Evaluation of environmental sustainability in additive manufacturing processes for orthopaedic devices production

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Abstract

Sustainability impact assessment of additive manufacturing represents one of the key issue of the European Union Horizon 2020 project "Driving up Reliability and Efficiency of Additive Manufacturing" (DREAM). Additive manufacturing is a versatile technology consisting in melting metallic powders to produce objects from 3D data, layer upon layer. Additive manufacturing applications in industry range from automotive, biomedical (e.g. prosthetic implants for dentistry and orthopedics), aeronautics and others. One of the main target is to assess the environmental sustainability of DREAM products and processes, conducted with laser-based powder bed fusion additive manufacturing systems through Life Cycle Assessment (LCA) methodology. Environmental impacts on different impact and damage categories due to manufacturing, use and end of life of the designed solution have been assessed adopting IMPACT 2002+ method.

Introduction

Additive Manufacturing (AM) is a rapidly growing technology that seems to be limitless. Its strengths are the capability in creating high geometrical complexity objects, precluded to traditional manufacturing, and the flexibility in meeting customer's requests, avoiding the increasing of productive costs. Powder bed fusion (PBF) is one of the latest terminology for the designation of an AM process in which a metal powder layer is laid in a bed and, often, it is sintered by high energy laser. AM technologies are used in a wide range of industries from aerospace, consumer electronics to medical applications.

The present study is part of the DREAM project (H2020-FOF-2016) that has received funding from the European Union's Horizon 2020 research and innovation programme.

DREAM's target is to significantly improve the performance of laser PBF of titanium, aluminum and steel components in terms of speed, costs, material use and reliability, also using an LCA approach, whilst producing work pieces with controlled and significantly increased fatigue life and with higher strength-to-weight ratios.

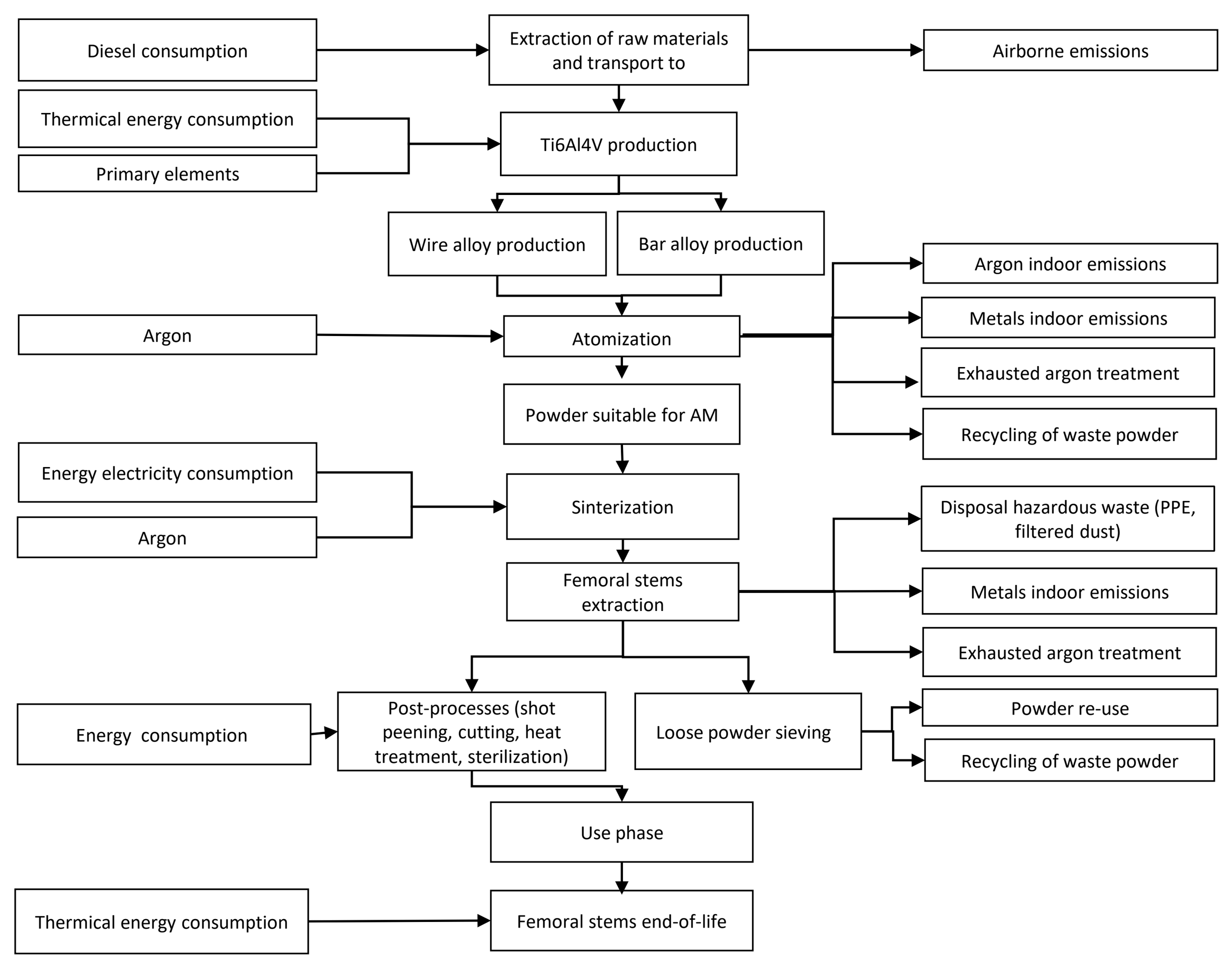
This work is focused on the study of environmental damage of a medical application of AM, femoral stems, over the whole life cycle. In particular, an environmental performance comparison between two different production routes of titanium alloy powder is performed, namely gas atomization (GA) and plasma atomization (PA) processes.

Materials and methods

The system studied is the additive manufacturing process with powder bed fusion of Ti6Al4V alloy powder. The function of AM is the application for biomedical devices, such as femoral stems. To the aim of the present study, 20 femoral stems produced with AM are analyzed.

The system boundaries cover the entire life cycle of the analyzed system, starting from the Ti6Al4V alloy production, Ti6Al4V powder production with two different atomization technologies (plasma atomization, PA, and gas atomization, GA), femoral stems production with EOS M290 machine, post-production treatments, use and end of life phases. The production, maintenance and disposal of facilities as well as other auxiliary materials are also included in the present study. Emissions to air and indoor emissions as well as solid and liquid waste produced in each step are considered and quantified.

The analysis is conducted using the SimaPro 8.3 software (Prè Consultants, 2014) and IMPACT 2002+ evaluation method (Jolliet et al., 2003), then modified (Ferrari et al., 2015). Moreover Human health, indoor category was added, including the substance Metals, unspecified indoor in Carcinogens, indoor for emissions of Ti6Al4V in indoor environment and inhaled by workers and the substance Argon, indoor for emissions of argon inhaled by workers introduced in Non-carcinogens, indoor impact category with a calculated damage factor.



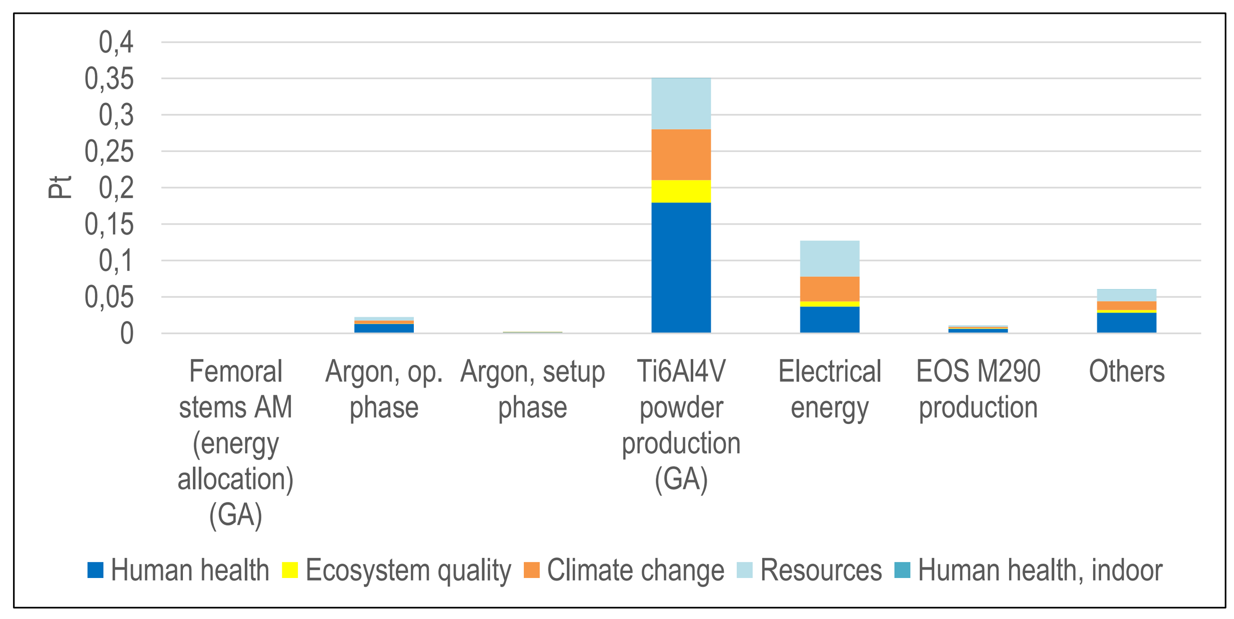
Flowchart of femoral stem

Results

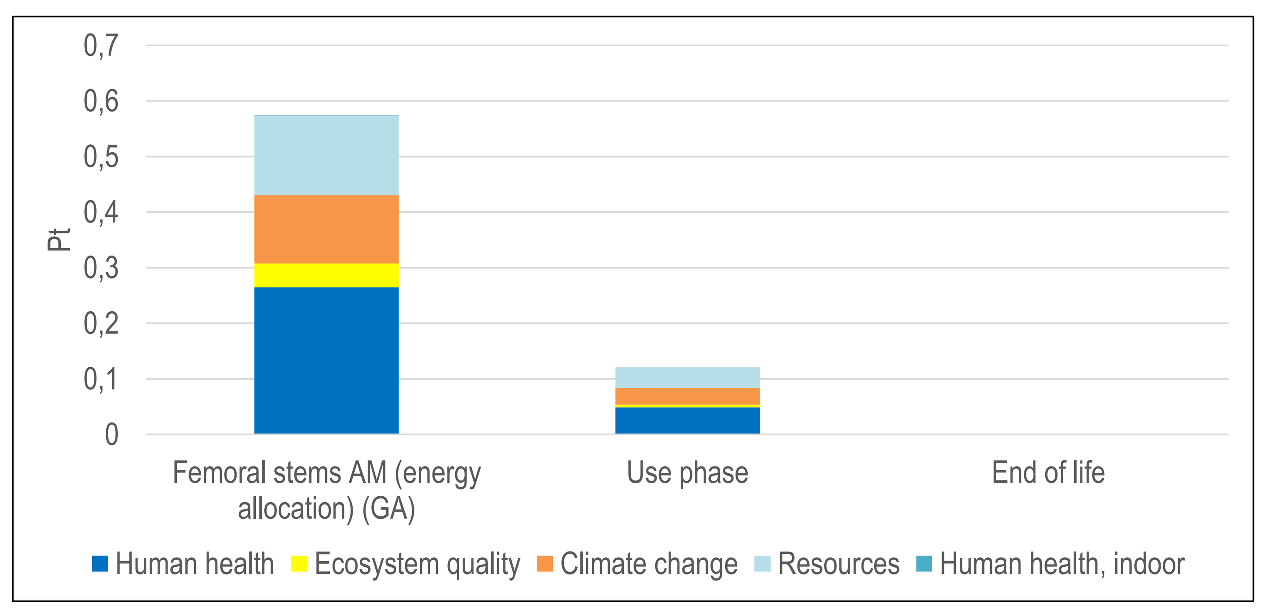
Femoral stems production with PA powder highlights total damage of 6,2E-1 Pt as result, +7,69% compared to GA powder. In fact, Ti6Al4V powder production process provides a higher contribution to total damage compared to the GA powder hypothesis because of the greater use of argon for PA (2,56 kg of argon to produce 1 kg of powder) compared to GA (0,007 kg for 1 kg of powder) and because of the lower atomization productivity of this technology (80 kg of powder produced in 16 hours) compared to GA productivity (500 kg in the same time) (EOS, 2017).

As GA represents the most sustainable choice, a deeper analysis of femoral stems production with GA powders is performed below. The environmental loads at the damage categories level of each step of 20 femoral stems production with EOS M290 machine is reported. Fig. 1 represents the use of Ti6Al4V powder produced with GA technology. The analysis of the results highlights that the single score damage for 20 femoral stems manufacturing process with GA Ti6Al4V powder usage is 5,72E-1 Pt, where the phases with the highest environmental loads are Ti6Al4V powder production (61,13%) and electrical energy consumption (22,22%). The damage assessment analysis shows that Human health category contributes with 46,16% of the total damage, Resources category provides 25,03% , the damage to Climate change (21,43%), Ecosystem quality (7,55% of the total damage. Finally, Human health indoor category contributes to total damage with 6,71E-5% due, mainly, to argon indoor emissions (3,75E-7 Pt, 6,55E-5% of total damage).

An analysis of the entire life cycle of 20 femoral stems produced with GA powder is reported below. Total damage is 6,94E-1 Pt and is due mainly for 82,5% to stems production, for 17,46% to the use phase (consisting in stem's implantation and medical examinations during patient lifetime) and for 0,02% to end of life (consisting in archiviation, prior sterilization). Damage in use phase is due almost to surgery (68% of total damage), in particular for damage caused by surgery sterilized towels produced with polyethylene terephthalate.



Femoral stems manufacturing process with GA powder



LCA of 20 femoral stems with GA powder

Conclusions

IMPACT 2002+ modified method showed that the main environmental load in the production phase is due to titanium alloy powder production. A comparison between two different titanium alloy powder production technologies is followed in order to make the most appropriate choices for minimizing environmental loads and protecting human health. In this context, plasma atomization and gas atomization are studied. The analysis of results illustrates that the most sustainable choice for powder production is represented by Gas atomization.

A cradle to the grave LCA analysis has been performed for 20 femoral stems produced with AM and GA powder, resulting in a highest environmental burden for the production phase, followed by the use and end of life phases.

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