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# An approach to design for environmental sustainability of additive manufactured metal components

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## Abstract

The present paper proposes an environmental sustainability-oriented Design for Additive Manufacturing approach, which takes into account material, shape, and additive process, in order to guide the designer towards environmentally conscious choices in terms of component characteristics, correlating them with the peculiarities of the additive process and its main parameters. In its formulation, the approach has been developed with reference to the specific class of "powder bed fusion" additive processes for metallic materials, in which the volume growth by stratified fusion of powder layers, takes place by means of power beams. As a reference process, that of Electron Beam Melting has been considered. The quantification of the environmental impact of built components focuses on the estimation of the intrinsic energy consumption of the additive process, correlating it to the main process parameters, and to some significant features that characterize the shape of the component. To analyze the dependence of the energy impact on the material and shape characteristics, the case of Ti6Al4V components is studied.

## 1. Introduction

The progression from rapid prototyping to the production of end-use product has projected the technologies of Additive Manufacturing (AM) toward a leading position in the panorama of manufacturing processes, also in the

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field of metal components fabrication. Compared to conventional ones (such as casting, forging, and machining), AM technologies have the primary advantages of very limited geometric constraints, that allows the building of complex part designs, and low average cost for small batch size manufacturing. Furthermore, they are also considered as cleaner production techniques, due to some aspects: the parts are built layer by layer, so that raw materials use is very efficient, and material waste is minimized; the freedom in shaping allows to obtain lightweight components, saving raw materials; no additional resources are required (such as dies, cutting tools, coolants, etc.).

Despite their wide spread in the most varied areas of production, and their predisposition to environmental sustainability, the issue of AM processes environmental impact has not been adequately analyzed in some essential aspects, such as energy and material consumption, pollution and waste, over the full lifetime of manufactured products (Kellens et al. 2017). Most of the studies in this field have adopted Life Cycle Assessment approaches to analyze the environmental impacts of specific AM processes, converting energy and resources consumption to environmental impact factors (Le Bourhis et al. 2014, Kellens et al. 2014, Faludi et al. 2016). Some authors have summarized the available life cycle inventory data on environmental impacts relative to AM processes, taking into account energy and resources consumption, and emission savings (Huang et al. 2016). Other authors have proposed comprehensive analyses of the studies that have compared environmental impacts related to metal components shaping by either AM and conventional manufacturing techniques (Ingarao 2017).

From the existing literature some observations can be made: the results vary widely across these studies, primarily because of the wide variability in data collection methods, material selections, component geometries, which preclude direct comparisons; none of the studies consider environmental sustainability improvements due to changes in material selection or component geometries. As a conclusion, generally the studies in this field are based on a life-cycle impact inventory approach, and do not take into account essential questions, closely related to the main dimensions of the design practice, such as the environmental outcomes due to the relationship that links the choice of material and its required properties to the process parameters, and the key role played by the shape properties of the component to be designed and manufactured.

The present paper outlines a Design for Additive Manufacturing (DFAdM) approach that allows to guide the designer towards choices on the shape properties of metal alloy components, such that they are environmentally efficient in their fabrication by additive process. In its formulation, the approach has been developed with reference to the specific class of "powder bed fusion" additive processes for metallic materials (Selective Laser Melting SLM, Electron Beam Melting EBM), in which the volume is built by melting of stratified powder layers, hit by power beams, and for which it has been shown that the energy consumption dominates environmental impact (Faludi et al. 2017). In particular, as a reference process, that of Electron Beam Melting technology has been considered. The quantification of the environmental impact of manufactured components focuses on the estimation of the intrinsic energy consumption of the additive process, that is the energy of the process beam during the various phases of the process, correlating it to the main process parameters, and to some significant features that characterize the shape of the component. Since the use of the intrinsic process energy calculation model requires the definition of the material, on which the setting of the process parameters depends, for the validation phase of the study Ti6Al4V alloy was chosen, a titanium alloy widely used in combination with EBM additive technique.

## 2. Development of the energy consumption model

### 2.1. Reference process and material

Between powder bed fusion processes, Electron Beam Melting (EBM) has become a metal-based AM technique of consolidated use in a wide variety of fields of application. It uses the energy of an electron beam to melt metal powder layer-by-layer and builds dense parts with limited geometric constraints. Since EBM operates in vacuum conditions, it is particularly appropriate for Ti powder processing, because this element has high affinity for oxygen. Furthermore, when Ti alloys are processed by EBM, the usual problems associated with conventional machining, such as heat generation, friction, use of many tools and consequent long production time, are avoided.

Ti6Al4V is the most used Ti alloy thanks to its excellent combination of mechanical properties (strength, fracture toughness, ductility) and corrosion resistance. Ti6Al4V components built by EBM are strictly influenced by process parameters, that are determining for bulk and surface properties, with consequent effects on mechanical behavior

(Al-Bermani et al. 2010). The high levels of strength and fracture toughness are confirmed (Lewandowski and Seifi 2016). The properties of creep resistance (Aliprandi et al. 2019) and the behavior with respect to dynamic phenomena at high strain rate (Mirone el al. 2016) are also relevant.

Some previous studies analyzed the environmental impact of Ti6Al4V components built by EBM process in terms of energy consumption (Paris et al. 2016, Baumers et al. 2017, Priarone et al. 2017). They are generally based on the analysis of machine power absorption and process times to assess energy consumption, and do not take into account the influence of very important factors such as component geometry and number of built components per build. Even when these factors are taken into consideration (Le and Paris 2018), the approach is limited by taking into account only the height of the components as geometric property, and neglecting the question of optimal packing of the components that make up a single build, and how the shape of the components affects it. They are therefore unsuitable for the analysis of process energy consumption depending on the design variables that will define the final component, which is required in a DFAdM approach.

## 2.2. Analysis of the process and model development

To define the main phases of the EBM process, it is necessary to refer to the main components of the build chamber of an EBM machine (Fig. 1a) (Arcam 2019). Inside the chamber, the build tank contains the process platform (start plane), which constitutes the building plane and will be moved downward along the vertical axis during the building process. The powder supply system consists of two hoppers, and a rake that distributes the powder on the building plane and controls the powder layer uniformity.
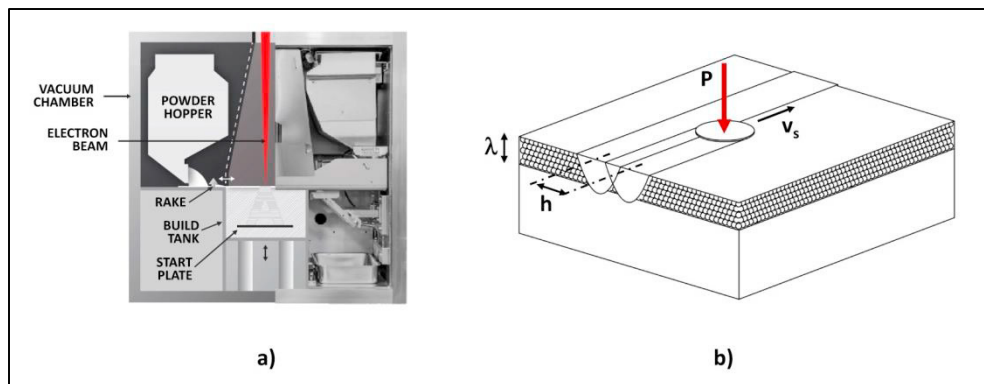


Fig. 1. (a) build chamber of an EBM machine; (b) reference scheme for powder bed melting process.

The process develops according to sequential steps (Gaytan at al. 2009), starting with some preliminary operations: creation of the vacuum in the chamber; heating of the start plane before the deposition of the first layer of powder. Then the steps of the actual building process begin: deposition of the first powder layer; preheating of the deposited powder bed by means of a series of not-focused, high-power and high-speed electronic beam passages; selective fusion of the first layer, during which the power and the scanning speed are reduced and the beam is concentrated. After completing the layer melting, the process platform is lowered by the thickness of a layer to allow the deposition of a new powder layer, and the sequence is repeated until the whole component is built.

Referring to the scheme for powder bed melting process in Fig. 1b, as basic starting point for the modeling of energy consumption due to process beam, the input energy of the beam per unit of material volume processed $E_{UV}$ (J/mm$^3$) can be defined by the following equation (DebRoy et al. 2018):

$$E_{UV} = \frac{P}{v_s \, \lambda \, h} \tag{1}$$

being P (W) the beam power, $v_s$ (mm/s) the scanning speed, $\lambda$ (mm) the layer thickness and h (mm) the line offset (or scan spacing). Each step of the process in which the power beam acts, involves an intrinsic energy consumption estimated according to the equation (1), calculated for the specific parameters (P, $v_s$, $\lambda$, h) corresponding to the process step and the material processed.

According to the previous description of the process, and neglecting the preliminary operations of machine starting (vacuum creation, start plate heating), independent of the components and the size of the batch to build, the main contributions to the overall energy consumption for the processing of a layer are the following: $CE_{PP}$ (powder layer preparation); $CE_{PH1}$ (first phase of pre-heating, by a number of not-focused beam scanning on the whole plate); $CE_{PH2}$ (second phase of pre-heating, by the scanning of the surface to be melted, lightly expanded on the inner and outer contours); $CE_{CM}$ (contour melting, i.e. the selective melting by focused beam of all the inner and outer contours of the surface to be melted); $CE_{IM}$ (inner melting, i.e. the selective melting of the surface inside the contours).

The energy consumption per unit volume $CE_{UV}$ associated to the building of a component can be calculated by summing all the energy consumption contributions previously defined, for each layer constituting the component, and dividing by the total volume of the component. Finally, distinguishing between the contributions of that concern the whole plate ($CE_{PP}$, $CE_{PH1}$), to be divided by the number of components per build, by the contributions concerning the scanning of the surfaces boundaries (part of $CE_{PH2}$, $CE_{CM}$), and by those concerning the scanning of surfaces (other part of $CE_{PH2}$, $CE_{IM}$), the total energy consumption per unit volume $CE_{UV}$ can be expressed in the form:

$$CE_{UV} = CE_{WP} + CE_{CS} + CE_{SS} = \alpha \cdot CE_{WP}^{*} + \beta \cdot CE_{CS}^{*} + CE_{SS} \tag{2}$$

In equation (2), $CE_{WP}$, $CE_{CS}$, $CE_{SS}$, are the energy consumption for operations on whole plate, and operations of contour scanning and surface scanning, respectively, all formulated as terms exclusively depending on process parameters. Fixed the material to be processed, and set the machine parameters for each step of the process (pre-heating 1 and pre-heating 2 have generally similar parameters; contour and inner melting parameters are the same; energy consumption for powder layer preparation has a constant value, estimated in the literature (Baumers et al. 2017)), these terms of energy consumption are functions of the input energy of the beam per unit of processed volume $E_{UV}$, calculated for each step by equation (1), varying the beam parameters (P, $v_s$, $\lambda$, h).

As evidenced by the second expression of equation (2), while the term $CE_{SS}$ is not dependent of the characteristics of the component, the first two terms are. They depend on $\alpha$ and $\beta$ parameters, that characterize the geometric and volumetric properties of the components, being $\alpha$ ($= H_I/n_c V_c$) a function of the height of envelope volume $H_I$, the number of components per build $n_c$, and the component volume $V_c$, and being $\beta$ ($= SL_c/V_c$) a function of the sum of inner and outer side surfaces of the component $SL_c$, and the component volume $V_c$. The number of components per build $n_c$, obviously depends on the sizes of the start plate, but it is also a function of the dimensional parameters of the base of the envelope volume, and of the shape characteristics of the component, having the latter a direct influence on the packing of the components on the plate.

Definitely, the formulation of $CE_{UV}$ expressed by equation (2) allows to estimate the incidence of the variations in the shape and volume characteristics of a component, on the specific energy consumption (per unit of volume) necessary to build the component, made of a chosen metal alloy, by EBM process.

## 3. Validation

To verify the efficiency of the formulation (2), in quantifying the specific energy consumption related to the fabrication of a component by means of the EBM process, and the variations of the different contributions ($CE_{WP}$, $CE_{CS}$, $CE_{SS}$) and of the overall value ($CE_{UV}$) depending on the design variables that define the properties of the component, here the use of the model to analyze a component with a class B shape (rectangular or cubic prism envelope), made of Ti6Al4V alloy, is proposed (Fig. 2a). Fixed the material, three different process parameters settings have been defined: pre-heating 1, pre-heating 2, selective melting (same setting for both contours and inner melting), and the corresponding values of $E_{UV}$ have been calculated by (1).

To evaluate the effect of changes in the characteristics of the component, on the terms of specific energy consumption, two modifications to B shape component have been simulated, under two conditions: at fixed volume

(this allows to evaluate alternatives in which the same volume is distributed according to different shapes); leaving unchanged (also in their mutual distance) the two functional surfaces of the component, that are the internal surfaces of the hole and of the prismatic groove at the base, except in their extension along the longitudinal axis. The considered variations of B shape are represented in the same Fig. 2a: B' is characterized by a reinforcement of the structure on the transversal plane, with an increase in the width of the base, and in the  height, but with a decrease in the longitudinal extension; vice versa B'' is characterized by a lightening of the structure on the transversal plane, with a reduction in the width of the base and in the height, and by an increase in the longitudinal extension.

Table 1 collects the values of geometric and volumetric properties, and $\alpha$ and $\beta$ parameters, corresponding to B shape component and its two variations. Fig. 2b compares the values of $CE_{UV}$ (red) and their compositions according to the terms $CE_{WP}$ (green), $CE_{CS}$ (blue), $CE_{SS}$ (yellow).
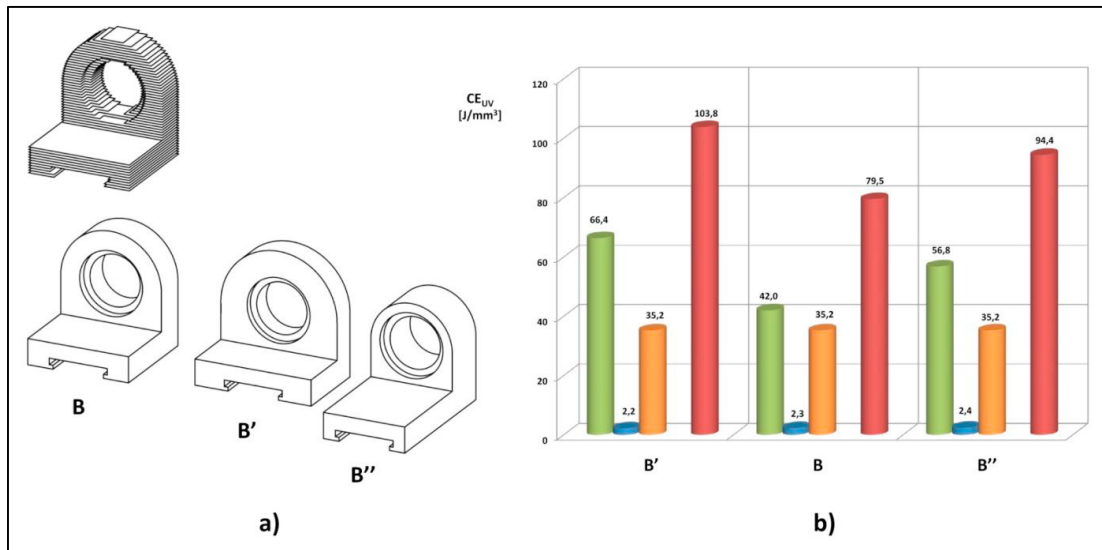


Fig. 2. (a) B shape component and derived variations; (b) specific energy consumption and its composition (comparison).

Table 1. Geometric and volumetric properties of the components, $\alpha$ and $\beta$ parameters.

|  | B | B' | B'' |
|---|---|---|---|
| $V_c$ [mm³] | 52947 | 52547 | 52672 |
| $H_I$ [mm] | 59 | 62 | 53 |
| $SL_c$ [mm²] | 9607 | 9184 | 10053 |
| $n_c$ | 9 | 6 | 6 |
| $\alpha$ [mm⁻²] | 0.000124 | 0.000197 | 0.000168 |
| $\beta$ [mm⁻¹] | 0.181446 | 0.174776 | 0.190860 |

In all three cases, the term related to the contouring operations is substantially equivalent, and negligible compared to the others (Fig. 2b). The first aspect is due to the limited variation of $\beta$, the second one is instead a characteristic of the EBM process, and is attributable to the limited incidence that the operations of contouring have in the overall process, compared to the other operations.

The most efficient solution from the energy point of view is the unchanged B-shaped one, while the two variations B' and B'' lead to an increase in the energy consumption per unit volume (Fig. 2b). In the first case (B'), this is due to a substantial increase in the $\alpha$ parameter (Table 1), to which contribute the slight increase in the height of the component $H_I$, and above all the substantial reduction in the number of components per build $n_c$; the slight decrease of the $\beta$ parameter, due to the reduction of the lateral surfaces $SL_c$, is irrelevant, as highlighted above, and

cannot compensate for the α effect. Also in the case of B'' a substantial increase of α is noted, despite the reduction in $H_I$; this is due to the reduction in $n_c$, which has the greatest impact; the β parameter, although irrelevant, however in this case plays against, as it increases its value, due to the increase in $SL_c$.

## 4. Conclusions

In the present paper a DFAdM approach, that allows to guide the designer towards choices on the shape properties of metal alloy components, such that they are efficient from the point of view of the energy sustainability of the additive process, has been outlined. The model to quantify the process energy consumption has been developed with reference to the EBM process, but could be extended to the class of "powder bed fusion" processes.

The example on Ti-6Al-4V components, with the variation of some properties of the shape, highlighted the appropriateness of the α and β parameters, introduced to characterize each design solution, expressing the geometric and volumetric properties of components. The model for quantifying the specific energy consumption, as a whole, allow for direct control on the effect in terms of energy sustainability, referable to design variables choice and process parameters settings, being the latter closely related to the choice of material.

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## References

Al-Bermani, S.S., Blackmore, M.L., Zhang, W., Todd, I., 2010. The Origin of Microstructural Diversity, Texture, and Mechanical Properties in Electron Beam Melted Ti-6Al-4V. Metallurgical and Materials Transactions 41A, 3422-3434.

Aliprandi, P., Giudice, F., Guglielmino, E., La Rosa, G., Sili, A., 2019. Creep Behavior of Ti-6Al-4V Alloy Specimens Produced by Electron Beam Melting. Metallurgia Italiana 6, 18-23.

Arcam EBM, Welcome to Manufacturing Unbound, www.arcam.com, accessed in May 2019.

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Hague, R., 2017. Shape Complexity and Process Energy Consumption in Electron Beam Melting: A Case of Something for Nothing in Additive Manufacturing? Journal of Industrial Ecology 21, S157-S167.

DebRoy, T., Wei, H.L., Zuback, J.S., Mukherjee, J.W., Elmer, J.O., Milewski, J.O., Beese, A.M., Wilson-Heid, A., De, A., Zhang, W., 2018. Additive Manufacturing of Metallic Components: Process, Structure and Properties. Progress in Materials Science 92, 112–224.

Faludi, J., Baumers, M., Maskery, I., Hague, R., 2017. Environmental Impacts of Selective Laser Melting: Do Printer, Powder, or Power Dominate? Journal of Industrial Ecology 21, S144-S156.

Gaytan, S.M., Murr, L.E., Medina, F., Martinez, E., Lopez, M.I., Wicker, R.B., 2009. Advanced Metal Powder Based Manufacturing of Complex Components by Electron Beam Melting. Materials Technology 24, 180-190.

Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2016. Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components. Journal of Cleaner Production 135, 1559-1570.

Ingarao, G., 2017. Manufacturing Strategies for Efficiency in Energy and Resources Use: The Role of Metal Shaping Processes. Journal of Cleaner Production 142, 2872-2886.

Kellens, K., Renaldi, R., Dewulf, W., Kruth, J., Duflou, J.R., 2014. Environmental Impact Modeling of Selective Laser Sintering Processes. Rapid Prototyping Journal 20, 459-470.

Kellens, K., Baumers, M., Gutowski, T.G., Flanagan, W., Lifset, R., Duflou, J.R., 2017. Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. Journal of Industrial Ecology 21, S49-S68.

Le, V.T., Paris, H., 2018. A Life Cycle Assessment-Based Approach for Evaluating the Influence of Total Built Height and Batch Size on the Environmental Performance of Electron Beam Melting. International Journal of Advanced Manufacturing Technology 98, 275-288.

Le Bourhis, F., Kerbrat, O., Dembinski, L., Hascoet, J.-Y., Mognol, P., 2014. Predictive Model for Environmental Assessment in Additive Manufacturing Process. Procedia CIRP 15, 26-31.

Lewandowsli, J.J., Seifi, M., 2016. Metal Additive Manufacturing: A Review of Mechanical Porperties. Annual Review of Materials Research 46, 151-186.

Mirone, G., Barbagallo, R., Corallo, D., Di Bella, S., 2016. Static and Dynamic Response of Titanium Alloy Produced by Electron Beam Melting. Procedia Structural Integrity 2, 2355-2366.

Paris, H., Mokhtarian, H., Coatanéa, E., Museau, M., Ituarte, I.F., 2016. Comparative Environmental Impacts of Additive and Subtractive Manufacturing Technologies. CIRP Annals 65, 29-32.

Priarone, P.C., Ingarao, G., Di Lorenzo, R., Settineri, L., 2017. Influence of Material-Related Aspects of Additive and Subtractive Ti-6Al-4V Manufacturing on Energy Demand and Carbon Dioxide Emissions. Journal of Industrial Ecology 21, S191-S202.