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 work packages (WP5) 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 of WP5 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.

1. 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 is laid in a bed and sintered by high-energy beam, often a laser. AM technologies are used in a wide range of industries from aerospace, consumer electronics to medical applications.

A cooperation study between EADS IW, the aerospace and defence group’s research and technology organisation, and EOS, the worldwide technology supplier for industrial 3D printing of metals and polymers, (EOS, 2015) provides a comparison, in terms of energy consumption, between traditional manufacturing and AM in an aerospace application (a bracket) over the whole life cycle. In the same study, a comparison focused on the static phases between rapid investment casting and an EOS platform is carried out, too.

Burkhart and Aurich (2015) presented a framework to assess the environmental impact of PBF in commercial vehicle production and identify product components/assemblies with high impact on vehicle performance and potential for improvements.

The present study is realized in the context of the DREAM project (H2020-FOF-2016) that has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 723699. Its aim 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 a LCA approach, whilst producing work pieces with controlled and significantly increased fatigue life, as well with higher strength-to-weight ratios. DREAM targets the development of a competitive supply chain to increase the productivity of laser-based AM and to bring it a significant step further towards larger scale industrial manufacturing.

This article 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.

2. Life cycle of a femoral stem produced with PBF

In the last decade and in the field of the prosthetic components, PBF processes have been applied to the production of titanium alloy parts, such as femoral stems. The entire life cycle of femoral stems produced with AM consists in Ti6Al4V powder production, femoral stems production, use phase and end of life.

Femoral stems production is realized by laser sintering of titanium alloy powder layers. End of life step analyses exhausted gas treatment and waste Ti6Al4V recycling processes. During the production process indoor emissions have been taken into account, for this reason air filters and personal protective equipment (PPE) have been included in this study. The main steps of the life cycle of femoral stems production are described below.

1.1. Ti6Al4V powder production

Ti6Al4V powder production is examined for gas atomization and plasma atomization. The main differences between these productive processes consist in alloy feeding and atomization technology. PA process uses a Ti6Al4V wire feedstock, straightened and positioned at the apex of three plasma torches. The plasma flow melts the wire, which droplets solidify in spherical particles during the fall through the atomization tower.

GA process uses a Ti6Al4V bar feedstock that gets rotated and, at the same time, lowered in an inductive coil that melts the bar without contact. Then the melt gets atomized by high-pressure argon jets. Both atomization processes are supposed to work 16 hours/day (EOS, 2017) and are characterized by indoor emissions of argon and metals. Since, IMPACT 2002+ method does not taken into account indoor emissions, characterization factors for argon and metal indoor emissions are calculated and introduced in the Life Cycle Impact Assessment (LCIA) method. This allows to evaluate and include the indoor emissions in the impact assessment stage.

1.2. Femoral stems production

Femoral stems production is realized by EOS M290 machine, where sintering takes place with a 400 W laser (EOS, 2017). The whole production cycle lasts 61 hours and 21 minutes with a production capacity of 20 femoral stems (Poly-Shape, 2017) per cycle. After a set-up phase, powder is fed by the dispenser system platform and then a 30 μm thick layer is stretched on a titanium plate with a recoater. Laser fusion involves selective melting of cross-sections, previously defined by CAD model. The powder bed is lowered progressively in order to allow a new layer deposition that, in turn, will be sintered.

In order to avoid the development of explosive atmospheres due to the raising of powder particles during sintering and to control N/O pick-up, argon flow is insufflated over the powder layer. An air recirculating filtering system works continuously to purify argon. At the end of the productive process, the parts are extracted by workers. Extraction considers the separation of solidified parts from the remaining loose powder, that will be reused in the following productive process. Indoor metals emissions that occurs during the machine cleaning and parts extraction are considered.

1.3. End of life

Femoral stems end of life consists in archiviation, prior sterilization. This information was obtained through direct interviews with technicians. Prosthesis average lifetime is supposed to be about 15 years (value obtained with weighted average of lifetime reported in Wyatt et al., 2014). The rate of deceases before stem's revision is equal to 25% of total implantations (rate of deceases within 10 years from stem's implantation, Wainwright et al., 2011). If death occurs before removal, the prosthesis will not be removed from the patient.

3. Life cycle assessment

2.1. Goal definition

The goal of the study is to assess the environmental impacts of Ti6Al4V based femoral stems produced with AM over their entire life cycle in order to identify the hot spots of the system considered in agreement with UNI EN ISO 14040-14044 regulations.

2.2. System, functional unit and function of the system

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. For the aim of the present study, 20 femoral stems produced with AM are analyzed.

2.3. System boundaries

The system boundaries cover the entire life cycle of the analyzed system. The analysis includes the Ti6Al4V alloy production, Ti6Al4V powder production with both plasma atomization and gas atomization, femoral stems production with EOS M290 machine, 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.

Moreover, the following assumptions are fixed:

- The transport of raw material, facilities, systems and machines has been supposed for an average distance of 100 km from the producer to the user;
- The distance of transport of femoral stems from the producer to the final customer has been fixed to 100 km and partitioned for 40% by rail and 60% by road;
- The electricity energy production has been assumed to be the European mix electricity energy created by Ecoinvent;
- The use of 99,97% efficiency HEPA air filter during femoral stems production and powder production steps;
- The use of 99% efficiency personal protective equipment (filter category P3) during EOS M290 machine cleaning, powder production and exhausted argon treatment steps.

2.4. Impact assessment methodology

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). The following additions are implemented in order to consider a wider and more representative scenario of the considered system:

- For emissions of Ti6Al4V in indoor environment and inhaled by workers, the substance Metals, unspecified indoor is introduced in Carcinogens, indoor impact category with a calculated characterization factor (Pini et al., 2016).
- For emissions of argon inhaled by workers, the substance Argon, indoor is introduced in Non-carcinogens, indoor impact category with a calculated damage factor. The limit of concentration of argon in a working space, considered to be 500 m^3, is equal to 0,18 kg/m^3 and it is calculated considering the increased percentage of argon (up to 10%) in air. Considering a breath rate of 2,5 m^3/h and 8 working hours per day, indoor argon limit of emission is calculated ad it is 3,57 kg. Referring to Europe (with population density of 386 millions, Goedkoop et al., 2001) and considering average lifetime of 80 years and 50 year old man

exposed to emissions, the damage factor on human health results 2,18E-6 DALY/kg and the resulting characterization factor is 0,78 kgC_2H_3Cl eq.

2.5. Life cycle inventory

The compilation of inventory data is conducted using primary data collected from DREAM project partners where possible, otherwise literature data are included. Eco-invent database (Ecoinvent Centre, 2014) included in SimaPro 8.3.0 software is used, too. The more representative data used in Life Cycle Inventory of femoral stems production with EOS M290 machine are reported in Table 1.

Table 1: inventory input data for 20 femoral stems production with EOS M290

Setup phase argon	**Operative phase argon**	**Ti6Al4V powder**	**Energy**
1700 l	**4 l/min**	**20 kg**	**88,8 kWh**

4. Impact assessment and concluding remarks

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 show that Human health category contributes with 46,16% of the total damage, in particular with the substance Particulates, <2,5 μm (air) (50,86%, partitioned for 72,04% for powder production and 8,8% for electrical energy consumption).

Resources category provides 25,03% of the total damage, mainly for the substance Coal, hard (27,95%, due especially for energy production for primary titanium production used in alloy powder). The damage to Climate change (21,43%) is generated almost entirely by the substance Carbon dioxide, fossil (93,93%) due to a quantity of 1215 kg CO2 eq., emitted for 56,51% during gas atomization process and for 28,35% during electrical energy consumption. Occupation, industrial area affects the category Ecosystem quality (7,55% of the total damage) and is linked to the furnace used in Ti6Al4V bar production process.

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) during exhausted argon treatment and Ti6Al4V powder production processes, and then to metals indoor emissions (9,36E-9 Pt, 1,63E-6% of total damage) occurring in exhausted argon treatment, Ti6Al4V powder production and femoral stems production processes.

Femoral stems production with PA powder (Fig. 2) highlights total damage of 6,2E-1 Pt as result, where the phases with the highest environmental loads are Ti6Al4V powder production (66%) and electrical energy consumption (19,44%).

In this hypothesis, Human health category provides 45,34% of total damage, Resources category 26,06%, Climate change category 21,84% (with 1341 kg CO2 eq. emitted), Ecosystem quality 6,91%, Human health indoor 0,018% (3 orders of magnitude higher than GA hypothesis for the higher quantity of exhausted argon sent to treatment during powder production).

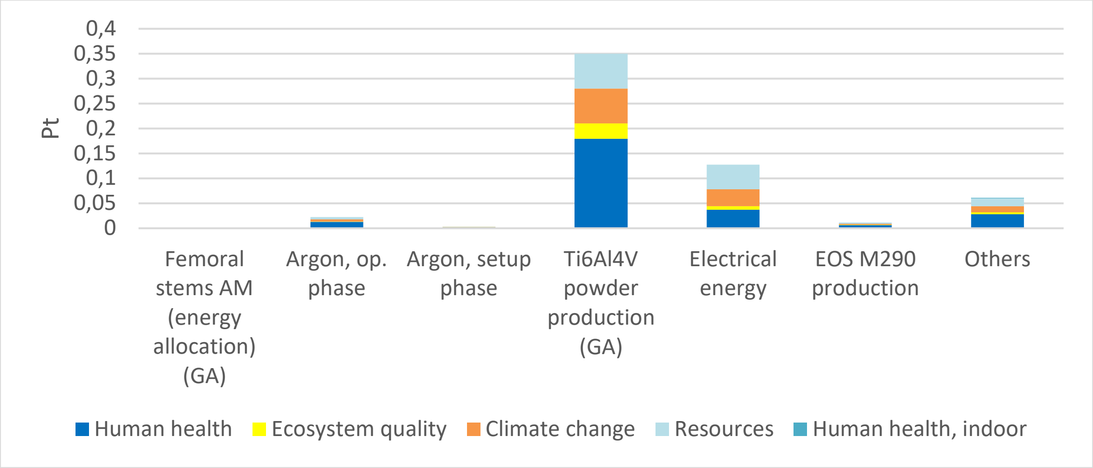

Figure 1: Femoral stems manufacturing process with GA powder

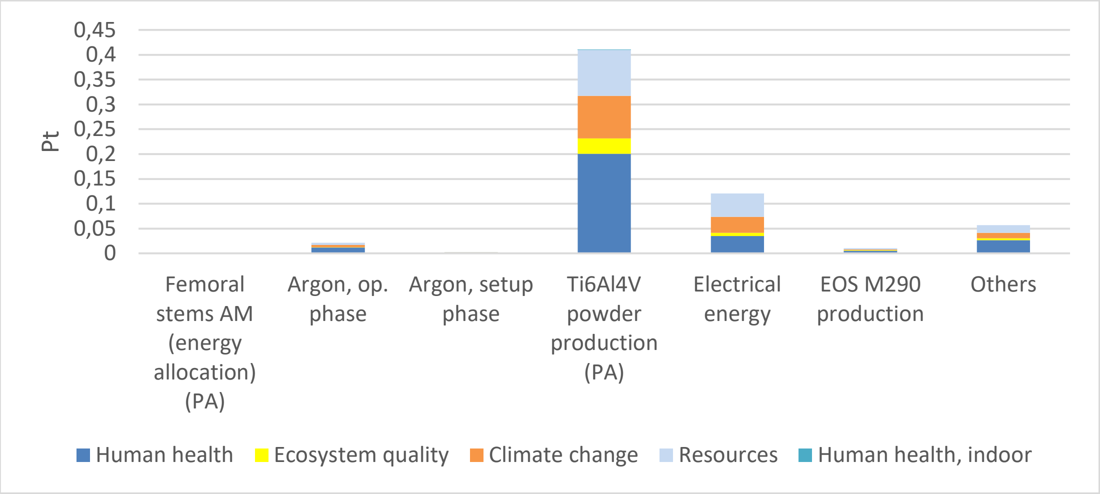

Figure 2: Femoral stems production with PA powder

Femoral stems production with PA powder presents a higher damage (+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).

The damage category with the highest increase is Resources (+11,22%), followed by Climate change (+9,33%) and Human health (+5,92%).

An analysis of entire life cycle of 20 femoral stems produced with GA powder is reported below. Total damage is 6,94E-1 Pt (Fig. 3) 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 (previously described). 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.

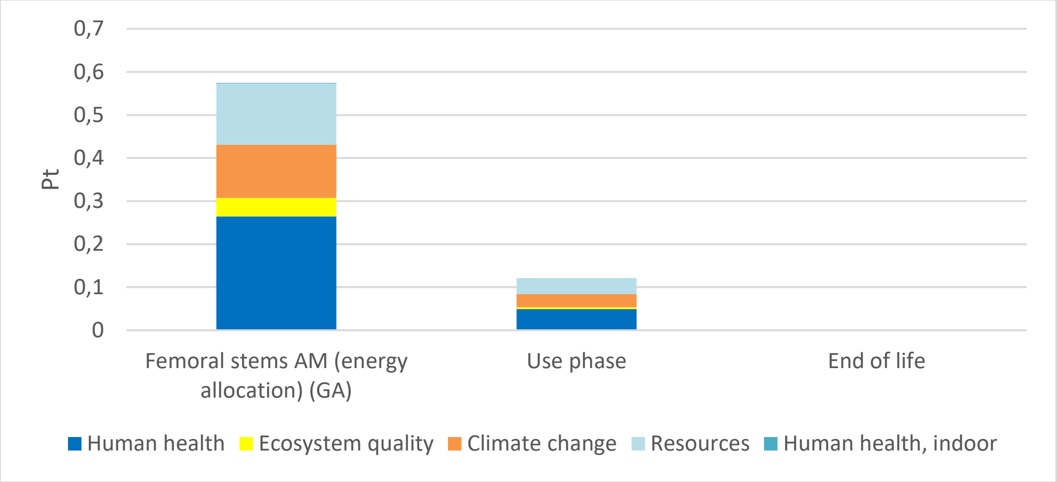

Figure 3: LCA of 20 femoral stems with GA powder

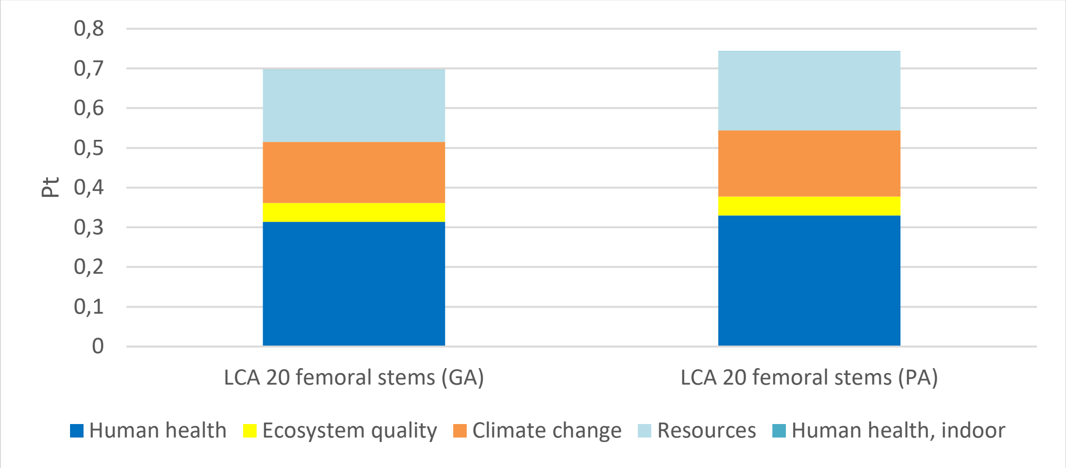

Figure 4: Comparison between entire LCA femoral stems (realized with GA powder) and entire LCA femoral stems (realized with PA powder)

The analysis of the comparison (Fig. 4) highlights that femoral stems produced with PA powder presents a higher impact (7,41E-1 Pt) during all life cycle compared to the GA powder hypothesis (+6,36%) due to higher damage of powder production with PA compared to GA. The damage category with the highest increase in LCA 20 femoral stems with PA powder is Resources (+9,12%), followed by Climate change (+7,61%) and Human health (+5,04%).

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