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Environmental analysis of the powder metallurgy value chain: a methodology for comparison with conventional manufacturing

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Abstract

Powder metallurgy (PM) includes a strong diversity of industrial processes such as press and sintering, near-net shape and additive manufacturing to produce metallic parts. Due to limited losses, these processes are known as promising environmental solutions compared to conventional manufacturing processes such as machining, forging or casting. By offering more integrated, flexible and adapted processes, PM promises an optimization of raw material resources along its value chain while improving energy efficiency on the manufactured parts life cycles. Our work done in the framework of H2020 SUPREME project, uses Life Cycle Assessment methodology and eco-design approaches to evaluate the environmental performances of different steps of the PM value chain, compared to traditional manufacturing value chain. The application fields analyzed are automotive, medical, cutting tools, molding tools and aeronautics. With our methodology, we are aiming at identifying environmental challenges and opportunities for PM, from mining operation and powder production to part manufacturing.

Key Words

Life Cycle Assessment, Powder metallurgy, Additive Manufacturing, Near Net Shape processes, Environment, Sustainability, Eco-design, Eco-innovation, Value Chain.

1. Introduction and context : environmental challenges of powder metallurgy value chain

Powder Metallurgy (PM) is defined as the art and science of producing metal powder and making semi-finished and finished parts and objects, from individual, mixed or alloyed powders with or without the addition of nonmetallic constituents [1]. The powder metallurgy technological value chain includes processes related to minerals and metals extraction, powder production and finally parts manufacturing. Parts manufacturing in PM includes a large diversity of industrial processes such as press and sintering, near-net shape and additive manufacturing [2]. Compared to traditional processes, such as machining, casting or forging, PM processes can limit raw material and energy consumption due to limited material losses and energy optimization during manufacturing [3,4]. Powder metallurgy enables as well a reduction of the number of process steps compared to other conventional manufacturing methods. Therefore, it can allow, more modularity for the production of complex and specific parts, while reducing environmental impacts due to material processing and transports between each processing steps [5,1]. However, for several processes of the technological PM value chain, there is a strong challenge for reaching better environmental performances to make PM processes competitive compared to the traditional ones; and reduce their environmental burden [6,7,8].

The first link of the PM value chain is mineral processing for the production of metals which will be used for powder production. Mineral processing separates minerals extracted from the mine into at least two products: valuable minerals present in the concentrates and invaluable particles in the tailings. These processes are water and energy consuming and environmental challenges are high for this link in the PM value chain [9,10].

For the second link of the PM value chain (metal powder production), environmental issues are dependent of the type of chosen process. For gas atomization, issues in literature are mainly related to energy and gas consumption [11], whereas for water atomization and milling processes, issues related to raw material consumption and energy are most commonly raised [11,12].

Finally, for the last link in the PM value chain (part manufacturing by additive manufacturing techniques or near net shape processes), there is today a real challenge in reaching better yield and better technical performances while enhancing energy efficiency, and raw material consumption to

make these PM advanced manufacturing processes competitive and interesting from an environmental point of view compared to conventional manufacturing [8,13,14].

The work presented in this paper is done in the context of the SUPREME H2020 project. The SUPREME project aims at regrouping key stakeholders of steel powder metallurgy, including industrials from mineral extraction, powder production and parts manufacturing, to obtain a sustainable Powder Metallurgy Value Chain (PMVC) and tackle the main environmental issues above mentioned. So far, eco-design and eco-innovative approaches for an environmental optimization of technological value chains have been used in a limited way for powder metallurgy applications. Most of the times, these approaches focus on a single link in the PM value chain, usually parts manufacturing or only on one or two aspects of sustainability such as energy or material consumption [7,15]. Moreover, these techniques or approaches do not integrate a global vision of the PMVC in comparison with conventional manufacturing [16].

Our work aims at providing a global environmental analysis of the SUPREME powder metallurgy value chain for a comparison with conventional manufacturing. The final objective is the identification of environmental hotspots along the SUPREME value chain. This will help to understand the interconnexions between PMVC processes in terms of process parameters that can have an influence on the final environmental impacts of the PM parts produced for automotive, medical, aeronautic, cutting and molding applications. A complete eco-design methodology, based on Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Environmental Value Chain Analysis (EVCA), has been developed in the framework of this project and is presented in this paper in section 2. Section 3 presents the first results obtained with the application of this methodology and finally, section 4 concludes on the interest of the approach for environmental analysis of PM value chain and opens some perspectives.

2. Environmental evaluation of SUPREME Powder Metallurgy value chain : Methodology

In order to ensure the relevance of the work realized in SUPREME for process environmental optimization, the project is monitored by a set of Key Performance Indicators (KPIs) applied to each production route (from mineral extraction, to part manufacturing). Three types of environmental KPIs are defined for the project: KPIs related to CO₂ emissions, to energy consumption and to resources consumption (raw materials and water).

The calculation of KPIs is supported by an eco-design methodology developed within the framework of the project. This methodology aims at facilitating environmental evaluation and KPI calculation of the SUPREME PM value chain, involving all partners in the project. It is a four-step methodology based on 1) value chain mapping, 2) environmental data collection, 3) processes modelling and 4) environmental evaluation, using Life Cycle Analysis approach. The four steps are described precisely in the following paragraphs.

2.1 Step 1 : SUPREME value chain mapping

Mapping a value chain aims at giving a graphic representation of the identified chain actors and processes. It is the first step of a VCA (Value Chain Analysis) [17,18]. The goal of this step is to provide an overview of all SUPREME value chain processes using material and product flows and their interactions. A total of 38 processes are analysed in the context of SUPREME, covering the SUPREMEPM value chain from metal and mineral production to metal parts manufacturing as well as conventional manufacturing. The method used for value chain mapping is product focused [17]: a functional unit is defined at each process step of the chain (e.g. 1 kg of 316L powder produced for gas atomization step, 1 automotive engine bracket part produced for Laser Powder Bed Fusion (LPBF) process...). The processes are then linked and grouped to each other in an illustrative map, according to three criteria:

- The main steps of the value chain (Metal production, Powder production or Parts manufacturing);
- The material and product interactions;
- And the application area (marine, automotive, aeronautics, moulding, cutting tools, medical).

Figure 1 presents this map and the main PM and conventional processes studied in SUPREME for environmental evaluation.

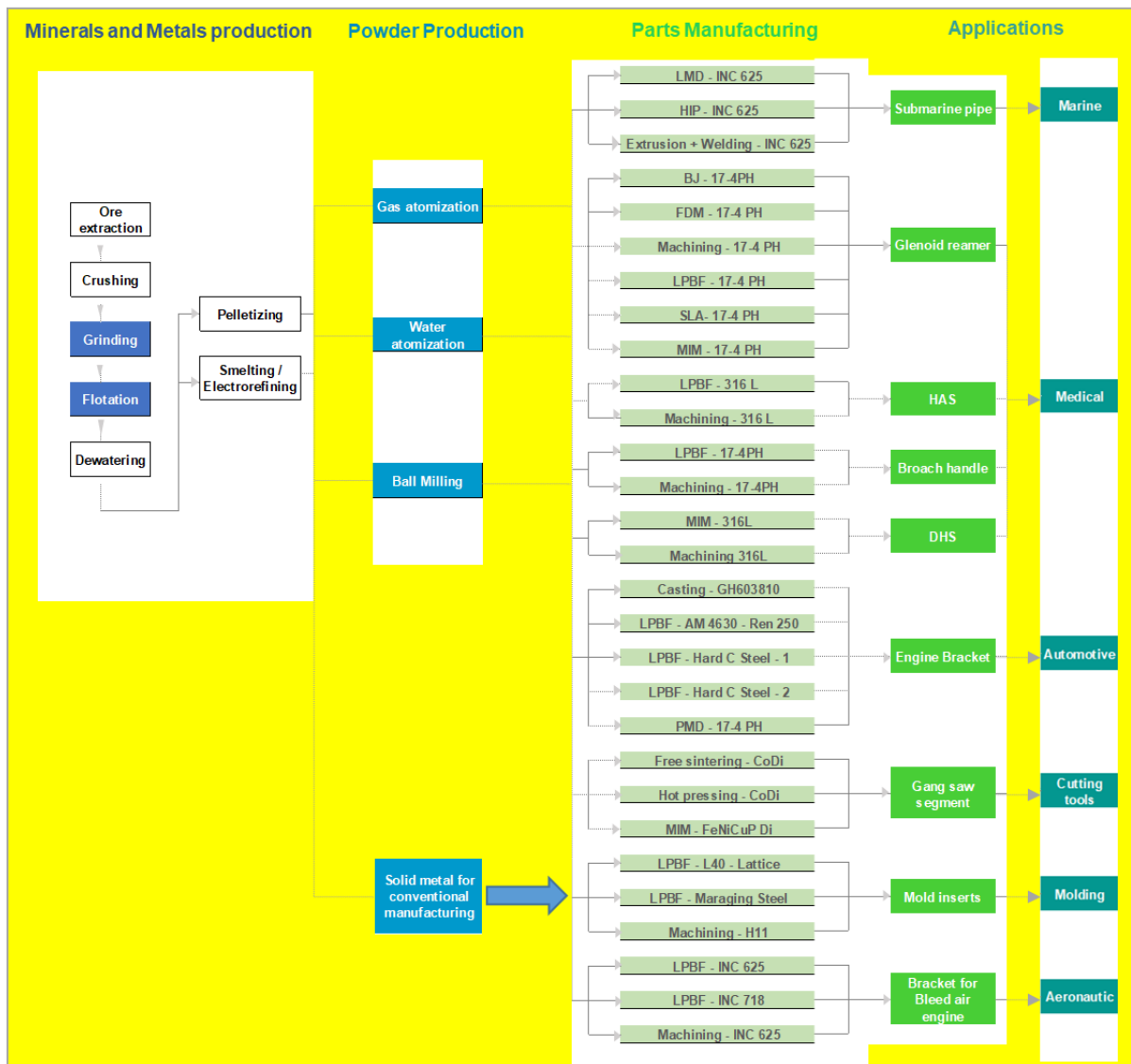


Figure 1: Overview of the SUPREME value chain, realized with VCA mapping technique. (LMD= Laser Metal Deposition, HIP= Hot Isostatic Pressing, BJ = Binder Jetting, FDM = Fused Deposition Modelling, LPBF= Laser Power Bed Fusion, SLA= Stereo lithography, MIM = Metal Injection Moulding, PMD= Powder Metal Deposition)

2.2 Step 2: Data collection for environmental evaluation

For the environmental evaluation of SUPREME processes and value chain, a set of measurable parameters is identified for each of the 38 processes. These parameters correspond to the inflows and outflows going through the processes (energy, materials, water, emissions in air, wastes...). The identification and quantification of these parameters is done using Material Flow Analysis techniques [19] and using three different data sources:

1. Technical sensors implemented on SUPREME demonstrators processes allowing online measurements;
2. Industrial existing knowledge (bills, existing sensors, internal report, audits...);
3. Information found in literature and environmental databases such as Ecoinvent [20] or ELCD database.

Once the parameters are collected, a data processing and analysis has been carried out in two steps to calculate the selected project KPIs and environmental evaluation (Figure 2).

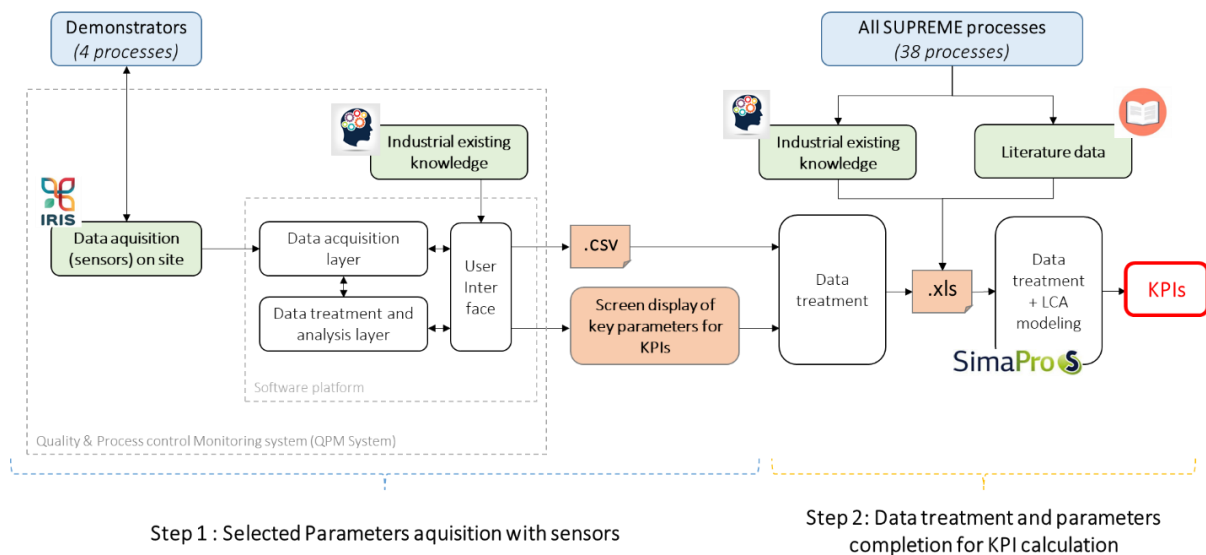


Figure 2: Methodology for environmental data collection in SUPREME project

A Quality Process Management (QPM) system designed in the project links a software platform with sensors directly installed on four demonstration sites. The software platform combines a data acquisition layer, a data processing and analysis layer with a user interface. Data, such as energy, water or gas consumptions is automatically collected through sensors. Once data collected, the data processing layer is able to display a set of key parameters useful for KPI calculation and environmental evaluation. Generated.csv files are then analyzed by industrial partners and environmental analysts in the project (Step 1 – Figure 2).

Finally, environmental analysts use then the data measured by sensors on site and complete them with industrial knowledge and literature data to be able to proceed to the next steps of environmental evaluation and KPI calculation (Step 2 – Figure 2).

2.3 Process modelling for environmental evaluation

Before starting environmental evaluation, processes diagrams for the 38 processes under study were drawn in a schematic representation. These processes diagrams aim at giving a visual representation of the input and output flows used for each step of the SUPREME processes (materials, energy, water, emissions, wastes...) for the environmental analyst. It gives a clear picture of the technical systems boundaries to be include in the environmental evaluation of the SUPREME processes.

2.4 Environmental evaluation methodology

The environmental evaluation is then realized using Life Cycle Analysis (LCA) methodology [21]. A functional unit has been defined for each process under analysis, taking into consideration functional units' consistency along the SUPREME value chain. This aims at enabling environmental comparisons between two or more processes and makes possible the evaluation of the impacts of process optimization along the entire value chain. The SimaPro Software V8 with Ecoinvent V3.2 database (system model 'allocation, recycled content') is used for LCA modeling. The LCA results are obtained using the ILCD 2011 Midpoint method, released by the European Commission, Joint research Center in 2012 [22]. This Life Cycle Impact Assessment method includes 16 environmental impact categories such as, "Climate change (kg CO₂ eq.)" which will be presented in this article. The various process flow charts realized in 2.3 were modeled on the LCA software to obtain the environmental assessment results. Other Key Performances Indicators are calculated, using data from process MFA, such as direct Energy Consumption (kWh), Raw Material Consumption (T or kg) or Water Consumption (L).

3. Results

Results on Minerals and Metals production: Grinding process

The optimization of the grinding operation in the mineral processing phase was conducted in the LKAB's Kiruna iron ore plant, where the ore is crushed and ground before concentrating and pelletizing. The environmental optimization of the grinding process is based on advanced controls (Model Predictive Controller) and sensors, such as grinding mill volumetric charge analyzer and

optical slurry particle size analyzer along with the conventional power and flow meters. The aim is to improve energy efficiency with a better stability of the grinding mill charge and product particle size. Thanks to the previous methodology described in section 2, environmental evaluation was conducted on the process to assess the environmental improvements in terms of raw material consumption, energy and water consumption and CO₂ emissions for this process. The process optimization allowed a reduction of 2.4% of CO₂ emissions for the process, 3.3% of resources consumption, 4.1 % of water consumption and 1.2% of energy consumption for the production of 1T of concentrate. Other environmental indicators from ILCD are available for further measurements of improvements.

Results on Powder production step: Gas Atomization and Ball Milling processes

First results for environmental optimization in SUPREME on metallic powder production steps are the following, at this stage of the project:

- reduction of 32% of CO₂ emissions for the Ball Milling process in the powder production step;
- reduction of 4% of N₂ consumption for Gas Atomization;
- improvement of 90% for the Gas Atomization yield;
- improvement of 23% for the Ball Milling yield.

Figure 3 presents the main environmental improvements calculated thanks to the previously described eco-design methodology on Ball Milling SUPREME process. KPI related to climate change and to resource, water, N₂ and energy consumptions for this process are presented.

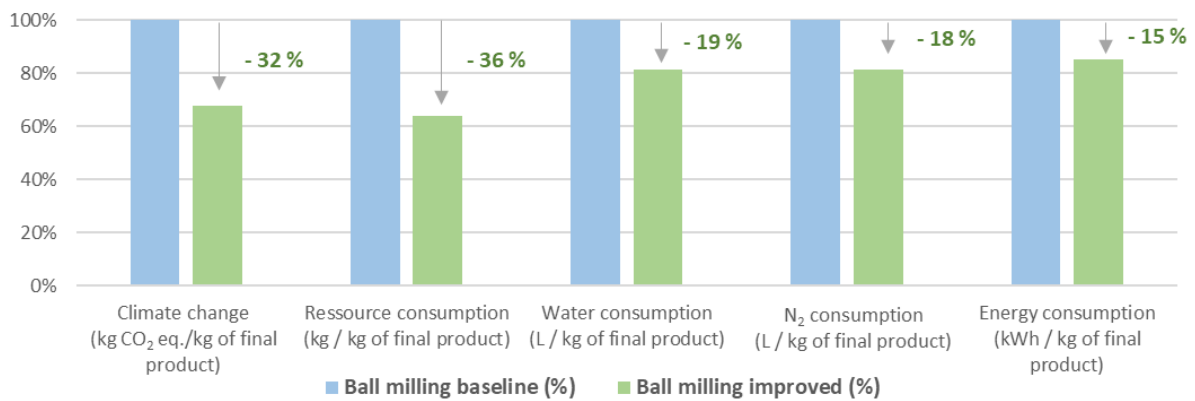


Figure 3: Results on environmental optimization of Ball Milling process of a Fe-based powder

Results on Parts manufacturing step: Laser Power Bed Fusion (LPBF) process

Preliminary results are available for the project regarding the influence of powder recycling and argon consumption optimisation for LPBF process, on the impact on climate change environmental indicator (kg CO₂ eq. / part manufactured). With a 30% optimization of argon consumption and 100% powder recycling, LPBF process can reduce its impact on climate change by 72% compared to no powder recycling and no argon optimization baseline (Figure 4). These tests have been realized on a 0.03 kg part, manufactured within 316L steel powder and will be consolidated with the further data collection in the project.

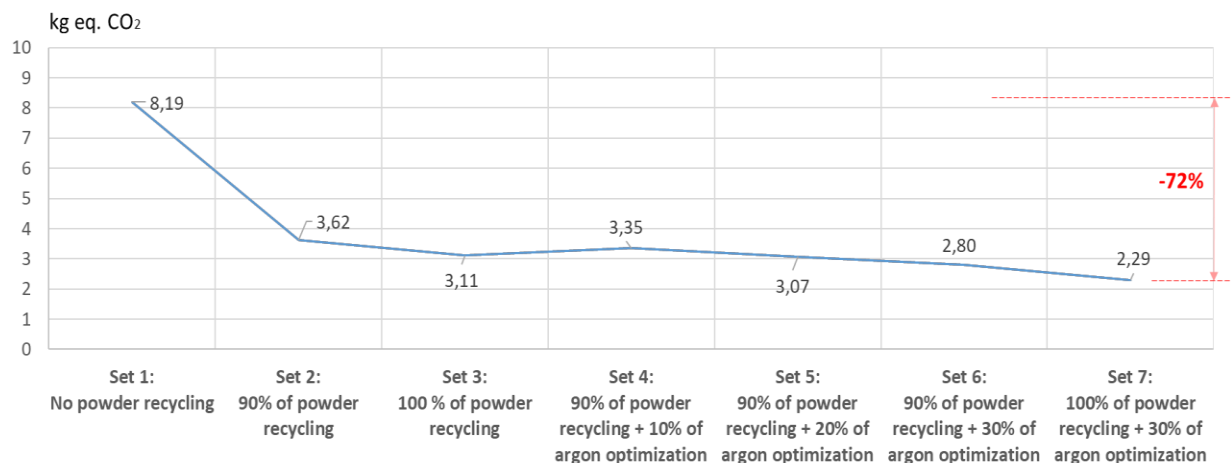


Figure 4: Results of sensitivity analysis on powder recycling and argon optimization - Contribution to Climate change for a 0.03 kg part manufactured in 316L with LPBF process

4. Conclusions and perspectives

This paper presents a methodology for environmental evaluation of powder metallurgy value chain from an eco-design and eco-innovation perspective. This methodology is based on Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Environmental Value Chain Analysis (EVCA) techniques. It is currently tested and applied in the context of H2020 SUPREME project. This methodology allows the environmental assessment of 38 processes from metal production to part manufacturing, including additive manufacturing, near net shape processes and conventional manufacturing processes. Current results show how the application of the methodology allows the calculation of environmental Key Performance Indicators (KPIs) for monitoring the environmental improvements resulting from process optimization, made by stakeholders of the PM value chain. First results on Grinding, Gas atomization, Ball Milling and Laser Powder Bed Fusion processes are available and show the potential for environmental improvements and performance in the PM value chain. Further results are expected for the project to compare environmental impacts of PM processes with conventional manufacturing.

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