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Investigation on Electron Beam Melting: Dimensional accuracy and process repeatability

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ABSTRACT

Electron Beam Melting (EBM) is one of a few Additive Manufacturing (AM) technologies capable of making full-density functional metallic parts. In particular, the ability of direct fabrications of metallic parts can accelerate product designs and developments in a wide range of metallic-part applications, especially for complex components, e.g., fine network structures, internal cavities and channels, which are difficult to make by conventional manufacturing means. In the field of aerospace industry it is crucial for quality certification purpose that components are produced through qualified and robust manufacturing processes ensuring high product repeatability. The work presented describes the results of an experimental study on the variability in the dimensional accuracy of rectangular parallelepiped samples manufactured in Ti6Al4V by EBM technology. The dimensional accuracy of obtained samples was put into relationship with EBM process parameters, such as orientation, location and height of the sample in the build chamber.

1. Introduction

Several techniques of building up geometries layer by layer have been developed and successfully commercialized under several trade names since the first introduction in 1986 [1,2]. All techniques have the layer-additive approach in common, so they are often generalized as Additive Layer Manufacturing (ALM). This group of technologies offers many design and manufacturing advantages, such as short lead time, complex geometry capability, and tooling free.

Among the others, the Electron Beam Melting (EBM) manufacturing process is a relatively new AM technology [3,4] and it is commercialized by ARCAM AB under patent-protected condition. Similar to electron-beam welding [5], EBM utilizes a high-energy electron beam, as a moving heat source, to melt metal powder and produce parts in a layer-building fashion by rapid self-cooling.

In the EBM, 3D parts are produced in a layer-building fashion by using a high-energy electron beam as a moving heat source to melt metal powder. EBM technology has been designed to process titanium alloys and in particular the Ti6Al4V alloy, as well as materials that require elevated process temperatures. The EBM process is characterized by the fine resultant microstructure, by very low residual stress, by surprisingly good mechanical properties and occur in a vacuum environment in order to minimize any contamination which is particularly critical when titanium alloys are being processed. The microstructure is much finer than seen in normally processed titanium [6,7] since the melting and solidification takes places in a matter of seconds. During the process, the Ti6Al4V powder bed is pre-heated in the range of 500 °C to 700 °C before the melting: such feature, peculiar of the EBM technology, reduce thermal gradient in the build (low residual stresses) and the material age hardens. Due to the relatively low oxygen level, the fine-grain size, and the in situ age hardening the mechanical properties of the Electron Beam Melted (EBMed) Ti6Al4V are similar to those ones of normally processed titanium [8–10].

The main applications of the EBM process are in critical fields like the biomedical and aerospace one where high product repeatability is very crucial. A very complex certification procedure is needed in order to demonstrate that additive manufactured parts meet a predetermined set of physical, mechanical and chemical properties.

The certification procedure of traditional manufacturing processes is a relatively simple and well established practice in the industry. On the other hands, in the additive manufacturing industry there are still no standard for terminology, test and quality control methods to be used in fabricating and certifying additive manufactured parts.

Especially in the aerospace field, the lack of knowledge about the

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robustness and repeatability of the EBM process makes the certification process very difficult and expensive. These problems limit the use of EBM technology in the massive production of aerospace components.

The objective of the present work is to assess the robustness and product repeatability of the EBM process in terms of dimensional accuracy on rectangular parallelepiped samples manufactured in Ti6Al4V.

2. State of the art on dimensional accuracy of additive layer manufactured parts

Dimensional accuracy of a part represents the degree of agreement between the manufactured component dimensions and its designed specifications. Another critical aspect is the repeatability of the dimensional accuracy connected to the manufacturing technology.

In additive manufacturing processes several factors, sometimes dependent by each other, affect the dimensional accuracy of the parts. For these reasons, a lot of study have been carried out aimed at understanding how to improve the dimensional accuracy of additive manufacturing processes. Many research experiences have pointed out as accuracy is mainly influenced by the STereo Lithography interface (STL) drawing quality and powder material quality.

In the ARCAM EBM machines the CAD model is inputted in the standard STL input file format. The STL file approximates the surface of the three dimensional CAD model by triangles. The use of small triangles during the STL file generation makes the representation of the surface of the component to be printed more precise. However, too small triangles generate too heavy STL files that are hardly manageable by the software and for this reason it is not possible to achieve too high levels of accuracy [11].

The particle size distribution also affect the part accuracy. In particular, the finer is the powder granulometry, the greater the surface quality that can be achieved [12]. Nevertheless, the choice of the granulometry is constrained by the kind of technology (laser or EBM) and by the properties and characteristics of the used material.

In addition, a further cause of part inaccuracy is the shrinkage during the solidification process which may not occur in a uniform manner. Indeed, the existing part substrate, wafer supports or the sintered powder acting as supports can constrain the shrinkage of a new layer. Moreover, parts with high thermal inertia (thick wall) can generate higher temperatures around them, resulting in a greater tendency to shrink with respect to low temperature zones. Scaling factors are applied in each direction to the STL file in order to compensate for shrinkage [13].

The dimensional accuracy achieved by additive manufacturing processes has been investigated in the research community especially for those technologies based on laser as heat source: selective laser sintering (SLS) [13], selective laser melting (SLM) and direct metal laser sintering (DMLS) [14–16].

Only few work assessing the dimensional accuracy of EBM process were found in literature. The geometric accuracy of metallic test part manufactured by EBM and other powder-based processes was studied in Ref. [17]. The model was a circle-diamond square test part with an inverted cone that is used to evaluate the performance of five-axis milling machines. The authors reported that overall, the observed errors of EBM parts are significantly larger than those of typical machined parts by at least an order of magnitude [17]. The errors seem to be repeatable, providing opportunities for compensation strategies.

The dimensional errors that result when manufacturing truss-like structure in EBM (such as those produced via structural topology optimization) were recently characterized and measured in Ref. [18]. The accuracy was evaluated through 3D scanning techniques. Process modifications have then been made which result in significant improvements in dimensional accuracy. This investigation highlighted the importance of heat management at features with negative surfaces to yield parts that are dimensionally accurate without introducing excessive internal melt defects in the form of voids and porosity.

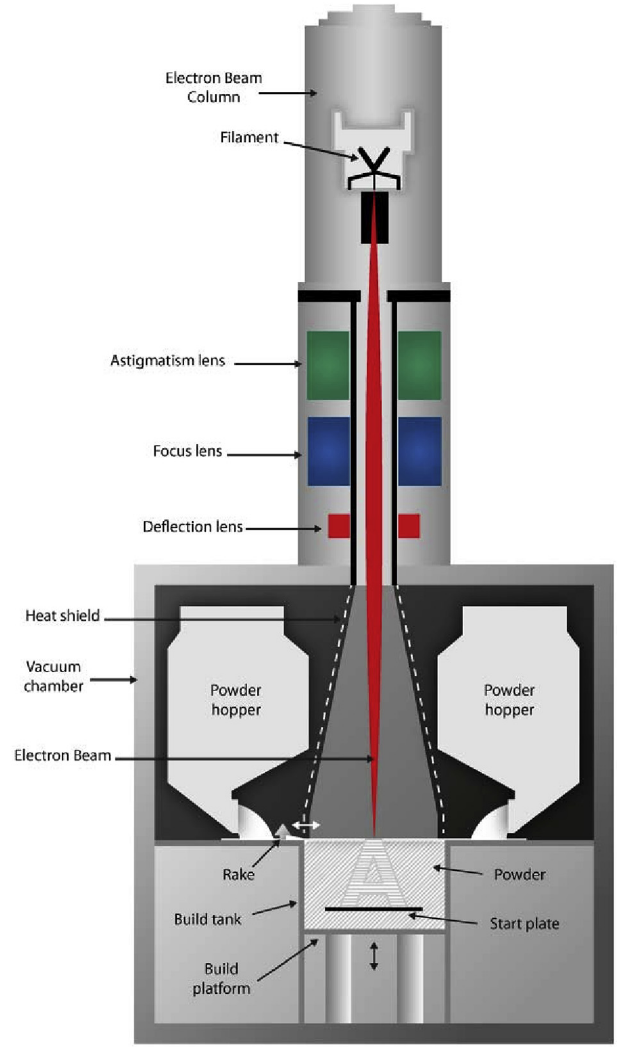

Fig. 1. Schematic representation of EBM system.

Table 1
Nominal chemical composition of the Ti6Al4V pre-alloyed powder.

Chemical Element	%	Required % ASTM F2924
Al	6.40	5.50–6.75
V	4.12	3.50–4.50
Fe	0.18	< 0.30
O	0.14	< 0.20
N	0.01	< 0.05
H	0.003	< 0.015
C	0.01	< 0.08
Ti	Balance	Balance

In the EBM process there are several intra-build process parameters that are strongly controlled by the job designer and may affect the dimensional accuracy of the manufactured parts. Indeed, the tendency to shrink can be influenced by the location of the manufactured part in the build chamber, its closeness to other components as well as by the chosen orientation growth. No research work has been found in literature assessing the influence of such parameters on the dimensional accuracy of EBMed parts although this knowledge could be very useful for job designer to improve the quality of their build. Moreover, a lack in literature was found on the repeatability of the dimensional accuracy related to the EBM manufacturing process.

The present work tries to fill such a gap by investigating on both the