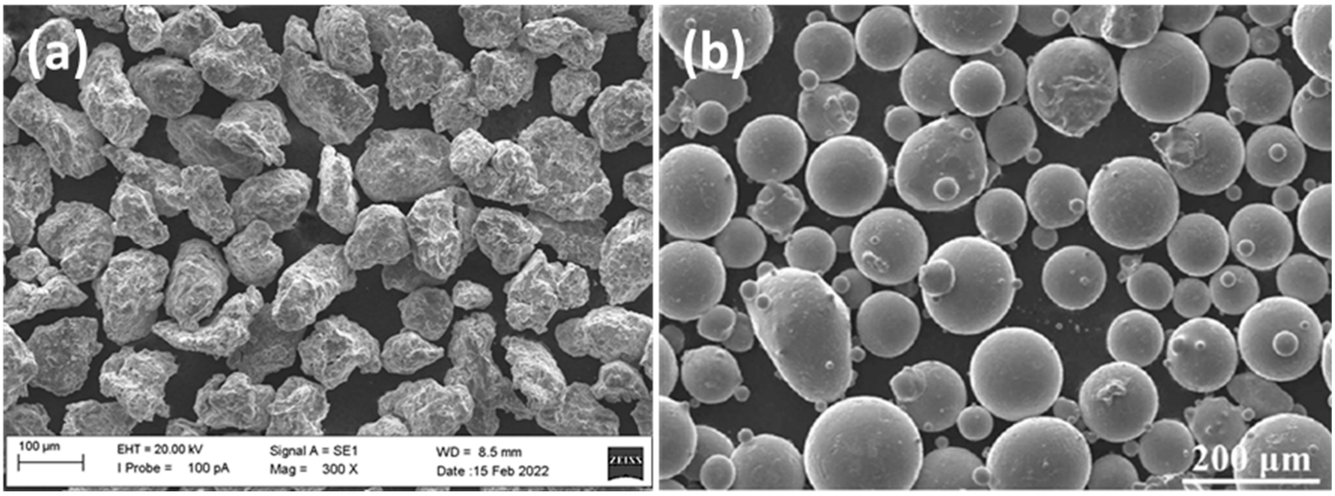

Figure 1. SEM image of powder morphology of (**a**) Ti6Al4V-3.8 wt.% TiC produced by HEBM and (**b**) Ti6Al4V produced by GA, extracted from G. Chen et al. [67].

3.2. Goal and Scope

As stated in the Introduction, the main aim of this Life Cycle Assessment is to inform about the environmental performance, developing a comprehensive analysis of the production process of metal powder appropriate for Additive Manufacturing processes. This is conducted using a Metal Matrix Composite material formed by a titanium alloy (Ti6Al4V) reinforced with TiC nanoparticles in a High Energy Ball Milling process, and comparing its performance with the production of Ti6Al4V powder under the conventional Gas Atomization process. Thus, environmental arguments for the selection between the different manufacturing technologies are provided. Aside from this, a cost analysis with the same aim and scope is performed in order to contribute to a balanced analysis between the environmental and economic impacts. In addition, the study intends to provide life cycle inventory datasets that can contribute to enhance the state of-the-art knowledge of these manufacturing techniques.

These two different manufacturing techniques are modelled consistently in terms of both methodological choices and selection of data to obtain a fair representation of the two systems, and comply with the ISO 14044:2006 requirements. The functional unit is the production of one kilogram of metallic powder suitable to be used in Additive Manufacturing processes, specifically for Direct Energy Deposition techniques. This is an appropriate unit to assess both systems considering all the current constraints and possible further study steps, and the fact that they share the same final purpose, despite their different composition and production methods. This study is framed in a cradle-to-gate system boundary, as downstream data are not yet available, where all the inputs (raw materials and energy) and the outputs (product, emissions, and wastes) associated with the core process are considered. Upstream activities, such as the extraction of materials and their transportation to the factory, are considered based on the database used, which collects and integrates data from all the production stages of each input in an average approach. Downstream activities such as distribution, final use, and disposal, were not considered at this stage of the study due to nuances to obtain accurate data and properly assess these outbound steps.

3.3. Life Cycle Inventory

For the inventory elaboration, the main data were provided by MBN Nanomateralia S.p.A, who are the MMC producers in their HEBM line. They also provided the data for the GA based on their previous knowledge and projects developed. All these data are backed by the progress of the LightMe project funded under the Horizon 2020 research program.

In the information about HEBM, a scaled-up production was contemplated, considering the reprocessing of un-used powders by sieving and reintroducing them in the process and argon recirculation. For the GA case, the recirculation rate was extracted from Wilson et al. [68], who conducted an LCA on GA for nickel, expecting a 98% argon use reduction in an augmented approach, which is also in line with industrial purification systems.

All these data were processed, together with information extracted from the literature and from LCA databases, using ecoinvent v3.8 [69], which allows the use of georeferenced data and different allocation approaches. In particular, the APOS (Allocation at the Point Of Substitution) system model was adopted, which follows the attributional approach in which burdens are attributed proportionally to specific processes. Moreover, as some processes and materials were not available in the existing LCA database, specific models were created ad hoc for this purpose based on scientific documentation, which will be disclosed later on.

Table 1 presents all the data specifications based on the production of one kilogram of powder, showing the raw materials, energy, and other items necessaries for the entire definition of the HEBM and GA processes, as provided by the producer.

Table 1. Inventory data for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

Products	**HEBM (Ti-6Al-4V—3.8 wt% TiC)**	**GA (Ti-6Al-4V Powder)**
Alloy quantity (kg/kg material produced)	1.13	1.3
NPs quantity (kg/kg material produced)	0.038	-
Energy consumption (kWh/kg material produced)	4.5	55
Argon (L/kg material produced)	0.4	200

Assumptions and Limitations

As was mentioned before, some of the processes and materials to be introduced in the model were not found in the ecoinvent v3.8 database, so it was necessary to create them for this study purpose. This is the case of the titanium alloy Ti6Al4V, which was not part of the current database. In order to fit the model with the European context, the energy expenditure production and average transport distance for the AlMg3 alloy production, which is also modelled for the same geography area, was selected. To include in the assessment the different components of the alloy, several sets of proportions were found to generate an average quantity of each of them, except for Vanadium, which was not available in the databases and did not have enough literature available to be modelled ad hoc for this case study. To overcome this, the Vanadium share in the alloy (4% weight) was substituted, adding it to the Titanium amount. In this way, it is possible to model the alloy and later obtain its environmental impacts. This information can be seen in the Supplementary Material, Table S1. In the case of the TiC, there were no data about its production process in the ecoinvent databases. However, the production of SiC and B4C was available, which are developed under similar processes, as is shown in the literature review performed in Table 2. According to this, the production process of TiC was modelled based on the SiC, because they have the same stochiometric reaction, changing the SiO_2 feedstock for TiO_2 and including the same transportation average based on an equal European context. From the B4C, only the type of chemical factory dataset was extracted, closer than a typical silicone factory used for the SiC case. The different datasets used can be found in Supplementary Material, Table S2.

Table 2. Overview of the literature review about TiC, SiC, and B4C production.

Author	Title	Reference	Main Findings
Guichelaar, 1997	Acheson Process. Carbide, Nitride and Boride Materials Synthesis and Processing	[70]	SiC production by Acheson method, pure silica (SiO_2) or quartz sand, and petroleum coke are used; the reaction that takes place has a 1:3 ratio.
Kumar and Gupta, 2002	Study of formation of silicon carbide in the Acheson process	[71]	Coke and silica sand are introduced into the Acheson furnace, highly energetic process over 6–12 kWh/kg SiC. After heating and subsequent cooling, it is taken to grinding and classification.
Chen et al., 2004	Synthesis and characterization of boron carbide nanoparticles	[72]	B4C nanoparticles were made via a reaction of boron, obtained from thermal decomposition of magnesium diboride, with multiwall carbon nano tubes at 1150 °C.
Woo et al., 2007	Formation of TiC particle during carbothermal reduction of TiO_2	[73]	The starting point is titanium dioxide TiO_2 and carbon resin (1:3 ratio), then put in a graphite furnace at 1500 °C, obtaining the product.
Nuilek et al., 2008	Production of titanium carbide from ilmenite	[74]	Ilmenite and carbon black are ground for 2 h at 250 rpm, in a ratio of 1:4, respectively, heated to a max. Tof 1500 °C maintained for 1 h.
Suri et al., 2013	Synthesis and consolidation of boron carbide: A review	[75]	B_2O_3 or H_3BO_3 with a carbon source in the furnace above 1400 °C for reduction, where the production of B4C will take place. The resulting powder is leached in acid to remove impurities.
Sen et al., 2011	Preparation of TiC powders by carbothermal reduction method in vacuum	[76]	Carbothermal reduction starting from TiO_2 takes place at a temperature of 1550 °C for 4 h.
Sonber et al., 2013	Synthesis, densification and characterization of Boron Carbide	[77]	B4C is produced commercially by carbothermal reduction in an electric arc furnace, reducing B_2O_3 with CO.
Kakiage et al., 2016	Low-temperature carbothermal nitridation of boron oxide induced by networked carbon structure	[78]	B4C powders are formed by carbothermal reduction with boron oxide through the reaction of $2B_2O_3 + 7C \rightarrow B_4C + 6CO$.
Kukushkin, 2021	Special Issue: Silicon Carbide: From Fundamentals to Applications	[79]	Silicon carbide is composed of silicon and carbon, manufactured by a patented method called the Acheson method.

3.4. Impact Assessment

This phase allowed us to transform the Life Cycle Inventory data, collected as described in the previous section, into quantifiable environmental impacts. A specific software tool was used to create the models for the impact assessment calculation: SimaPro® 9.3 by Pre' Consultants, one of the most predominant LCA software. The impact assessment method used in this study was the EF method of the Environmental Footprint (EF) initiative, launched by the European Commission in 2013, in constant updating and transitioning phases. It was designed to support the use of Product Environmental Footprint Category Rules (PEFCR) and Organisation Environmental Footprint Sector Rules (OEFSR), and with the aim of creating a harmonised EU methodology with relevant environmental performance criteria using a life cycle approach [80]. This method provides information on 16 midpoint impact categories, extracted from Fazio et al. [81]: climate change (kg CO_2 eq.); ozone depletion (kg CFC11 eq.); ionising radiation (kBq U-235 eq.); photochemical ozone formation (kg NMVOC eq.); particulate matter (disease incidence); human toxicity, non-cancer (CTUh); human toxicity, cancer (CTUh); acidification mol (H+ eq.); eutrophication, freshwater (kg P eq.); eutrophication, marine (kg N eq.); eutrophication, terrestrial (mol N eq.); ecotoxicity, freshwater (CTUe); land use (Pt); water use (m3 deprived); resource use, fossils (MJ); resource use, minerals and metals (kg Sb eq.).

In this study, a normalisation factor was included, which according to ISO 14044:2006 is an optional step, to offer a common unit scale, providing a comparable set of results and solving in this way the incompatibility of different units by expressing the total impact occurring in a reference region for a certain impact category within a reference year. The normalisation factors in this assessment were based on Crenna et al. [82]. With this, the more significant impact categories for the product system under investigation arise. These are dimensionless results, meaning that, for instance, a global warming potential of 0.5 for a product or system means that it is responsible for half of the GWP emitted by an average person per year in that particular reference region. According to the ISO standard, weighting it is also an optional step, but it is included in the study because it can help in decision making, ensuring the focus is on the important aspects, and to add up the results, obtaining a single score that can serve as a comparison between technologies and with the cost analysis. This step aggregates in averages, three weighting sets: panel-based approach—general public survey; panel-based approach—LCA experts' survey; and evidence- and judgement-based approach, according to Sala et al. [83]. These sets are later multiplied by the normalisation factor of each category previously obtained, resulting in a score value measured in mPts.

3.5. Cost Analysis

When performing the LCA to identify the environmental impacts and study the different alternatives, it is also crucial to assess the economic impacts that the innovation can suppose. It may happen that changes are made to production processes to improve their environmental impacts, but the cost of implementing the innovation makes the business model unprofitable.

In this case, HEBM and GA processes have been assessed to calculate the cost of producing one kilogram of metallic powder suitable to be used in Additive Manufacturing processes, so the same functional unit as the one used for the LCA was considered. For this calculation, different activities incurred in the production processes were evaluated, obtaining economic information to facilitate the identification of cost-drivers and to be combined with the environmental impacts in a single matrix.

The economic data were collected from the same provider, MBN Nanomaterialia S.p.A, for one kilogram of produced powder (same FU as for the environmental assessment) to facilitate the comparison, including the capital cost and the operational costs. No more detailed disclosure is shown, as some data could be sensitive for the production company. This data can be found in Table 3.

Table 3. Economic data for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

Products	HEBM (Ti6Al4V—3.8 wt.% TiC)	GA (Ti6Al4V Atomized Powder)
Alloy price (EUR/kg)	27	17
NPs Price (EUR/kg)	3.7	0
Overall plant cost (EUR/kg)	51	38
Manufacturing time (kg/h)	4	6
Electricity (EUR/kg)	2	11
Personnel (EUR/kg)	1.6	4
Argon cost (EUR) (3 EUR/m^3)	0.0012	0.6
Total cost per kg (EUR)	85.3	70.6

4. Results and Discussion

After the modelling process, the calculation output is a set of values for the characterisation factors, which are presented in Supplementary Material, Tables S3 and S4. Then, the software helps to calculate the normalisation factors, accessible in Tables S5 and S6, which are necessary to obtain the final weighting factors shown in a single score value (mPts), which can be seen in Figures 2 and 3. The detailed score for each technology, showing the impacts produced by the inputs involved, can be found in Supplementary Material, Tables S7 and S8.

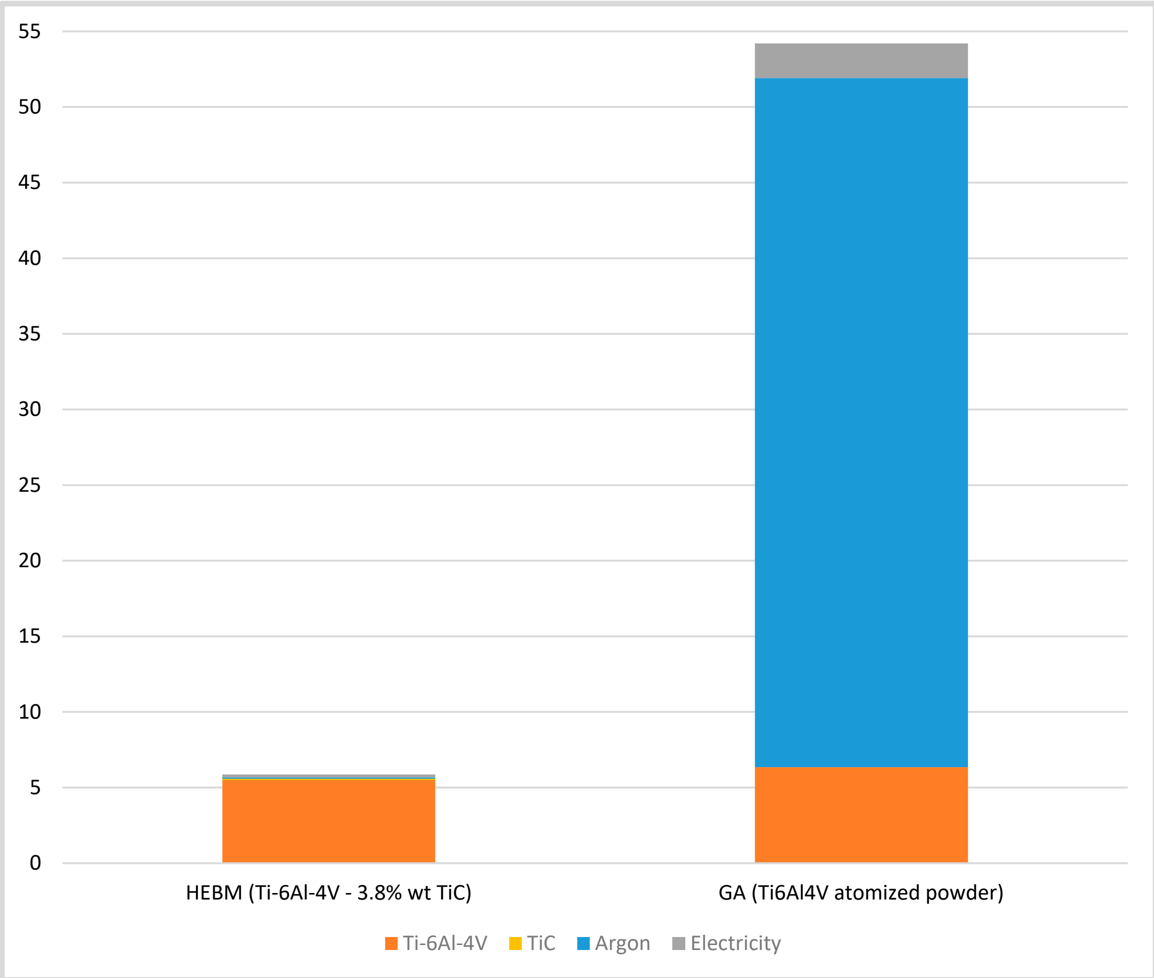

Figure 2. Weighting factors, by input material, for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

The outcome of the previous analysis clearly shows that the production of one kg of metallic powder, useful for additive manufacturing techniques, is more environmentally harmful if is processed by GA rather than by HEBM. For instance, the single score of GA is more than 54 mPts, mainly due to argon use (84% of contribution), while almost 6 mPts are obtained for the HEBM technology, of which 94% of the impacts are due to Ti6Al4V use. Therefore, an 89% reduction is achieved by the implementation of the new process. Aside from argon, the environmental profile of the GA process is also influenced by the input of titanium alloy (12% on the single score). In relation with the energy expenditures, the GA process is almost 10 times more energetic than HEBM, as shown in the inventory table. However, its contribution to the total impact of each process is similar, explaining 4% and 3%, respectively. Regarding the HEBM process, the other process flows, TiC and argon, have a contribution lower than 2%.

Concerning the impact categories, the most important ones for the single score are Climate change and Use of fossil resources, for both technologies. In relation with the GA process, argon has the highest impact in the Water use category, with a 97% contribution. The Ti6Al4V alloy has its largest impact in Human toxicity, cancer, with more than 50% of the impacts. Electricity has a lower impact in all categories, representing a maximum of 5%

in the Ionising radiation category. In the case of the HEBM, titanium alloy represents more than 98% both in the Particulate matter and Human toxicity, cancer categories. Electricity has is highest contribution in Ionising radiation with almost a 19%. The rest of the materials, argon and TiC, have a lower contribution, with their highest in the Water use category, representing 8% and 3%, respectively.

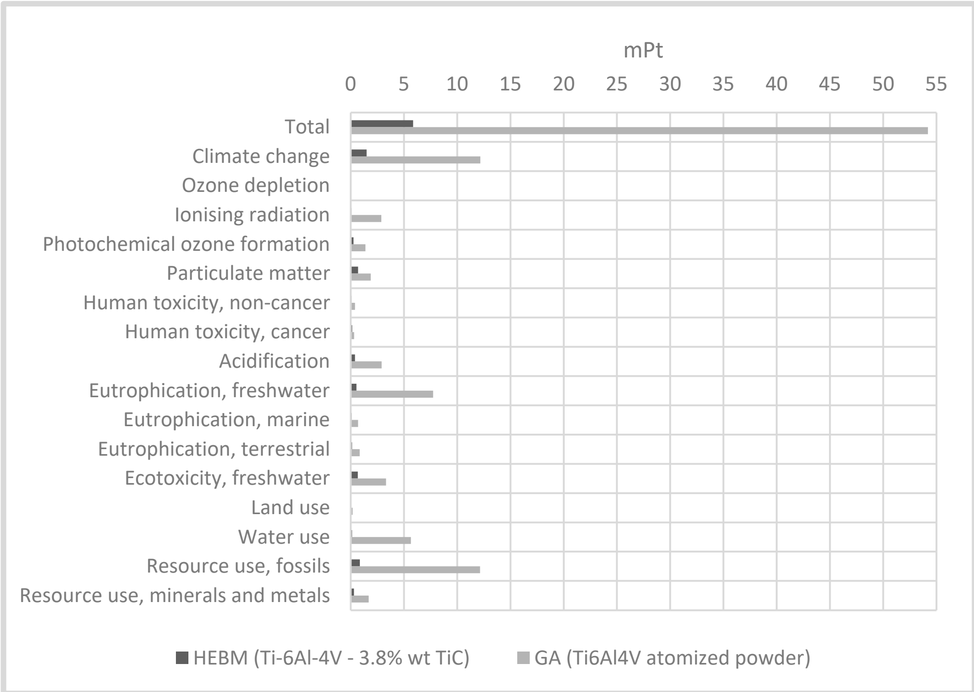

Figure 3. Weighting factors, by impact category, for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

On the subject of the economic analysis, as can be observed on Table 3, the production of one kilogram of powder by the HEBM process has a higher economic impact than that of GA, with an almost 21% increment. This is due to the higher price of the raw material (alloy), the addition of the NPs, and the cost of the production plant.

The total weighting scores can be integrated with the cost analysis results, putting them together in a single matrix, and obtaining a valuable comparison between both technologies (Figure 4).

Other important data to consider are the energy consumption, with a total expenditure of 55 kWh in the GA and only 4.5 kWh used in the HEBM process, which represents a reduction of a 91.8%.

Certain constraints and limitations identified during the design process for the assessment concerning alloy and nanoparticle modelling increase the uncertainty of some of the aforementioned results, as described in the "Assumptions and limitations" subsection. In addition, the use of a global average transport approach for the materials and a standard European electricity mix could also have a slight implication on the final results. These limitations found during the modelling phase have low relevance in the final outcomes, but it was still necessary to address them to guide future replications of the study.

As mentioned in the Introduction, there is not vast research on this topic, using equal materials, to compare and discuss the obtained results of our study. However, a recent work by Dhiman et al. [84] demonstrated a 68% lesser global warming potential from Ti6Al4V swarf processed to powder by ball milling, in comparison with its conventional GA counterpart. In this study, the swarf material used needed a pre-treatment involving different chemicals and energy flows, which could explain the impact reduction differences with the present study. This is aligned with the results here presented, also considering it uses different boundaries, impact methodology, and database.

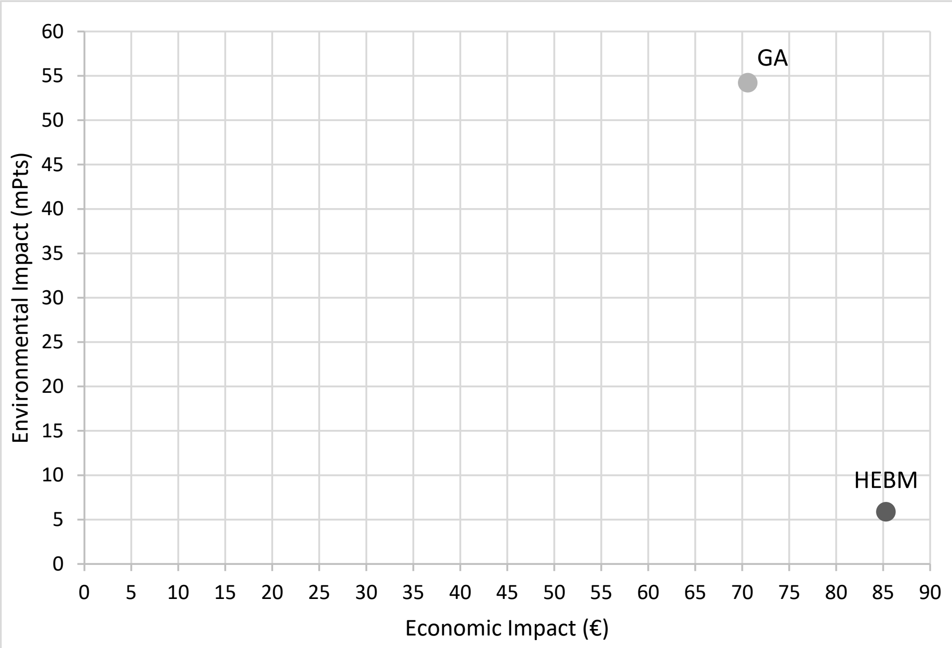

Figure 4. Comparison matrix chart of both technologies, HEBM (High Energy Ball Milling) and GA (Gas Atomization), with the environmental impact measured in mPts and the economic impact measured in EUR.

5. Conclusions

After the complete assessment, it is plainly evident that the production of one kilogram of metallic powder suitable for additive manufacturing techniques produces less environmental impact if it is manufactured under High Energy Ball Milling instead of that in the conventional Gas Atomization process, achieving a reduction in the order of 90%, measured under the weighting single score scale. This comparison has allowed us to find and better interpret the hotspots and cost-drivers of the assessment.

The main environmental issue comes from the intensive use of argon in the GA process, which leads to a higher damage score as the quantity used is 500 times bigger than that in the HEBM. For instance, the argon used in HEBM emits 0.77 kg CO_2 eq., while more than 384 kg results from GA. The use of this type of gas is necessary to achieve a good performance in the GA process, so a significative reduction in its quantity is not expected. Even in a hypothetical scenario with a smaller amount of argon needed, the higher energy expenditure of the conventional process would still generate more environmental impacts. Regarding the economic terms, which makes HEBM technology more expensive than its counterpart (about EUR 15 more per kg produced), it is the price of the alloy and the nanoparticle used, and specially the overall cost of the plant, which have not reached yet the same level of optimisation and maturity as those of the GA, so a possible cost reduction in the near future could be possible. In addition, the improvement in the HEBM powder properties can increase the value of the final product and make the innovation viable while reducing the environmental impacts. Moreover, the powder produced in the HEBM process has better characteristics than a regular alloy when applied to the manufacturing of any kind of component, making it lighter and more durable, which will also enhance the environmental performance during the use phase, having a longer life or, for instance, if it is applied in the transport sector, reducing fuel consumption by its lower weight. Further studies in this regard considering a specific application would be needed to verify to what extent the improved performance would compensate the costs. Additionally, to allow a more reliable comparability between systems, further research is needed to integrate other calculation methods and techniques, such as uncertainty and sensitivity analyses, to consolidate the LCA results. Additionally, in other fields of study, the mechanical behaviour and final functionality of the different powders should be compared with supplementary tests to assess different characteristics of the products, such as density.

This environmental evaluation, performed under the Life Cycle Assessment methodology, helps with the comparison of both technologies in order to evaluate their environmental performance. It has been demonstrated that the new process is not only capable of producing powder for additive manufacturing with improved properties from the industrial and consumer perspective, but it also can conduct it in a more environmentally friendly way. The integration of the cost analysis also supports the decision making, providing data of great interest for manufacturers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15086649/s1, Table S1: Average values and database sets for Ti-6Al-4V alloy (based on [58,85,86]), Table S2: Database sets for the inputs involved in the HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes, Table S3: Characterisation factors for the HEBM (High Energy Ball Milling) process, Table S4: Characterisation factors for the GA (Gas Atomization) process, Table S5: Normalisation factors for the HEBM (High Energy Ball Milling) process, Table S6: Normalisation factors for the GA (Gas Atomization) process, Table S7: Weighting factors for the HEBM (High Energy Ball Milling) process, Table S8: Weighting factors for the GA (Gas Atomization) process.

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