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Procedia CIRP 136 (2025) 677–682

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Recycled powders: an Eco-Design approach for Laser-Powder Bed Fusion

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Abstract

Additive manufacturing processes could reduce environmental impacts by optimizing the material distribution and achieving lightweight products. The sustainability of the additive processes can be further improved by using recycling methods. The most used practices are reusing metal powders for multiple builds and recycling components throughout the additive manufacturing process to make recycled powders. This paper addresses the current state of the art recycling practices regarding the use of metal powders in Laser-Powder Bed Fusion process propose an approach to consider the environmental impact of the product during the design phase. The approach considers a mix of virgin, reused, and recycled powders as the material input. The design optimization workflow and Life Cycle Assessment provide useful tools to achieve feasible and sustainable solutions.

Keywords: Laser-Powder Bed Fusion; L-PBF; Recycled powders; DfAM

1. Introduction

Additive Manufacturing (AM) enables designers to create products free of the typical constraints of Conventional Manufacturing by adding materials layer by layer. This presents an opportunity for the designers to maximize the efficiency of the product: it can reduce its weight by the usage of lattice structures; it can create a new kind of product, which replaces assembly parts by incorporating them in one single unit; it can optimize the geometry by adding material only where is needed; in some cases, it can incorporate multiple materials in the same build.

Manufacturing companies have a substantial role in attaining 2030 climate targets regarding the reduction of greenhouse gas emissions due to their impact on the environment. This entails the need to improve process sustainability by finding new and different ways to lessen waste and energy consumption.

By their nature, AM processes reduce the waste of material, thereby defining a more sustainable way of creating objects [1]. Intrinsically, the 3D printing process is very environmentally friendly, most of the emissions occur during the preprocessing and post-processing phases [2]. The most used way to lessen the environmental impact is to work on the treatment of raw materials, which is mainly done by reusing and recycling techniques. Diminishing the environmental impact presents a challenge because the different quality of the starting material has a strong impact on the end-item mechanical properties, therefore, it needs to be considered in the design phase along with all the other choice parameters. Current Design for Additive Manufacturing (DfAM) practices enable designers to assess the high number of parameters that contribute to the component mechanical properties once the technology at use has been defined. In the case of Laser-Powder Bed Fusion for metal (L-PBF-M), DfAM techniques can assist designers to: optimize the product geometry, decide the geometrical and process parameters such as layer thickness, build orientation, laser power and many more to ensure the feasibility of the artefact [3]. The current state of the art seems to propose DfAM methods that don't account for environmental impact in the design phase.

This paper aims to fill the current lack in literature by proposing a method to consider the environmental aspects in

10.1016/j.procir.2025.08.116

design practices focusing on Laser-Powder Bed Fusion, which is one of the most used processes for metal alloys.

2. State of the art

DfAM refers to specialized approaches that focus on optimizing geometry specifically for AM processes, by considering the technology's opportunities and constraints during the design phase, by following the principles of integrated design, individualization, lightweight design and efficient design [4]. DfAM methods often use optimization methods such as Generative Design [5], Topology Optimization [6], and Genetic Algorithms to obtain the final design [7]. How DfAM methods operate and constrain the CAD geometry is defined via software through a set of rules defined by the experience in the process under consideration, therefore the knowhow on possible limits of the design optimization is highly dependent on the company, mainly due to differences in the production process, machinery and materials.

Examples of DfAM guidelines based on previous experiments are minimum wall thickness of 0.5 mm, minimum embossed or engraved details of 0.1 mm, horizontal bridges of 2 mm, considering the L-PBF process [8]

The optimization objectives can be multiple and usually, they result in conflicting needs concerning the component's geometry.

One factor often neglected at the design stage is the environmental impact of the component, which often can only be evaluated after manufacturing completion.

The methodology commonly used to calculate the environmental impact of processes or components is the Life Cycle Assessment (LCA). In the case of AM processes, the majority of LCA studies find themself in agreement that the most impacting factors are material consumption and energy consumption [9], factors that strongly depend on the component geometry and the printer parameters. Material consumption is very impactful due to the high energy demand for powder atomization to obtain powders that fit the requirements. The high energy consumption is attributable mainly to post-processing and laser process parameters.

DfAM optimization methods and constraints focus mainly on the feasibility of the product from a mechanical point of view, oversighting the environmental impact. On the other hand, Life Cycle Assessment (LCA) studies account for the ecological issues without keeping in mind the product mechanical properties, thereby they are used as additional information of the products which they refer and not as an integrated part of the designing process.

The support these methods provide to designers, when they are used individually, is insufficient to clearly determine the optimal product solution and consequently diminishing the advantages of adopting AM processes instead of Common Manufacturing (CM). During the design phase, the designer considers a lot of variables that contribute to the properties of the product. To help designers in making the right and informed choices, DfAM techniques and tools should be improved by considering LCA and cost assessment results.

The LCA of AM processes shows that most of the emissions are made during the feedstock material production and post-processing phases of AM processes. Finding the real environmental impact of the products may be done by using predictions ex-ante and confronting the predicting values with real monitored data ex-post. Results are vastly altered by the real path of the items involved in all the life phases of the product and by the process parameters chosen by the operator, consequently the variability of the data must be taken into consideration. Besides, numeric information about LCA results is scarce [10], and sometimes in conflict between different studies. Therefore, further studies to obtain more precise results are required in order to support the robustness of ex-ante predictions and to create models to easily calculate the environmental impact at the early design phases.

Moreover, it's preferable to use a "cradle to grave" approach than a "cradle to gate" in order to provide results that consider the effect of recycling practices.

In the case of L-PBF-M the feedstock material production step involves the production of powders that meets the technical specifications needed for the 3D printer at use. Moreover, most of the printed parts require post-processing such as thermal treatment and surface finishing. All the process phases have an influence on the product's final properties. Defining the correct parameters early in the process helps in reducing production waste by diminishing the defective parts and focusing the research on the most impactful areas can improve the overall result.

Since powders are the starting material of printing process, their quality impacts all the phases that happen next and therefore needs to be assured. The ways to characterize feedstock material are described in ISO/ASTM 52907 and test methods appropriate to ensure customer requirements are agreed with the supplier at the time of the sale. [11]

Powder characteristics are examined from a sample representative of the powder lot to analyze the following parameters:

- Chemical Composition
- Particle Size Distribution (PSD)
- Characteristic densities
- Morphology
- Flowability
- Contamination

Studies have shown that powder properties strongly affect the printing phase and consequently they impact the build feasibility [12]. Besides, the final product properties are altered by other classes of parameters, such as: design parameters, which are defined during the constitution of the CAD virtual model; and process parameters, usually provided by the 3D printer's constructor. Therefore, the high number of parameters [11] involved in the production of 3D parts requires the use of software able to consider them all and methods to streamline the designing phase.

The most used approaches to be more environmentally friendly in L-PBF-M are the reuse of virgin powders for multiple builds, after printing the first one, and the recycling of scraps, waste, and products at the end of life. The first approach is the most studied since it is easy to implement and very cost effective, especially if the component has a lightweight design. The second approach needs cooperation between multiple entities of the supply chain and therefore it is harder to realize but could yield more impact on the overall LCA analysis of the product and the Carbon Footprint of the process.

2.1. Powder reuse

The expression “powder reuse”, or sometimes “powder recycle” refers to the operation of retrieving the powder particles unfused during the L-PBF-M process and reusing them for the setup of the following print. The powders that participate in the print suffer from deterioration, even if they are not involved in the melted geometry, hence they need to be checked to guarantee conformity with printing quality specification. The possible deterioration happens mainly by three phenomena: the degradation due to laser sputter, the near-melt zone region of the powder bed and the foreign element contamination [13]. The effect of powder reuse differs significantly depending on the material, the 3D printer used and the process parameters [14] and therefore involves a high number of variables. Current practice [14] is to sieve the powders after their use, reuse them and fill the tank of the printer with virgin powder, this enables to lower the cost and the waste of material (table 1 shows the current price of metal powders).

Table 1. Cost and environmental impact of the most commonly used alloys for L-PBF-M [16]

Material (virgin powder)	Cost (€/kg)	Energy Consumption (kWh/kg)	CO_2-equ Emissions (kg CO_2/kg)
Ti6Al4v	200 - 500	140 – 300	10–40
AlSi10Mg	50 - 150	30 – 60	15–35
Inconel 718	80 - 200	120 – 200	8–12
Stainless steel 316L	50 - 120	50 - 100	4–8

The powder supplier usually provides a maximum number of cycles to reuse powder until it complies no more with specification. The factor limiting more reusing seems to be element contamination such as oxidization [17], which effects mechanical properties of the component and the powder melting process, and morphology deterioration, which diminishes flowability, hence spread ability, and therefore makes the obtained layer thickness uneven [14].

2.2. Recycling practices

Recycling practices are a much more complex issue in the context of L-PBF-M than the reuse of powder. They consist in recovering the material from other objects to produce the feedstock material for AM process. Since the route of the materials involved may vary due to the state of the object entering the recycling process, AM recycling proceedings may be classified according to the starting material origin (see figure 1). To produce powder ready to be feedstock it needs to be a production step of powder atomization, in which the starting material (usually in the form of billet or rod) is converted into powder of the right size and correct specification. To recycle the material efficiently it needs to be efficient to convert the recycled input into material ready for atomization. It is also very important that the input material meets the element percentage imposed by the specifications.

In this context, it appears advantageous to adopt the recycling of components initially produced by AM practices at the end of their life cycle, components which provide insurance in terms of quality of the chemical composition.

The same argument can be applied at parts that fail during the print and supports that are truncated after powder removal, the same composition of the metal alloy certifies that the powder produced in that way are suitable for recycling.

One other area in which recycling can be optimal is the use of waste chips from machining. Coupling AM practices with machining can have huge environmental benefits for the impact of both processes. In this instance stricter tests are required to ensure that the flakes composition is acceptable due to the oxidization that happens during the removal process.

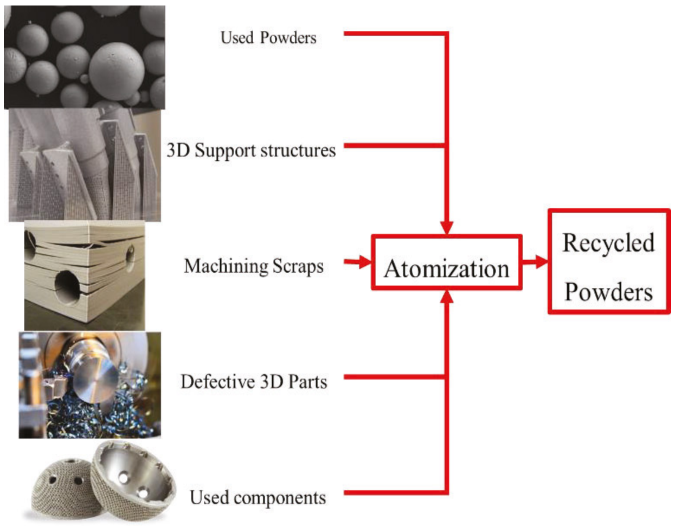

Fig. 1. Examples of components to be recycled in the L-PBF supply chain

From an environmental perspective, the most interesting alloy to recycle is aluminum due to the high energy consumption during the primary aluminum ingot production by electrolysis from alumina [19]. This process step that can be passed by adopting recycling practices such as recovering the material from a later stage of the component life, grinding it and providing feedstock for atomization. A study conducted by M. Coşkun et al [20] shows that specimens produced by L-PBF recycled AlSi10Mg powder present a slight decrease in yield strength and comparable values for ultimate tensile strength when compared to their virgin powder counterparts. Recycle effects on mechanical properties depend on a high number of variable and needs to be studied further to have a better understanding of the correlations with the design parameters and process parameters.

3. Method

Considering the effects of recycling in the design process, it may be useful to get an assessment of the ecological impact of the product before its manufacturing. This requires conciliating the current DfAM techniques with some elements of EcoDesign thus defining a method to streamline the designing process while examining those two different aspects that have different main objectives.

A way of integrating the environmental impact in the current way of designing a component to be printed may be using validation or iteration loops to update in an integrable way the software to accommodate the designer choices regarding ecological issues.

The proposed method (Figure 2) can be easily implemented by current DfAM methods and provides designers with an easy to achieve approach to consider environmental issues, provided that the factors for the optimization process and the LCA are known. The method focuses on using a sustainable powder mix, combining different percentages of virgin, reused, and recycled metal powders.

DfAM methods generally are constituted by several steps in which the proposed model is evaluated and optimized. In this instance it has been considered an optimization DfAM method in which a design proposal is optimized considering both geometric and process parameters. Since the design proposal acts as a starting point for the optimization sequence, the method works best in the hands of an experienced designer. To make a solid starting point, the proposed design needs to follow common preliminary sizing practices of the component considering loads under operating conditions. Also, it's fundamental that the starting proposal for the design is valid and coherent with DfAM guidelines, otherwise the optimization executed by the software might yield unexpected results. If the data is sufficient, the designer can decide to propose from the start the use of recycled powders and reused powders, or a mixture of the two ecological choices with virgin powders. In order to guarantee the possibility of using reused or recycled powders without compromising the end result designing choices need to be supported by testing campaigns, thereby providing more solidity to the data on which the decisions are derived. A Material Database collects the mechanical properties of the powder mix.

Machine parameters are usually suggested by the printer constructor in the form of ranges or specific targets depending on the parameter and the selected material. In this instance, testing campaigns are useful to explore possible parameters combination to identify better solutions for the use of ecological powders due to the fact that data may be unavailable. Due to the high quantity of variables, testing campaigns need to be programmed thoroughly, simulated previously, and carried out in order to have useful results. For example, some

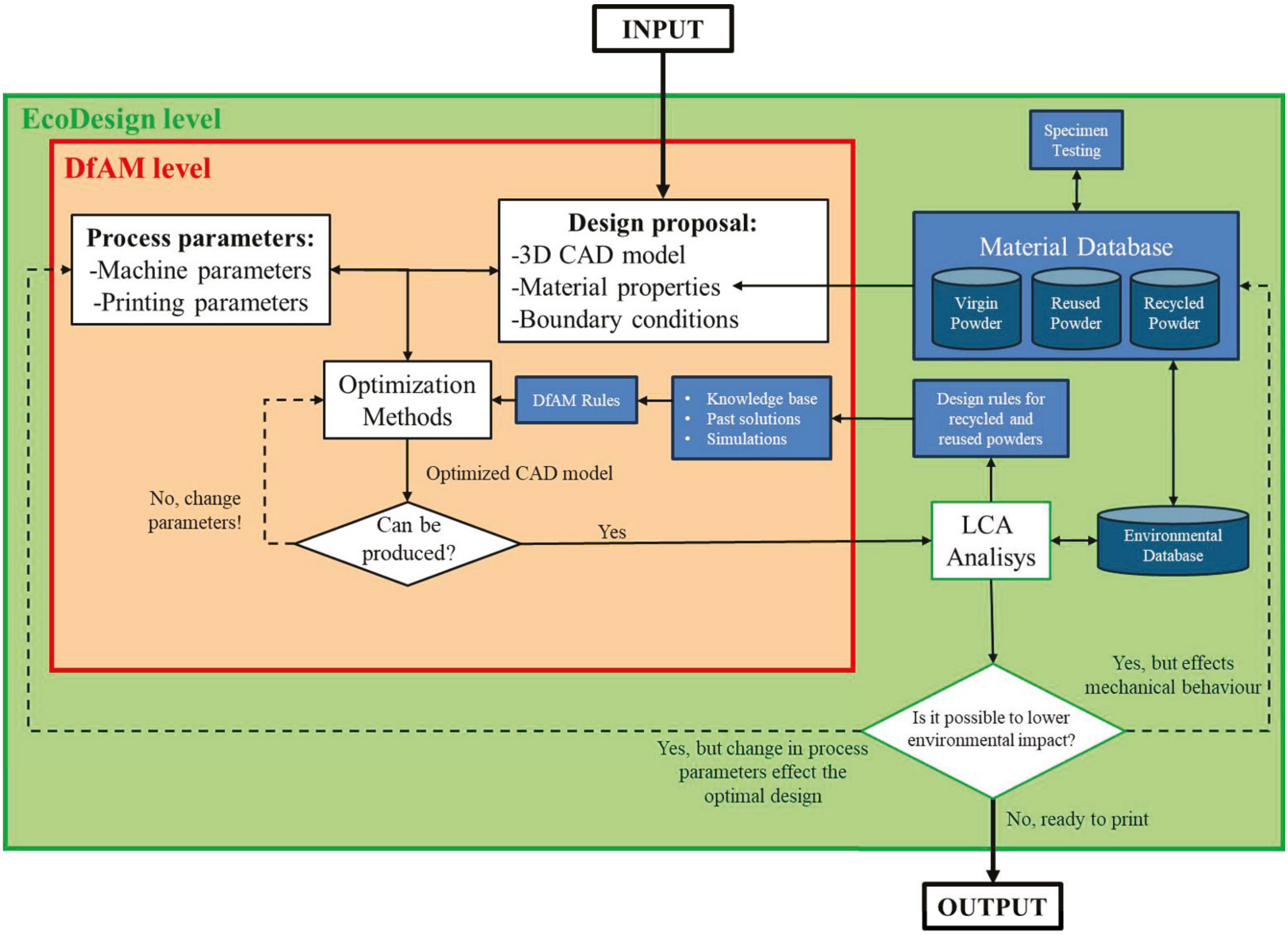

Fig.2. The proposed EcoDesign-DfAM method

studies focus on trying to find solutions to carry out prints with powders out of specification parameters by readjusting process parameters [12]

Printing Parameters are chosen by the designer mainly on the basis of his experience and carefully selected considering the product geometry and the support removal process. These kinds of parameters have a strong impact on the residual stresses of the component once is produced, the printing time and the total manufacturing costs, therefore in order to guarantee process competitivity need to be optimal.

The optimization process is a very helpful step to fully capitalize on the benefits of AM processes and to lower the costs. It can be achieved by a number of methods such as topology optimization, generative design, shape optimization, material optimal design, lattice structure designing and many more [21]. All the optimization methods need to provide solutions according to DfAM guidelines in order to guarantee product feasibility. At this point most DfAM methods converge to a solution, providing a design proposal.

The extended EcoDesign method proposes to evaluate the component's environmental impact after the DfAM stage is completed. In this phase, the environmental impact is calculated by considering the design choices, the selected material and the data from LCA studies (Environmental Database). At this stage, the designer can find ways of improving the components from an environmental standpoint and confront them, this step is facilitated by the fact that most LCA software work by progressive comparisons. After that, the feasibility of the improved design must be validated, the validation step must be calibrated carefully with feasibility data from experiments and previous knowledge, considering the specific material, application, and CAD geometry features with relation to DfAM indications. If the renewed project is feasible, it passes the revision and is ready to be printed. Otherwise, the reason why the component does not pass revision must be examined. Sometimes it may be possible to accommodate the process parameters to make the print achievable without changing the CAD model, but most of the time [14] the use of recycling practices leads to a decrease in material properties that can only be overcome by readjusting the geometry of the component.

The proposed EcoDesign level of the method exploits an easy-to-use workflow in order to review the components considering environmental impact parameters. In this way, the optimization level stands before the LCA, without direct correlation. An overall mechanical-LCA-DfAM optimization may be more precise and more functional to the designer's needs but requires further studies and a complete dataset that includes every parameter combination effect on the component's properties.

Nevertheless, a positive of using the proposed method is that the DFAM level and the EcoDesign level are independent of each other, providing a way of attributing environmental characteristics without adopting drastic changes to the pre-existing design procedures and software adopted by the companies. However, design rules and material database are the connections between DfAM and LCA levels.

4. Conclusions

This work aims to provide designers with a method to consider the use of recycled powders in the L-PBF process. The proposed method focuses on integrating an evaluation of environmental impact in DfAM methods, a factor often left out of the design phase.

The workflow considers the possibility of recycling and reusing practices by accessing their effect on mechanical component's properties though a database, which can be updated by testing campaigns or as the companies build their knowhow. The scope of the Material Database is to collect the properties of the powder mix. On the other hand, the Design Rules aim to support the definition of the project parameters and the composition of the powder mix. The design proposal is then optimized by considering both process and machine parameters. In order to promote the integration of EcoDesign in existing DfAM practices, tools and software need to consider the environmental impact of the product before production.

Future work into this matter should concentrate on the effects of the recycling process on the component's properties and more precise accounts of recycling benefits. Building knowledge in this direction should improve the current state of the art and help designers in streamlining decision making to include recycling and reusing practices in the LPB-F production process.

Acknowledgements

Project "Eco-Design for Additive Manufacturing (EcoDAM): a framework to support the lightweight design", Project Number 2022FKLTSB, CUP F53D23001750001, Italian Ministry of University and Research, Progetti di ricerca di Rilevante Interesse Nazionale (PRIN) 2022.

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