Heliyon 10 (2024) e38961

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

A comparison of cold spray, atmospheric plasma spray and high velocity oxy fuel processes for WC-Co coatings deposition through LCA and LCCA☆

E. Rúa Ramirez [a,b], A. Silvello [a,*], E. Torres Diaz [a,b], F. Tornese [c], M.G. Gnoni [c], I. Garcia Cano [a]

[a] Thermal Spray Center (CPT) University of Barcelona, Martí i Franqués 1, 08028, Barcelona, Spain
[b] Mechanical Engineering, Research USTA (IMECI-USTA), Santo Tomás University, Tunja, Colombia
[c] Department of Innovation Engineering (DII), University of Salento, 73100, Lecce, Italy

ARTICLE INFO

Keywords:
APS
CGS
Coatings
HVOF
LCA
LCCA
WC-Co
Sustainability

ABSTRACT

In this study, an environmental and economic assessment of WC-Co coatings deposited by Cold Gas Spray (CGS), Atmospheric Plasma Spray (APS) and High Velocity Oxy Fuel (HVOF) spray technologies is carried out. Using SimaPro LCA software, several environmental impact categories are analyzed to compare their environmental performance. The economic analysis includes capital and operating expenditures. The results have highlighted that all three processes exhibit low environmental impact in terms of CO2 emissions but the performance of the CGS process is heavily influenced by the low deformability of WC-Co, while the APS process is affected by high electricity consumption. In terms of economic analysis, the HVOF process exhibits the best performance, while the CGS process requires most time to deposit the coating, and consequently, it is the process where the workforce component is most significant. These results depend on the fact that CGS might not be the most suitable deposition technique for fabricating WC-Co coatings.

1. Introduction

Within the continuum of surface engineering advancement, the deployment of tungsten carbide-cobalt (WC-Co) coatings has garnered significant attention, primarily attributable to their exceptional attributes such as remarkable hardness, wear resistance, and superior mechanical properties. These coatings have emerged as fundamental elements owing to their efficacy in diverse realms, notably in cutting tools and corrosion-resistant applications [1]. Advantages of WC-Co coatings are well known in the scientific community. WC-Co coatings provide exceptional hardness and wear resistance, making them ideal for applications in abrasive

Abbreviations: LCA, Life Cycle Assessment; LCCA, Life Cycle Costs Analysis; APS, Atmospheric Plasma Spray; HVOF, High Velocity Oxy Fuel; CGS, Cold Gas Spray; WC-Co, Tungsten Carbide-Cobalt.

☆ This research was funded by "Proyectos de Generación de Conocimiento 2021" by Ministerio de Ciencia e Innovación (Spain), grant number PID 2021-128917NA-I00, financed by MICIU/AEI/10.13039/501100011033 FEDER UE, and 2021SGR00712, Generalitat de Catalunya, Spain. Funding Ph.D. Students, Rúa Ramírez Edwin and Torres Díaz Edwin were funded by COLCIENCIAS—Ministry of Science, Technology, and Innovation of Colombia, call for PhD applications 885–2020, and 906–2021.

* Corresponding author.
E-mail addresses: asilvello@cptub.eu, alessiosilvello@ub.edu (A. Silvello).

https://doi.org/10.1016/j.heliyon.2024.e38961
Received 18 June 2024; Received in revised form 1 October 2024; Accepted 3 October 2024
Available online 5 October 2024
2405-8440/

environments [2]. They can maintain their mechanical properties even at elevated temperatures, making them suitable for high-temperature applications [3]. Moreover, the erosion resistance of these coatings is well established in the aerospace and mining sectors because they can withstand high-velocity impacts from particles. For example, aerospace turbine blades, engine components, and other parts exposed to high wear and thermal stress or tools and machinery parts that encounter high levels of abrasion and erosion used in mining, benefit from WC-Co coatings. So, WC-Co coatings offer a corrosion-resistant protective barrier against chemical and environmental corrosion, extending the lifespan of components. However, the development and application of these coatings entails important environmental and economic considerations that need to be considered as a matter of priority. The materials and application process for WC-Co coatings can be expensive, which may limit their use in cost-sensitive applications. Additionally, the thermal spraying process requires specialized equipment and expertise, increasing operational complexity and cost. Regarding mechanical properties, despite their hardness, WC-Co coatings can be brittle and prone to cracking under heavy impact or stress [4]. Furthermore, damaged coatings are difficult to repair and often require complete reapplication, adding to maintenance costs.

Atmospheric plasma spray (APS) [5] and high velocity oxy-fuel (HVOF) [6,7] are the most commonly used techniques for depositing WC-Co coatings due to their intrinsic process characteristics. For example, the high temperatures achieved in APS allow for the melting of WC-Co powders, ensuring good adhesion and a dense coating. On the other hand, HVOF propels coating particles at extremely high speeds, resulting in a dense and well-adhered coating but at a lower temperature than APS. This lower temperature avoids the risk of coating oxidation and preserves the desirable properties of WC-Co, such as hardness and wear resistance. Cold gas spray (CGS) is a thermal spray technique that utilizes kinetic energy instead of high temperatures to deposit coatings. While WC-Co is traditionally deposited using high-temperature techniques like atmospheric APS or HVOF, there are certain advantages to using CGS, such as low temperature process and less substrate heating. CGS operates at much lower temperatures compared to traditional thermal spray methods. This is beneficial for materials like WC-Co, which can be prone to oxidation at very high temperatures and at the same time, it minimizes heat input to the substrate, reducing the likelihood of distortion or damage to heat-sensitive materials. Finally, CGS propels particles at supersonic speeds [8], resulting in high-velocity impacts upon deposition. This could lead to excellent coating adhesion and density, even with hard ceramic materials like WC-Co [9]. Although the mechanical properties and wear and corrosion resistance of WC-Co coatings deposited by CGS are excellent [2,10,11], the challenge to be addressed is the low deposition efficiency due to the limited deformability of the ceramic material. Hence, they may not be economically viable despite the excellent properties of these coatings. To resume, the APS and HVOF techniques were analyzed because they are among the most widely used in various industrial sectors, while CGS is a relatively new deposition technique that has attracted the attention of experts due to the advantages arising from its deposition mechanism, which is based on plastic deformation rather than the melting of starting feedstock powders.

While the technical properties, applications and main challenges related to these techniques have been discussed in literature [12], studies providing an environmental and economic analysis of these methods are still scarce, leaving a research gap to explore in order to assess the sustainability profile of such techniques. In our previous study [13], we began to investigate this issue by conducting the Life Cycle Inventory (LCI) analysis of the three processes. In the past, other authors have addressed the topic of the environmental and/or economic impacts of some thermal spray processes, but there are either no data or still limited data available in the literature regarding WC-Co deposited using APS, HVOF, and CGS. In 2021, some authors investigated the Life Cycle Assessment (LCA) of the APS process [14] used to deposit Fe-based alloys, concluding that the major environmental impact stems from electricity consumption. Moign et al. [15] studied the LCA of yttria-stabilized zirconia coatings, comparing three different APS techniques. Vardelle et al. [16,17] carried out the LCA analysis of the HVOF process used to deposit hard-chromium particles on aircraft landing gear. Moreover, they conducted a first tentative comparison between APS, HVOF, and CGS using Ni as feedstock starting powders. Their study showed that LCA results are strongly influenced by the deposition efficiency of each process, as well as the high resource consumption of the APS, HVOF, and CGS processes. Additionally, a recent LCA analysis [18] of the HVOF process used to deposit Ni50Cr alloy for steam turbines is available. Taking the durability of the coatings into account, the results suggest not depositing this alloy using the HVOF process. Finally, Darut et al. [19] addressed the issue of environmental emissions from some thermal spray processes but used metallic starting feedstock powders rather than ceramics. All things considered, it is evident that there is a lack of information in the scientific literature regarding the deposition of WC-Co coatings using the thermal spray techniques we have employed.

The aim of this investigation is to provide a comprehensive view of the environmental burdens and costs associated with the WC-Co coating process, obtained by APS, HVOF and CGS, facilitating the identification of opportunities for environmental performance improvement. It involves an in-depth analysis that encompasses goal definition, scope, inventory analysis, impact assessment, and interpretation, ensuring a thorough environmental evaluation of the coating processes [20].

To this aim, this study employs a comparative analysis through the LCA and Life Cycle Cost Analysis (LCCA) methodologies, aiming at evaluating the environmental impact and cost-effectiveness of WC-Co coatings applied through CGS, APS, and HVOF technologies. LCA provides a systematic method for assessing the environmental aspects and impacts associated with the lifecycle of WC-Co coatings, enabling the identification, quantification, and evaluation of energy and material inputs, as well as environmental emissions [21]. The analysis is conducted in accordance with the ISO 14040 and 14044 standards [22]. The LCCA complements the environmental evaluation by incorporating the economic aspects of the WC-Co coatings' lifecycle, allowing for a balanced assessment of environmental sustainability and cost efficiency, thereby facilitating decision-making in a sustainability perspective.

2. Materials and methods

The comparative environmental and economic impact assessment of WC-Co coatings applied through CGS, APS, and HVOF is performed in this study through LCA and LCCA. The system in analysis and the methodologies applied are described as follows.

2.1. System description

The coating process was carried out in two steps, as shown in Fig. 1.

In the initial phase, the substrate is prepared for the effective application of the coating using the abrasive sand blasting method. The primary purpose of this technique is to create a rough surface on the substrate, enhancing the adhesion of the applied coating. This process is conducted using an air pressure system that propels abrasive particles, such as alumina, at high speed towards the surface of the substrate. These abrasive particles are supplied from a container or reservoir located within the blasting machine., where a dosing mechanism controls their flow to the nozzle. Upon system activation, compressed air generates a flow directing particles to the nozzle, where they are accelerated before impacting the substrate. This impact removes contaminants and induces a rough texture on the surface. Subsequently, particles and residues are collected and recycled via a recovery system. The machine operates at 6 bar pressure, with a motor power of 0.37 kW and voltage of 230 V at 50 Hz.

The second step of the process involves the deposition of coatings, which can be carried out using any of the three methods under analysis: APS, HVOF, or CGS.

HVOF utilizes gas combustion (such as hydrogen, kerosene, among others). This combination of fuel and oxygen ignites at precise temperatures and pressures, generating a supersonic-speed flame. Powder is introduced into this flame and propelled towards the substrate to create the coating. The high temperature of the combustion gases (around 3000 °C) softens the powder particles before impacting the substrate surface, facilitating coating formation. Due to the high velocity achieved (approximately 1800 m/s), it is possible to deposit metallic or ceramic powder onto the substrate. The high kinetic energy of these particles allows them to bond with the substrate, resulting in a highly dense coating [23].

The APS process relies on a plasma gun serving as the heat source, a ceramic particle injector for feeding metallic and ceramic powders, and a substrate where coating formation occurs. An injector facilitates the introduction of solid particles into the plasma jet via a carrier gas. When plasma comes into contact with powder particles in the heating region, exceptionally high temperatures are reached, ranging theorical temperatures between 6000 and 15,000 °C. The particles, averaging between 10 and 100 μm in size, are accelerated and melted in the plasma jet before impacting the substrate surface, typically positioned 100–120 mm from the plasma exit. Consequently, the coating is generated through the deposition and accumulation of melted particles, known as "splat", which solidify instantly onto the substrate [24].

The CGS is a solid deposition method that propels powder particles towards a substrate, where they undergo significant plastic deformation, forming dense coatings or even independent components. In this case, the process is so called Cold Spray Additive Manufacturing (CSAM). This process begins with the acceleration of particles using a high-speed gas jet, which can consist of air, N_2, He, or a combination of these gases. The gas is divided into two streams: one hot and one cold. The hot stream carries the powder from a feeder to a nozzle, where it mixes with the cold stream before being accelerated. Subsequently, the powder and gas mixture are further accelerated through a convergent-divergent Laval nozzle, converting pressure and thermal energy into kinetic energy. This allows the particles to reach supersonic speeds ranging from 300 to 1200 m/s, while remaining below their melting points. The key to this process lies in the plastic deformation experienced by the particles upon impact with the substrate, promoting excellent adhesion of the coating. This is how CGS produces high-quality and highly resistant coatings [25].

Fig. 2 shows the starting powder and the coatings obtained with the three different deposition techniques. The process parameters used, as well as the deposition efficiency and mechanical properties of the obtained coatings, are available in our previous publication [13].

2.2. Life Cycle Assessment (LCA)

The LCA has been conducted following the international standard:

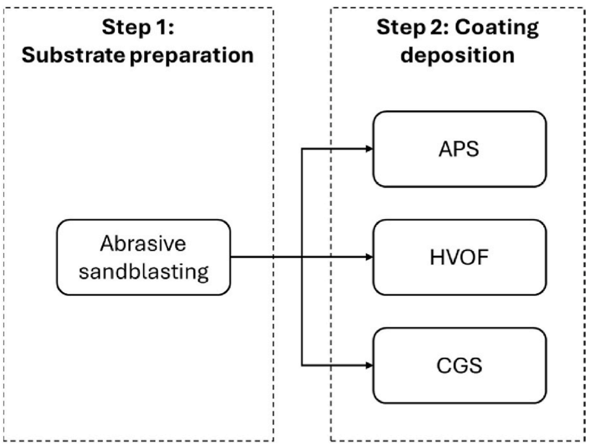

Fig. 1. Schematic illustration of the process analyzed.

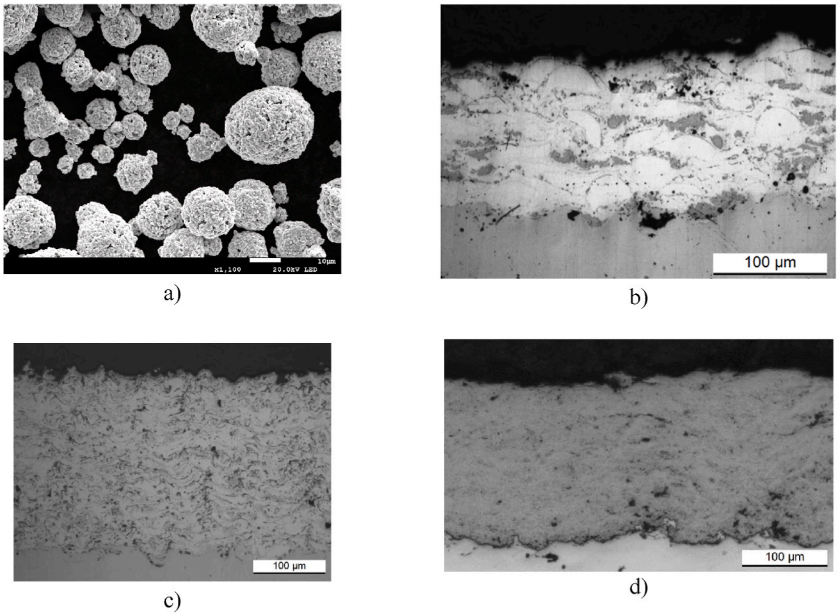

Fig. 2. a) SEM image of the deposited WC-Co powder, b) HVOF coating, c) APS coating, and d) CGS coating.

- UNI EN ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework [26].

The analysis was performed using the software Simapro® release 9.1.1, the most used software for LCA studies in academia that allows the adoption of different impact assessment methods and the access to several databases [25,27], and it was articulated in the four phases defined by the standards and detailed as follows.

2.2.1. Goal and scope description

In the first phase of LCA, the goal and scope of the analysis are detailed, clarifying the main objective, the system boundaries and the functional unit. The specific objective of this analysis is to identify, quantify, and compare the environmental impacts associated with each of the three coating techniques presented. With this purpose, the functional unit defined for the LCA is 1 m^2 of WC-Co coating applied on a C-steel substrate using the optimized process parameters for each deposition technique available at the Thermal Spray Center. Since the analysis is meant to compare the techniques adopted in the coating process, a "cradle-to-gate" approach is adopted: the system boundaries include only the raw materials extraction and the coating process, while it does not account for further processing, use phase, and end of life.

2.2.2. Life Cycle Inventory analysis (LCIA)

In phase 2, the Life Cycle Inventory (LCI) of the process is defined, providing all inputs and outputs referred to the functional unit for each activity included in the systems boundaries. Data regarding the inputs and outputs of the process have been collected from primary sources, through direct observation and measurements on field. It has to be noted that LCI data here presented have been successfully submitted to ecoinvent for publication in their database (ecoinvent v.3.10), therefore undergoing a review process that confirmed their robustness and reliability [11]. For this reason, this study does not include a sensitivity analysis in the phase of results interpretation.

In particular, the coating process has been performed through the following equipment:

1) APS coatings using AG A300 gun (Plasma-Technik AG, Winterthur, Switzerland);
2) HVOF coatings using Diamond Jet Gun Model 2600DJM (Sulzer Metco, Westbury, NY, USA) with H2 as fuel;
3) CGS coatings using Kinetics 4000/34 system (CGT, Haun, Germany)

The inputs and outputs related to each phase have been measured and registered. In particular, during the deposition process, we carried out real-time measurements of energy consumption, gas emissions, and noise levels in the spraying booth, including CO2 and CO emissions, using the equipment listed in Ref. [13]. The WC-12Co feedstock powder dataset was obtained from the Ecoinvent database [28].

Tables 1–4 show the LCI of the four activities identified in section 2 (abrasive sandblasting, deposition by APS, deposition by HVOF and deposition by CGS). The column "Modeling data" indicates how the flow has been modeled in the software, considering the options available in the Ecoinvent database.

2.2.3. Life Cycle Impact Assessment

In phase 3, the Life Cycle Impact Assessment is performed. In order to assess the environmental impacts of the process described, the method ReCiPe2016 has been selected [29]. The impact categories analyzed in this method are shown in Table 5, and include 18 midpoint indicators and 3 endpoint indicators. This method has the advantage of capturing a broader set of impact categories compared to others (e.g., both CML-IA and TRACI 2.1 methods have 10 categories) and of presenting a global scope. In compliance with the ISO 14040 standard, the impact analysis with ReCiPe2016 includes two mandatory steps (classification and characterization) and may include optional elements (normalization, ranking, grouping and weighting). In this study, we report the results of classification and characterization: with the classification, flows from the LCI are assigned to the impact categories chosen, while in the characterization step these flows are multiplied by specific factors to calculate the global impact for each category. The study also includes the normalization step, which aims at simplifying the interpretation of results, comparing the impact for each category with a "normal" value to assess its relative dimension, also allowing comparisons between different categories [30].

The ReCiPe2016 method can be applied following three different perspectives: the individualistic perspective, "based on the short-term interest, impact types that are undisputed, and technological optimism with regard to human adaptation"; the hierarchist perspective, "based on scientific consensus with regard to the time frame and plausibility of impact mechanisms"; and the egalitarian perspective, which is "the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data is available" [31]. This study adopts the hierarchist perspective, which is considered the default one.

Finally, in phase 4 the results of the analysis are presented and discussed. A description of these results is provided in section 4.

2.3. Life Cycle Cost Analysis (LCCA)

The economic assessment of the three techniques presented has been conducted through an LCCA, with the aim of highlighting the main costs related to each solution and compare them from an economic perspective. The system boundaries are the same considered for the LCA.

The analysis is based on the calculation of the total cost referred to the system life cycle during a specific time period. In this case, the analysis is carried out for each of the three techniques, and all the costs included are referred to the use of the systems to provide 500 m^2 of coating per year, considering a time horizon (T) of 10 years. The coating area of 500 m^2 was hypothesized considering approximately 225 working days per year and a full working day of 8 h. As shown in Table 6, the CGS process using WC-Co as starting feedstock powder is the one that requires the most time to deposit 1 m^2 and for this reason, it was chosen as the maximum production limit. It is evident that APS and HVOF have a higher production rate due to the shorter time required to spray 1 m^2, but this approach allowed for a comparative analysis between the three processes, considering the same coated surface area.

The total cost per year (C_t) is calculated as the sum of acquisition costs ($C_{a,t}$) and operative costs ($C_{op,t}$):

$$C_t = C_{a,t} + C_{op,t}$$

In this study, acquisition costs include the purchase, installation and testing of the equipment used, and are attributed entirely to the first year. Operative costs include the annual expenses sustained to operate the system, calculated as follows:

$$C_{op,t} = C_{w,t} + C_{ent,t} + C_{mat,t} + C_{main,t}$$

where:

- $C_{w,t} = C_{wu} * h_t$: cost of workforce in year *t*, calculated as the salary per hour (C_{wu}) multiplied by the working time in year *t* (h_t);
- $C_{en,t} = C_{enu} * h_t * En_t$: cost of energy consumed in year *t*, calculated as the unitary cost of energy (C_{enu}) multiplied by the working time in year *t* (h_t) and the total energy consumed in year *t* (En_t);
- $C_{mat,t} = \sum_i (C_{mat,i} * Q_{i,t})$: cost of materials used in year *t*, calculated as the sum for all materials used of the unitary cost ($C_{mat,i}$) multiplied by the quantity of the material used in year *t* ($Q_{i,t}$);

Table 1
LCI of abrasive sandblasting. Functional unit: 1 m^2 coating.

	Material/energy flow	Modeling data	Unit	Amount
Input	electricity, medium voltage	market group for electricity, medium voltage	kWh	14.667
	compressed air, 600 kPa gauge	market for compressed air, 600 kPa gauge, RoW	m^3	81.73882
	compressed air, 600 kPa gauge	market for compressed air, 600 kPa gauge, Europe	m^3	33.26118
	aluminium oxide, non-metallurgical	market for aluminium oxide, non-metallurgical ROW	kg	0.855213
	aluminium oxide, non-metallurgical	market for aluminium oxide, non-metallurgical EU27 & EFTA	kg	0.144787
	steel, low-alloyed	market for steel, low-alloyed	kg	0.01
Output	inert waste	market for inert waste, RoW	kg	−0.78529
	inert waste	market for inert waste, Europe	kg	−0.22279
	inert waste	market for inert waste, CH	kg	−0.00192
	emissions CO_2		kg	0.0266
	emissions CO		kg	0
	noise		db	90

Table 2
LCI of APS process. Functional unit: 1 m2.

	Material/energy flow	Modeling data	Unit	Amount
Input	argon, liquid	market for argon, liquid	kg	30.57935
	WC-12Co powder	market for tungsten carbide powder	kg	1.8947
	electricity, medium voltage	market group for electricity, medium voltage	kWh	56.27
	Ar, liquid	market for argon, liquid	kg	6.441654
	H_2, liquid	market for hydrogen, liquid, RoW	kg	0.043495
	H_2, liquid	market for hydrogen, liquid, Europe	kg	0.009505
Output	hazardous waste, for underground deposit	market for hazardous waste, for underground deposit, RoW	kg	−0.089
	hazardous waste, for underground deposit	market for hazardous waste, for underground deposit, Europe	kg	−0.00573
	emissions CO_2		kg	0.0089
	emissions CO		kg	0
	noise		db	105

Table 3
LCI of HVOF process. Functional unit: 1 m^2.

	Material/energy flow	Modeling data	Unit	Amount
Input	WC-12Co powder	market for tungsten carbide powder	kg	1.818
	O_2, liquid	market for oxygen, liquid	kg	17.63277
	H_2, liquid	market for hydrogen, liquid, RoW	kg	2.793552
	compressed air, 800 kPa gauge	market for compressed air, 800 kPa gauge	m^3	18.17587
	electricity, medium voltage	market group for electricity, medium voltage	kWh	4.17
	O_2, liquid	market for oxygen, liquid	kg	4.838233
	H_2, liquid	market for hydrogen, liquid, Europe	kg	0.610448
	compressed air, 800 kPa gauge	market for compressed air, 800 kPa gauge	m^3	7.396128
Output	hazardous waste, for underground deposit	market for hazardous waste, for underground deposit, RoW	kg	−0.76859
	hazardous waste, for underground deposit	market for hazardous waste, for underground deposit, Europe	kg	−0.04951
	emissions CO_2		kg	0.0398
	emissions CO		kg	0
	noise		db	107

Table 4
LCI of CGS process. Functional unit: 1 m^2.

	Material/energy flow	Modeling data	Unit	Amount
Input	N_2, liquid	market for nitrogen, liquid, RoW	kg	245.099
	WC-12Co powder	market for tungsten carbide powder	kg	3.529
	N_2, liquid	market for nitrogen, liquid, Europe	kg	67.27803
	electricity, medium voltage	market group for electricity, medium voltage	kWh	8.88
Output	hazardous waste, for underground deposit	market for hazardous waste, for underground deposit, RoW	kg	−2.75182
	hazardous waste, for underground deposit	market for hazardous waste, for underground deposit, Europe	kg	−0.17725
	N_2		kg	312.377
	emissions CO_2		Kg	0.2159
	emissions CO		kg	0
	noise		db	103

- $C_{main,t}$: cost of maintenance in year *t*.

The life cycle cost (LCC) of the three options is calculated as follows:

$$LCC = \sum_{t=1}^{T} \frac{Ct}{(1+r)^t}$$

where, t is the year in which the cost occurs, r is the discount rate, which allows to consider the actual value of the money in the future. In this analysis, we assume a discount rate r = 2 %.

Cost data were obtained from supplier quotes and interviews with industry experts, and are summarized in Table 6. Data on the use of materials and energy are derived from the LCI presented in section 3.1.

3. Result and discussion

The results of the LCA and LCCA are summarized in the next sections.

Table 5
Midpoint and Endpoint indicators included in the ReCiPe2016 method.

Midpoint Indicators	Endpoint Indicators
Global warming	Damage to human health
Stratospheric ozone depletion	Damage to ecosystems
Ionizing radiation	Damage to resource availability
Ozone formation, Human health	
Fine particulate matter formation	
Ozone formation, Terrestrial ecosystems	
Terrestrial acidification	
Freshwater eutrophication	
Marine eutrophication	
Terrestrial ecotoxicity	
Freshwater ecotoxicity	
Marine ecotoxicity	
Human carcinogenic toxicity	
Human non-carcinogenic toxicity	
Land use	
Mineral resource scarcity	
Fossil resource scarcity	
Water consumption	

Table 6
Data used for the cost analysis.

	SAND BLASTING	APS	HVOF	CGS
Acquisition cost (C_a) [€]	15.000	340.000	340.000	450.000
Unitary cost of workforce (C_{wu}) [€/h]	12			
Operation time (h_t) [h/m2]	0,55	2,48	1,16	3,21
Unitary cost of energy (C_{enu}) [€/kWh]	0,43			
Unitary cost of materials ($C_{mat,i}$)				
Al_2O_3 [€/kg]	4			
WC-12Co Powders [€/kg]	140			
N_2 [€/kg]	0,43			
H_2 [€/kg]	11,25			
Ar [€/kg]	1,30			
O_2 [€/kg]	1,26			
Compressed Air [€/m^3]	0,21			
Maintenance cost per year ($C_{man,t}$) [€/y]	100	3.000	3.000	3.000

3.1. LCA: Interpretation of results

Table 7 summarizes the results of the characterization phase for the midpoint indicators of the ReCiPe2016 method. In this step, the environmental impact is quantified according to the impact categories selected. These results show that the CGS technique has higher

Table 7
LCA results, ReCiPe2016 midpoint indicators, characterization.

Damage category	Unit	APS	CGS	HVOF
Global warming	kg CO_2 eq	157,20	259,25	103,96
Stratospheric ozone depletion	kg CFC11 eq	$1{,}03*10^{-4}$	$1{,}56*10^{-4}$	$0{,}71*10^{-4}$
Ionizing radiation	kBq Co-60 eq	47,25	28,63	16,75
Ozone formation, Human health	kg NO_x eq	0,56	1,01	0,45
Fine particulate matter formation	kg PM2.5 eq	0,42	0,80	0,33
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0,56	1,02	0,45
Terrestrial acidification	kg SO_2 eq	1,60	2,80	1,35
Freshwater eutrophication	kg P eq	0,29	0,45	0,23
Marine eutrophication	kg N eq	0,08	0,14	0,07
Terrestrial ecotoxicity	kg 1,4-DCB	191,64	321,10	160,89
Freshwater ecotoxicity	kg 1,4-DCB	102,76	187,09	97,78
Marine ecotoxicity	kg 1,4-DCB	129,93	236,33	123,45
Human carcinogenic toxicity	kg 1,4-DCB	27,49	43,87	23,47
Human non-carcinogenic toxicity	kg 1,4-DCB	4190,55	7695,39	3967,86
Land use	m2a crop eq	25,61	26,14	14,78
Mineral resource scarcity	kg Cu eq	21,11	39,07	20,27
Fossil resource scarcity	kg oil eq	40,83	63,78	29,43
Water consumption	m^3	4,46	5,38	2,00

impacts for all categories, except for "ionizing radiation" for which the APS performs worse than the other two methods. Overall, HVOF results in lower impacts in all categories.

The following normalization step is useful to understand the relative importance of each impact assessed: in this case Fig. 3 highlights that the most impacted categories are by far "Freshwater ecotoxicity", "Marine ecotoxicity" and "Human carcinogenic toxicity", followed by "Freshwater eutrophication" and "Human non-carcinogenic toxicity". It is also evident that the CGS technique presents higher impacts for all these categories compared to APS and HVOF. This latter seems to have the better environmental performance according to the categories analyzed. To fully understand the meaning of the results and avoid interpretation misinterpretation, it is important to specify that in this particular case, the poorer indicators of the CGS depend on the intrinsic mechanical properties of the WC-Co starting feedstock powder. It is well-known that the ceramic material WC-Co is characterized by extremely high hardness, and consequently, high fragility and low ductility. As explained in the preceding paragraphs, it is evident that the formation of the coating using the CGS process relies on the plastic deformation of the powder particle rather than its melting, as in the case of the APS and HVOF processes. For this reason, the deposition efficiency of the three processes, calculated in Ref. [13], is significantly lower in the case of CGS. This lower deposition efficiency results in the use of nearly double the amount of starting powder, as well as a greater quantity of carrier gas to ensure the deposition of an acceptable thickness. The influence of deposition efficiency on the results of the LCA analysis had already been addressed in Ref. [17], with similar conclusions.

Considering the three Endpoint indicators, the values of the impacts classified in the three damage categories are summarized in Table 8, while Fig. 4 shows the results of the normalization step, highlighting that the most impacted category is "human health", while damage to ecosystems and to resource availability are far less impacted by all the three techniques analyzed. Finally, Fig. 5 summarizes the single score of the three methods obtained on the three endpoint indicators, showing once more that, while the overall impact of APS and HVOF is quite similar, CGS performs much worse than the other two techniques analyzed.

Looking at the contribution of the single activities and materials to the overall impacts of the techniques analyzed, the use of the WC-Co powder is the most impacting voice in all three cases. This is followed by the use of nitrogen and compressed air for the CGS, the use of oxygen, compressed air and electricity for HVOF, and the use of argon, electricity and compressed air for APS. As previously mentioned, the very high hardness of WC-Co starting feedstock powder results in lower particle deformation and in lower deposition efficiency for CGS and consequently, increased consumption of nitrogen as the carrier gas.

Lastly, a consideration on the "Global Warming" category, which is related to the Carbon Footprint of the three processes, is also necessary. Table 7 shows that this impact index is not the most critical aspect of the analysis performed. CGS remains the deposition process with the highest carbon footprint, primarily due to the use of a ceramic starting feedstock powder that is not easily deformable, followed by APS, which requires large quantities of electrical energy to generate the plasma. As the results of the normalization phase show (Fig. 4), the emissions of CO_2 equivalent of three processes are relatively neglectable compared to other impact categories, and for this reason eventual improvement strategies should include a broader environmental perspective.

3.2. LCCA results

Fig. 6 summarizes the results of the LCCA, showing the total life cycle cost of the three techniques over a 10 years period. The results include the sandblasting phase, which is present in all the three scenarios. A first consideration regards the strong prevalence of material costs for all the three techniques, which are comparable for APS and HVOF, amounting at about 1,5 million € in both cases, while become almost double for CGS (2,9 million €). This result is related to the higher quantity of WC-12Co powders used in the CGS

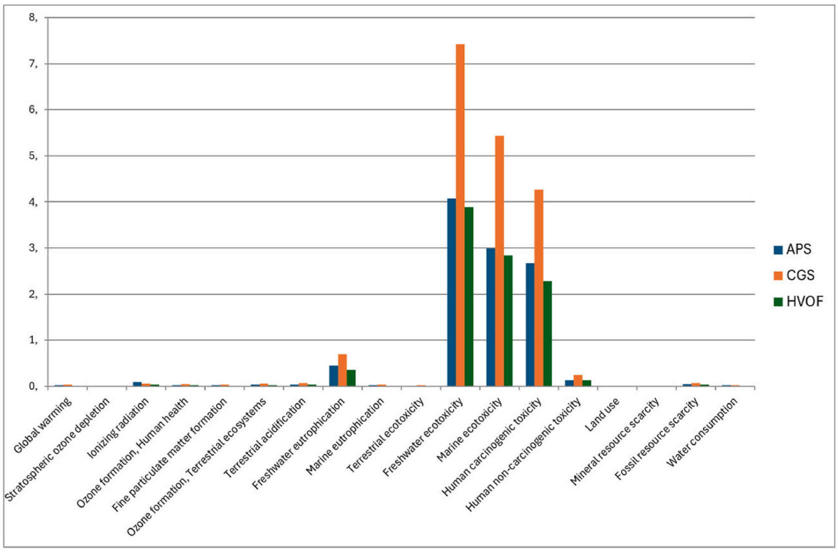

Fig. 3. LCA results, ReCiPe2016 midpoint indicators, normalization.

Table 8
LCA results, ReCiPe2016 endpoint indicators, Damage quantification.

Damage category	Unit	APS	CGS	HVOF
Human health	DALY	1,46*10^{-3}	2,65*10^{-3}	1,29*10^{-3}
Ecosystems	species.yr	1,40*10^{-6}	2,20*10^{-6}	1,02*10^{-6}
Resources	USD2013	13,33	22,31	12,09

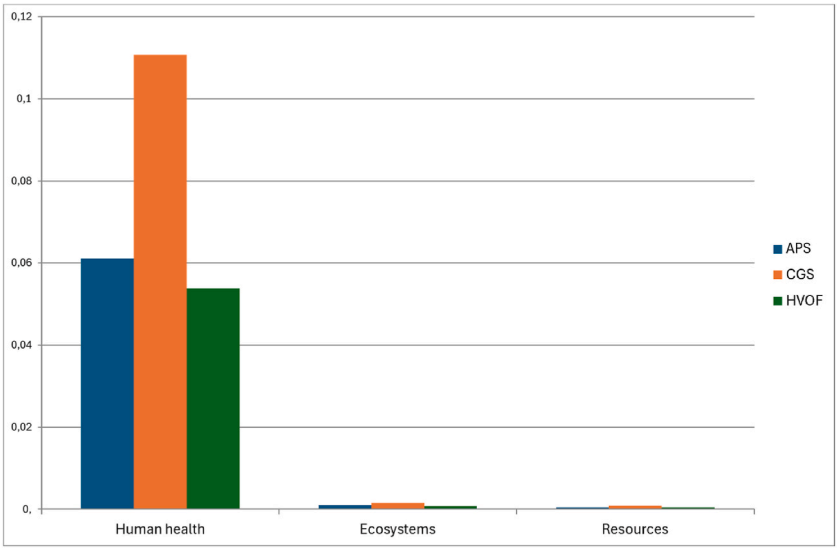

Fig. 4. LCA results, ReCiPe2016 endpoint indicators, normalization.

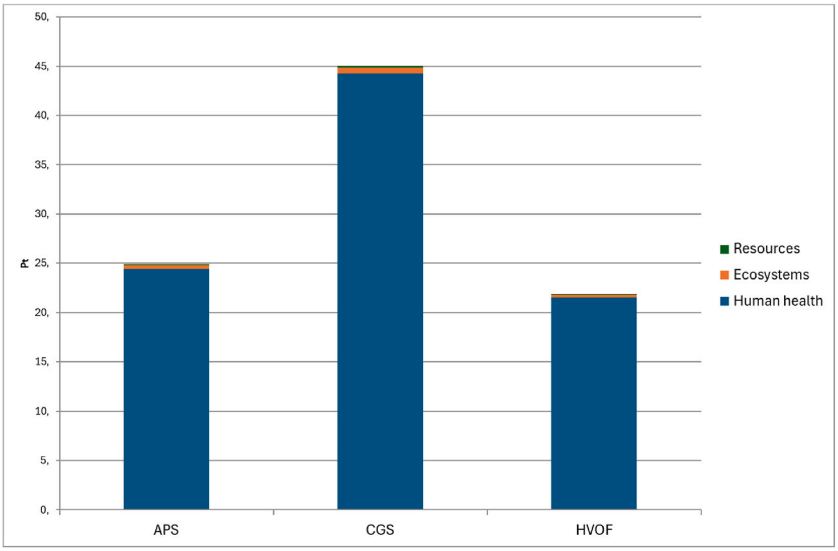

Fig. 5. LCA results, ReCiPe2016 endpoint indicators, single score.

method, which is about twice as the quantity used in the other two cases. Once again, because WC-Co starting feedstock powder is extremely hard and has low ductility, it undergoes minimal plastic deformation during CGS deposition, resulting in limited bonding between particles and the substrate. The low deformability of WC-Co powder stems from its intrinsic material properties, primarily its composition and microstructure. Tungsten carbide (WC) is an extremely hard and brittle ceramic material, while cobalt (Co) serves as a ductile binder phase. When combined to form WC-Co, the resulting composite exhibits a balance of hardness and toughness suitable for many industrial applications. However, it may not be the optimal choice for deposition using kinetic energy-based thermal spray

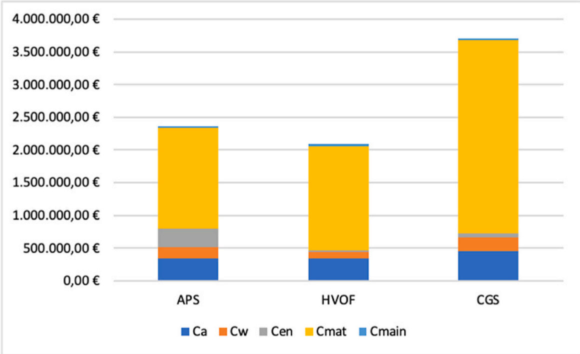

Fig. 6. LCCA results of the three techniques (10 years period).

processes rather than fusion-based methods. Considering the other costs, while acquisition and maintenance costs are quite similar in the three scenarios, workforce costs are lower for HVOF (about 92.000€) than for CGS and APS (about 200.000€ and 160.000€ respectively). Once again, this result can be justified by deposition efficiency, that is heavily affected by low deformability of WC-Co. The CGS deposition process requires longer processing times to achieve the desired thickness compared to HVOF and APS. This means that the operator must dedicate more time to the work. Another difference can be observed for the energy costs, which are considerably higher for APS (285.000€) than in the other two techniques (about 25.000€ for HVOF and 70.000€ for CGS). This is strictly related to the characteristics of the APS process. The high electricity consumption in the APS process can be attributed to plasma generation, plasma torch efficiency, and high gas flow rates. APS relies on the generation of a high-temperature plasma jet to heat and propel the coating material onto the substrate. Generating and sustaining this plasma requires significant electrical power. Additionally, plasma torches used in APS systems often have lower efficiency levels, leading to higher electricity consumption. Some of the electrical energy supplied to the torch may be lost as heat, reducing overall efficiency. Finally, the APS system requires a continuous flow of gases, such as argon, to stabilize and sustain the plasma jet. The high gas flow rates necessary for plasma stability contribute to increased electricity consumption, as compressors and other equipment must work harder to maintain the required flow rates. Electricity consumption is lower in the CGS and HVOF processes because their deposition mechanisms differ. In the CGS process, deposition is based on the plastic deformation of particles, while in the HVOF process, it relies on the combined action of velocity and temperature. Overall, the adoption of CGS results in a total life cycle cost increase of about 57 % compared to APS and about 77 % compared to HVOF.

4. Conclusions

The LCI data recollected in our previous work, and recently included in the ecoinvent database, lay a solid and firm foundation for a comprehensive cradle-to-gate LCA of three thermal spray processes, enabling the identification, quantification, and comparison of the environmental impacts of the APS, HVOF, and CGS processes using WC-Co as starting feedstock powder. Such an analysis not only illuminates the relative sustainability of these processes but also offers insights into opportunities for process optimization and environmental impact mitigation. The LCA analysis returned the worst indicators for the CGS, but to avoid misinterpreting these results, it is important to remember that they are closely related to the low deformability of WC-Co powder. This might represent a limitation of the present study, therefore, it could be extremely useful to repeat the analysis in the future using a starting feedstock powder for the CGS process with intrinsic mechanical properties more suited to a kinetic energy-based process rather than a fusion-based one, such as metallic powders instead of ceramic ones. Another possible limitation is related to the choice of the software for the LCA analysis: using SimaPro might generate some differences in the results of the environmental impacts compared to other software tools (e.g., Gabi), due to different characterization factors employed in different tools [29,32]. Finally, the present study focuses only on three thermal spray technologies, which have been directly performed and observed in laboratory, allowing access to primary data. Future research could also extend the analysis to other widely applied thermal spray technologies (such as High Velocity Air Fuel, HVAF).

Overall, this study provides the scientific community involved in the thermal spray field with information that was previously unavailable for the APS, HVOF, and CGS processes, such as electrical energy consumption and gas emissions. These insights can be utilized by industries that employ these processes on a large scale.

To resume and conclude:

- About electrical consumption, the APS process exhibits higher electrical consumption mainly due to its reliance on a plasma torch, which requires significant electrical power to generate high-temperature plasma for melting and depositing the coating material;
- Deposition efficiency has a clear and significant impact on the results of the LCA analysis and for this reason, the low deformability of WC-Co significantly affects the performance of the CGS process;
- The adoption of CGS results in a total LCC increase of about 60 % compared to APS and about 80 % compared to HVOF, using WC-Co as starting feedstock powder;

- All three processes exhibit relatively low CO_2 equivalent emissions, indicating that the direct impact on global warming from the operations is lower than impacts in other categories analyzed, such as freshwater ecotoxicity and human carcinogenic toxicity;
- In the future, it may be useful to perform the LCA and LCCA analysis of the CGS process again using a metallic starting feedstock powder that is more ductile and deformable than WC-Co;
- For practical applications when using ceramic particles, the authors recommend optimizing the deposition parameters (temperature, pressure, spray distance) of the CGS process.

Data availability statement

The authors confirm that the data used for the analysis in this study are available within the article.

CRediT authorship contribution statement

E. Rúa Ramirez: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Silvello:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **E. Torres Diaz:** Investigation, Formal analysis. **F. Tornese:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.G. Gnoni:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis. **I. Garcia Cano:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A. Furberg, R. Arvidsson, S. Molander, Environmental life cycle assessment of cemented carbide (WC-Co) production, J. Clean. Prod. 209 (2019) 1126–1138, https://doi.org/10.1016/j.jclepro.2018.10.272.
[2] X.T. Luo, C.X. Li, F.L. Shang, G.J. Yang, Y.Y. Wang, C.J. Li, WC-Co composite coating deposited by cold spraying of a core-shell-structured WC-Co powder, J. Therm. Spray Technol. 24 (2014) 100–107, https://doi.org/10.1007/s11666-014-0133-y.
[3] A.A. Tracton, Coatings Technology Handbook, Taylor & Francis, 2005.
[4] S. Tao, J. Yang, F. Shao, H. Zhao, X. Zhong, Y. Zhuang, et al., Atmospheric plasma sprayed thick thermal barrier coatings: microstructure, thermal shock behaviors and failure mechanism, Eng. Fail. Anal. 131 (2022), https://doi.org/10.1016/j.engfailanal.2021.105819.
[5] P.G. Lashmi, P.V. Ananthapadmanabhan, G. Unnikrishnan, S.T. Aruna, Present status and future prospects of plasma sprayed multilayered thermal barrier coating systems, J. Eur. Ceram. Soc. 40 (2020) 2731–2745, https://doi.org/10.1016/j.jeurceramsoc.2020.03.016.
[6] G. Ghosh, A. Sidpara, P.P. Bandyopadhyay, Fabrication of mechanically durable slippery surface on HVOF sprayed WC-Co coating, Surf. Coat. Technol. 394 (2020), https://doi.org/10.1016/j.surfcoat.2020.125886.
[7] L. Fedrizzi, S. Rossi, R. Cristel, P.L. Bonora, Corrosion and wear behaviour of HVOF cermet coatings used to replace hard chromium, Electrochim. Acta 49 (2004) 2803–2814, https://doi.org/10.1016/j.electacta.2004.01.043.
[8] P. Khatake, R. Taluja, M. Sunil Kumar, M. Mahendar Reddy, F.H. Al-Ataby, S. Sood, et al., Cold spray coating: a review of material systems and future perspectives, Mater Today Proc (2023), https://doi.org/10.1016/j.matpr.2023.11.015.
[9] S. Dosta, G. Bolelli, A. Candeli, L. Lusvarghi, I.G. Cano, J.M. Guilemany, Plastic deformation phenomena during cold spray impact of WC-Co particles onto metal substrates, Acta Mater. 124 (2017) 173–181, https://doi.org/10.1016/j.actamat.2016.11.010.
[10] H.J. Kim, C.H. Lee, S.Y. Hwang, Fabrication of WC-Co coatings by cold spray deposition, Surf. Coat. Technol. 191 (2005) 335–340, https://doi.org/10.1016/j.surfcoat.2004.04.058.
[11] Da Silva FS, Cinca N, Dosta S, Cano IG, Couto M, Guilemany JM, et al. Corrosion Behavior of WC-Co Coatings Deposited by Cold Gas Spray onto AA 7075-T6. n.d.
[12] L. Thakur, et al., Thermal Spray Coatings (2022), https://doi.org/10.1201/9781003213185.
[13] Ramirez E. Rúa, A. Silvello, Diaz E. Torres, R.F. Vaz, I.G. Cano, A comparative study of the life cycle inventory of thermally sprayed WC-12Co coatings, Metals (Basel) 14 (2024) 431, https://doi.org/10.3390/met14040431.
[14] J. Liu, L. Wang, F. Li, Y. Li, X. Ran, L. Kong, et al., Evaluation and improvement of the greenness of plasma spraying through life cycle assessment and grey relational analysis, Int. J. Life Cycle Assess. 26 (2021) 1586–1606, https://doi.org/10.1007/s11367-021-01910-4.
[15] A. Moign, A. Vardelle, N.J. Themelis, J.G. Legoux, Life cycle assessment of using powder and liquid precursors in plasma spraying: the case of yttria-stabilized zirconia, Surf. Coat. Technol. 205 (2010) 668–673, https://doi.org/10.1016/j.surfcoat.2010.07.015.
[16] G. Montavon, A. Vardelle, N. Krishnan, P. Ulloa, S. Costil, H. Liao, Life cycle assessment (LCA) of thermal-sprayed and chromium electroplated coatings, in: Thermal Spray 2006: Proceedings from the International Thermal Spray Conference, vol. 83669, ASM International, 2006, pp. 1399–1406, https://doi.org/10.31399/asm.cp.itsc2006p1399.
[17] A. Moign, A. Vardelle, J.G. Legoux, N.J. Themelis, LCA comparison of electroplating and other thermal spray processes. Proceedings of the International Thermal Spray Conference, 2009, pp. 1207–1212, https://doi.org/10.1361/cp2009itsc1207.
[18] M. Baranda, C. Mayo, R. Diaz, R. Rodriguez, F.J. Pérez, Comparative environmental assessment of coated ferritic steels suited to steam turbines of coal-fired supercritical and ultra-supercritical power plants, J. Clean. Prod. 443 (2024), https://doi.org/10.1016/j.jclepro.2024.141226.
[19] G. Darut, S. Dieu, B. Schnuriger, A. Vignes, M. Morgeneyer, F. Lezzier, et al., State of the art of particle emissions in thermal spraying and other high energy processes based on metal powders, J. Clean. Prod. 303 (2021), https://doi.org/10.1016/j.jclepro.2021.126952.
[20] A.M. Ferrari, L. Volpi, D. Settembre-Blundo, F.E. García-Muiña, Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment, J. Clean. Prod. 286 (2021), https://doi.org/10.1016/j.jclepro.2020.125314.
[21] Y. Xiong, K. Lau, X. Zhou, J.M. Schoenung, A streamlined life cycle assessment on the fabrication of WC-Co cermets, J. Clean. Prod. 16 (2008) 1118–1126, https://doi.org/10.1016/j.jclepro.2007.05.007.
[22] ISO 14044, Environmental Management-Life Cycle Assessment-Requirements and Guidelines. 2006, 2006.
[23] V. V. Sobolev Jmg and Jn. HIGH VELOCITY OXY-FUEL SPRAYING. 2004th ed. London: MANEY; n.d.

[24] Pierre L. Fauchais, V.R. Joachim, M.I.B. Heberlein, Thermal Spray Fundamentals from Powder to Part, 2014.
[25] P. Poza, M.Á. Garrido-Maneiro, Cold-sprayed coatings: microstructure, mechanical properties, and wear behaviour, Prog. Mater. Sci. 123 (2022), https://doi.org/10.1016/j.pmatsci.2021.100839.
[26] AENOR. (EX)UNE-EN_ISO_14040=2006. UNE-EN ISO 14040 2006.
[27] C. Pieragostini, M.C. Mussati, P. Aguirre, On process optimization considering LCA methodology, J. Environ. Manag. 96 (2012) 43–54, https://doi.org/10.1016/j.jenvman.2011.10.014.
[28] M.E. Ruiz, Documentation of Changes Implemented in the Ecoinvent Database V3, vol. 10, 2023, 12.14). n.d.
[29] M.A.J. Huijbregts, Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M. Vieira, et al., ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, Int. J. Life Cycle Assess. 22 (2017) 138–147, https://doi.org/10.1007/s11367-016-1246-y.
[30] Consoli F, Allen D, Boustead USAI, Jensen AA, Parrish R. Guidelines for Life-Cycle Assessment: A "Code of Practice." n.d.
[31] M.A.J. Huijbregts, Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M. Vieira, et al., ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, Int. J. Life Cycle Assess. 22 (2017) 138–147, https://doi.org/10.1007/s11367-016-1246-y.
[32] R. Speck, S. Selke, R. Auras, J. Fitzsimmons, Life cycle assessment software: selection can impact results, J. Ind. Ecol. 20 (2016) 18–28, https://doi.org/10.1111/jiec.12245.