New concept of support structures in Electron Beam Melting manufacturing to reduce geomtricdefects

Experimental investigation

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Abstract*—Since few years, additive manufacturing is used not only to manufacture prototypes but also functional products in many applications as aircraft, dental restorations, medical implants and automotive sectors. The Electron Beam Melting (EBM) process is considered in this study. Using an EBM process and considering overhang parts, support structures are required to improve the heat energy dissipation and to reduce the geometric defects as curling or warping, the loss of thickness and the side loss. A methodology for designing and optimizing support structures is proposed in the presented work. A contact-free support structures were applied in the experiments. An enhancement is observed for reducing geometric defects but such as support structures are not optimized (material and manufacturing). Therefore, another types of support structures are proposed and used in experiments to valid their efficiency. A good enhancement is observed analysing the overhang parts manufactured with proposed support structures. Using the proposed support structures, the geometric defects as curling and the loss of thickness are eliminated and the side loss is reduced with a good reproducibility of the CAD at the side. Experimental results prove the efficiency of the proposed support structures concept which could be implemented in industrial software.

Keywords —Metalic Additive Manufacturing, Electron Beam Melting,Support structures, Overhang, Geomtric defects.

I. INTRODUCTION

Early use of additive manufacturing (AM) in the form of Rapid Prototyping focused on preproduction visualization models (prototypes). More recently, metallic additive manufacturing technologies (Selective Laser Melting -SLM, Selective Laser Sintering -SLS, Electron Beam Melting -EBM) are being used to manufacture functional products in many applications as aircraft, dental restorations, medical implants and automotive sectors. While the adding of layer-by-layer approach is very simple, there are many applications of AM process with degrees of complexity needs enhancement in order to improve the quality of the products as well as the functional parts or surfaces. So, it is necessary to adapt parts to this new process and adapt the process to the manufacturing of functional parts and to overcome the limitation of manufacturing only prototypes.

In this study, EBM is considered as one of the few AM technologies capable of making full density metallic parts in a wide variety of industries. Therefore, scientific works in AM technologies especially in EBM focus on how to help designers to redesign the products according to the new process possibilities and constraints by creating new design rules [1].

Considering the manufacturing of the overhang parts by EBM process, some rules should be taken into account to avoid some geometric defects during the manufacturing phase and have high quality parts. The geometric defects (deformations) as curling, loss of thickness, side loss, delamination and porosity occur during manufacturing could be caused by temperature, residual stress and deflections.So, support structures have been proposed as solution to avoid these deformations of the part during its built due to thermal effects and improve the manufacturing of the overhang parts.

Béraud*et al.*[2]have been proposed new trajectories in Electron Beam Melting manufacturing to reduce curling effect focus on the adaptation of the process to the production offunctional parts. In fact, to produce them the quality of the built material has to be controlled together with the geometry of the built part. Their studies wereconducted to find the best part orientation during the built in order to reduce geometric defects [3] or to improve the geometric model description [4].Understanding of the thermal phenomena causing deformations of the part, a new strategy based on the modulation of the energy input using specific beam trajectories has been proposed.

In this paper, overhang parts are considered, for that, support structures are needed to carry the weight of the overhang section and demanded a post-processing. Therefore, Overhang parts are not suitable geometries for EBM process.

Indeed, the EBM process is considered as powder-bed-fusion additive manufacturing process and support structures are not necessary for an overhang section due to the powder bed itself that is able to support the weight of overhang portion. But, in the experiments, some deformations or defects such as warping, curling, … may occur. So support structures are required to overcome the overhang geometric defects. Infact, the geometric defects associated with overhang geometry problems using EBM process suffer of a lack of investigations in literature.

The support structures for selective laser sintering (SLS) or selective laser melting (SLM) have been investigated focus on the design and manufacturing of support structures. An approach is reported by Jhabvala*et al.* [5] using pulse laser, instead of a continuous mode, to manufacture support structures that make much easier the post-processing of the part by removing the supports. ‘‘Cellular lattice’’ as support structures and the effect of cellular geometry parameters have been investigated byYan *et al.* [6] and Hussein*et al.* [7]. Their main objectives are to make easy the access and the removal of the support and to minimize the material volume needed for support. Cellular supports for overhang parts have been developed by Strano*et al.* [8]. They developed a periodic implicit surface functions that were used to generate different cellular sizes and shapes of lattice supports in CAD files. Indeed, Calignano [9] investigated different types of support structures listed by the geometry. A point, a web and a line supports are used for very small features, circularareas and for narrow down-facing areas respectively.Considering the SLM Process overhang defects have been investigated by Thomas [10]. The main results reported is the curling as geometric defect will be affected by the raster scan pattern, more severe for the raster scan pattern perpendicular to the curl direction during the manufacturing of an overhang part.

All these studies have been addressed the aspect of the support structures and the easy removal in the post-processing but not investigated deeply the need of supports for an overhang and the reason of geometricdefects associated with overhang geometry problems.

Especially, in the EBM process, a few studies related to support structures and the source of the geometric defects are reported. Recently, Vora et al. [21] attempted to benchmark the problems with overhangs and reported cases that overhang warping occurs.More recently, Cheng and Chou [11] investigated support structures in part overhang fabrications by EBM additive manufacturing. A 2D developed thermomechanical FE model able to simulate the deformation of overhang parts in EBAM is reported. Their results suggest that a solid piece with a small gap considered as contact-free support may enhance the heat flow and restore the thermalbehaviour closer to that in the solid substrate area. In fact, including a solid piece beneath the overhang can reduce the overhang deformations. In addition, the heat support with contact-free method is easy to be detached without any post-processing.

In this paper, we propose to investigate the Contact-free support using to overcome the overhang geometry problems based on experimental methods in EBM process. The paper is organized as follows. Section 2 presents the EBM process and the Ti-6Al-4V material. Sections 3 is dedicated to present the geometric defects occur during the building of the overhang parts. Section 4 presents and analyses the experimental results with contact-free supports for overhang parts and the overhang deformations. Section 5 proposed a new type of support and analyse the role of the support that combines the heat behaviour and the maintain of the overhang portion during the building. Support structures were designed with different support parameters in powder-bed EBM process. The overhang parts with the developed support structures were studied, examined andcompared to evaluate the efficiencyof the designed support and to validate the role of the support.

II. EBM Process and Material

A. EBMprocess

This paper will study the case of the Electron Beam Melting (EBM), a layer based metallic additive manufacturing process where the energy source is an electron beam.

This process allows building parts from metallic powder layer bylayer. First, a layer of metallic powder is spread by a rake. Then the heat source, an electron beammoved by electromagnetic deflection. The high reactivity and the high speed of scan (until 8000m/s) allow to move the beam from a place to another one so quickly as it creates the effect of multiple beams and allows to maintain at the same time several baths of molten metal. The process involves a high vacuum and high temperature (up to 1000°C), which leads to differences in the training of the metal (during transformations in the solid state following the solidification). Then, it consolidates the entire layer. Second, melts selectively the powder in the zones where the part has to be built. The build table then goes down for a height corresponding to the layer thickness. The cycle can then restart from layer spreading stage. The part is formed by stacking each layer’s melted area. Finally, the built, the unmolten powder is removed by blasting it.

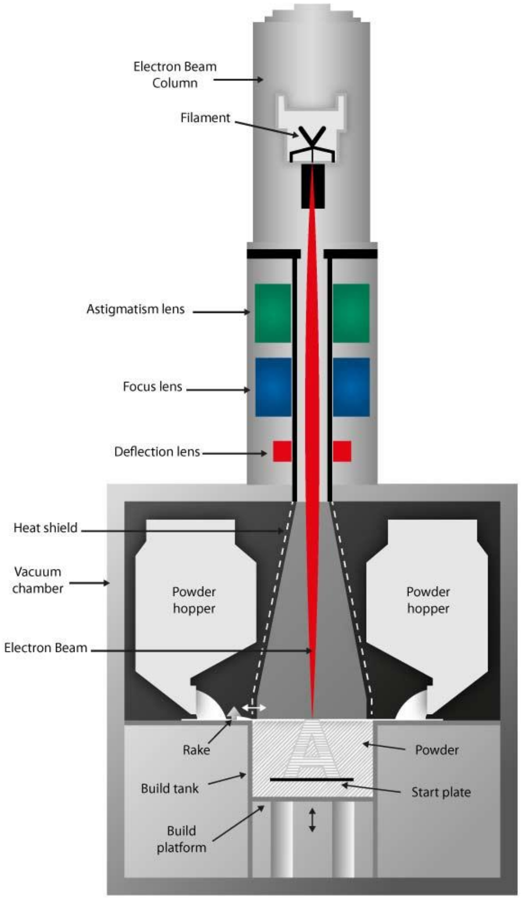


Figure 1. ELECTRON BEAM MELTING PROCESS [12]

B. *Material Ti-6Al-4V*

In our experiments, Ti6Al4V the most widely titanium alloy is used to build all parts and support structures. It features good machinability and excellent mechanical properties. The Ti6Al4V alloy offers the best all-round performance for a variety of weight reduction applications in aerospace, medical equipment and automotive. The Titanium Ti6Al4V powder has a particle size between 45 and 100 microns. This limit on the minimum particle size ensures safe handling of the powder.

The mechanical properties of a typical ArcamTi6Al4V is presented in table 1.

	ArcamTi6Al4V
	Typical
Yield Strength (Rp 0,2)	950 MPa
Ultimate Tensile Strength (Rm)	1020 MPa
Elongation	14%
Reduction of Area	40%
Fatigue strength* at 600 MPa	>10,000,000 cycles
Rockwell Hardness	33 HRC
Modulus of Elasticity	120 GPa

Table 1. MECHANICAL PROPERTIES OF ARCAM TI6AL4V [13]

The mechanical properties of materials produced in the EBM process are comparableto wrought annealed materials and are better than cast materials.

III. GEOMTRIC DEFECTS IN EBM MANUFACTURING

The part presented in figure 2 is chosen as study overhang part in this paper according to [2],[9] and [14]. The thickness of the overhang portion is chosen 2 mm according to the published scientific works in order to observe the deformation in this part and don't damage the rake in case of a contact occur between the deformed part and the rake.

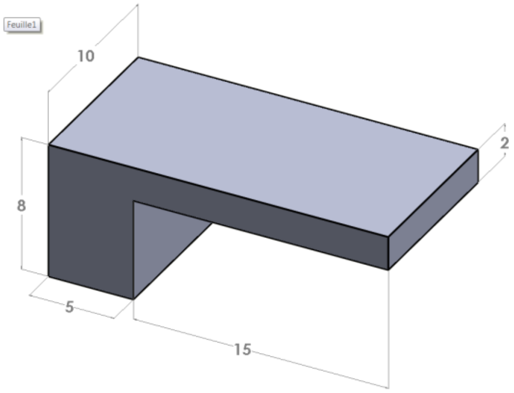


Figure 2. STUDY OVERHANG PART – CAD MODEL

Investigating the overhang part presented in figure 2 some geometric defects are occurred during the build as curling, loss of thickness, side loss, porosity and delamination. Here, we are investigated the main three defects the curling, the loss of thickness and the side loss.

A. *Curling or warping*

In additive manufacturing where the part is divided to many layers, a real problem is identified. The overhang surfaces of the part which are not supported by support structures. These surfaces are supported only by the consolidated powder underthe overhang surfaces that is strong enough to support them. So supports structures is not required in EBM manufacturing

However, in the experiments, a difference in the thermal characteristics between consolidated powder (wafer) and melted material (melt) could be affected the temperature of the melted layers and, after cooling, a curling of overhangsurfaces can be observed where the extremities go upwards (figure 3).

Figure 3. THE CURLING DEFECT

B. *Loss of thickness*

The decease of the melted material in the middle of the overhang part or between two solid supports could be influence the thickness of the overhang portion. This loss of thickness geometric defect is occurred due to the thermal phenomenon between the melted layers and supports (figure 4). So that, a good choice of the support structures is required to avoid this geometric defect of the loss of the thickness.

Figure 4. THE LOSS OF THICKNESS DEFECT

C. Side loss

Figure 5 presents the side loss defect. The decrease of the layer length due to the cooling phenomenon from melted layer to the new melted layer caused a loss of side geometry at the end of the overhang portion.This geometry defect is the most important defects that is not investigated in the literature. So the main question is: what is the origin of this deformation and how can avoid it?

Vora et al. [15] proposed a method by adding copper in order to reduce the curling defect. They show that the reduce of the curling defect does not allow the reduce of the loss side. Therefore, the reason of the occurrence of two defects curling and loss side is different. In fact, experiments are required to investigate in depth the origin of this defect.

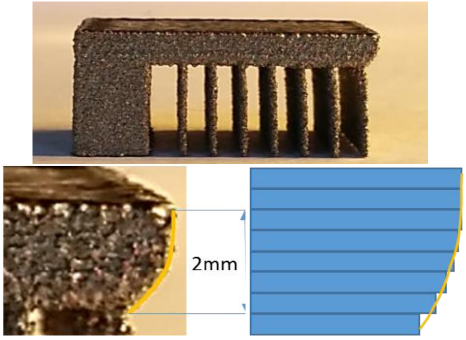


Figure 5. THE SIDE LOSS DEFECT

IV. EXPERIMENTS, CONTACT-FREE SUPPORT AND SUPPORT STRUCTURES

Based on the published scientific works [11] focus on the thermomechanical 2D FE Model that developed a contact-free heat support (figure 6). Cheng and Chou suggest that solid columns can avoid a serious overhang warping defect. A solid part beneath the overhang in the powder bed with a gap of 0.63 mm can reduce the overhang deformation such as presented by figure 7.

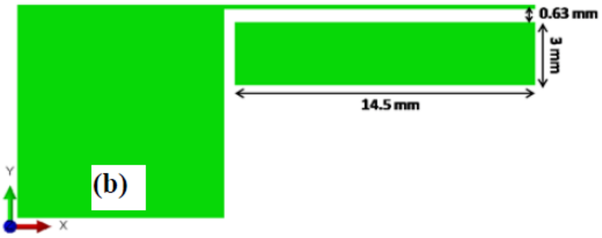


Figure 6. FE 2D MODEL OF OVERHANG PART WITH CONTACT-FREE SUPPORT [11]

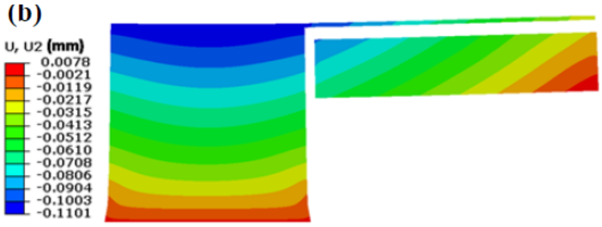


Figure 7. SIMULATION RESULT OF THE OVERHANG PART WITH CONTACT-FREE SUPPORT [11]

A series of experiments was conducted to investigate the effects of the proposed contact-free supportand to valid the finite element 2D model, the numerical results and the enhancement of the overhang parts observed numerically [11]. In the first step, experiments are addressed to contact-free support.The overhangs parts with a contact-free support using another overhang part in the inverse direction were designed with a gap of 0.5 mm. Two gap values are tested (1 mm and 0.75 mm) but they are not suitable to finish the manufacturing of the total build. A very high geometric defects are occurred and caused the broke of the rake. The conventional support was generated using the Magics software to support the inverse overhang part that has a support function to the second overhang part. Two cases are designed to test the efficiency of contact-free support in the overhang part to avoid geometric defectssuch as illustrated by figures 8 and 9.

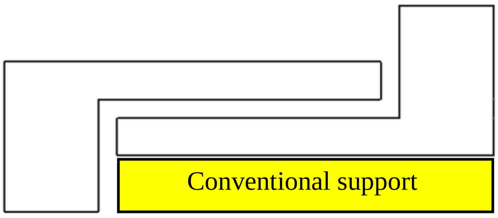


Figure 8. CONTACT-FREE SUPPORT IN AN OVERHANG PART : CAD MODEL CASE 1

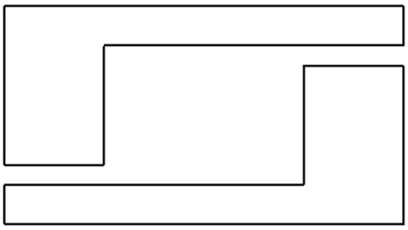


Figure 9. CONTACT-FREE SUPPORT IN AN OVERHANG PART : CAD MODEL CASE 2

The experimental results (figures 10 and 11) show that contact-free support enhances the geometry of the overhang part. However, some geometric defects are presented in the overhang part manufacturing used a contact-free support. Indeed, the solid part used as a contact-free support demand a huge quantity of material and this contributes to increase the material use and not reduce the mass and material consumption.

Figure 10. MANUFACTURED OVERHANG PART WITH CONTACT-FREE

SUPPORT CASE 1

Figure 11. MANUFACTURED OVERHANG PART WITH CONTACT-FREE SUPPORT CASE 2

Taking into consideration the objectives to reduce material consumption and to reduce mass. Support structures are developed to avoid the geometric defects and to valid the main role of the support. Two kind of support structures are used and presented in figures 12 and 13.

The objective of this section is to examine the overhang part with the proposed support structures (type 1 and 2) based on experimental manufactured overhang parts.

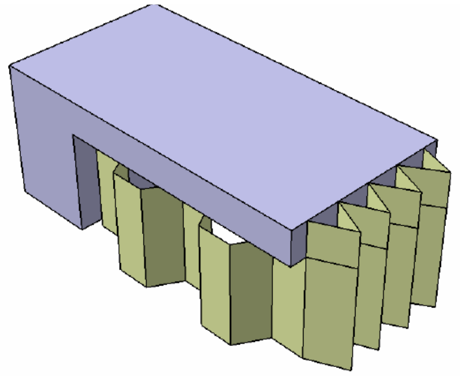


Figure 12. CAD MODEL OVERHANG PART WITH PROPOSED SUPPORT STRUCTURE TYPE 1

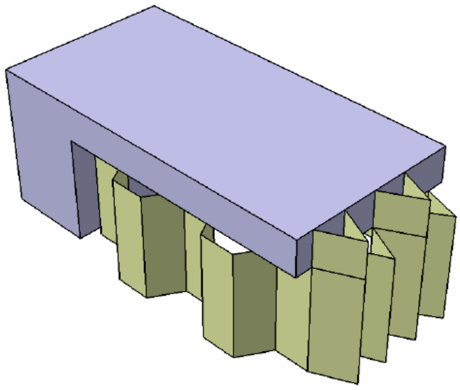
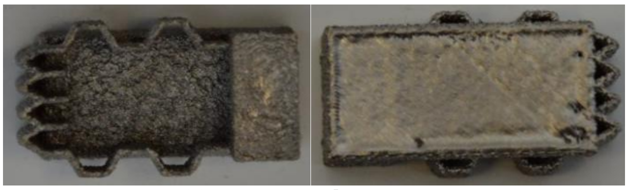


Figure 13. CAD MODEL OF OVERHANG PART WITH PROPOSED SUPPORT STRUCTURE TYPE 2

Careful analysis of the manufactured overhang parts using EBM processwithour proposed support structures (figures 14 and 15) suggest that a pronounced enhancement is observed. The curling defect is avoided as well as the loss of thickness. A pronounced enhancement in the loss side is observed where support structures used in the overhang parts are maintained the side and avoid the loss side and the curling. So that, experiments conduct that the main role of support is to maintain the overhang portion of the part in addition to the heat transfer function.

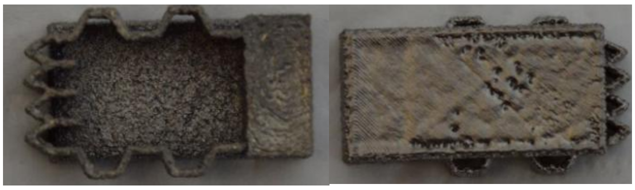


(a) Bottom and top views

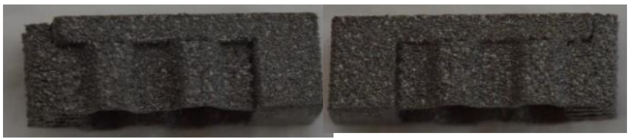
(b) Side views

(c) Front view

Figure 14. MANUFACTURED OVERHANG PART WITH PROPOSED SUPPORT STRUCTURE TYPE 1



(a) Bottom and top views



(b) Side views

(c) Front view

Figure 15. MANUFACTURED OVERHANG PART WITH PROPOSED SUPPORT STRUCTURE TYPE 2

Focus in the side loss defect, figure 16 present a pronounced enhancement at the reproducibility of the side. Indeed, the support structures at the font of the side are necessary to avoid the deformation of the melted layers at the cooling phase. Therefore, we can conclude that the main role of the support structures is the maintain the melted layers and avoid the deformation as curling and side loss.

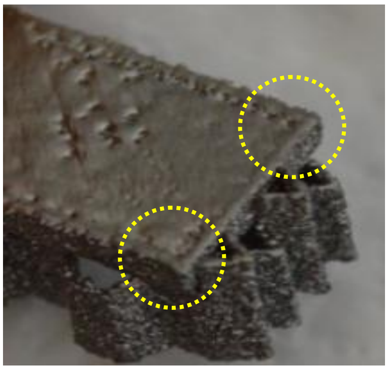


Figure 16. A GOOD ENHANCEMENT AT THE SIDE USING OUR PROPOSED SUPPORT STRUCTURE TYPE 2

V. CONCULSIONS AND PRESPECTIVES

This paper focus on the geometric defects and the deformations of the overhang part during its built caused by the thermal effects and residual stresses using a EBM process. The aim is to show the interest to use a new concept of support structures to reduce these thermal effects and ensure the reproducibility of the overhang parts comparing by CAD model.

In the first section, a free-contact heat support proposed in the literature using numerical study based on 2D FE model to simulate the EBM process is investigated. Thissolution (free-contact heat support structures) to avoid these deformations is discussed. The efficiency of the contact-free support is validated by experimental study (manufacturing of the overhang parts with contact-free support using the EBM process). Experimental results show that the geometric defects are reduced byminimizing overhang distortions. But, the contact-free support structures required a huge quantity of material that cannot be recycled under the built of the overhang parts. An optimization study could be realised for the contact-free design.

In the second section, the thermal phenomena and the EBM technology process layer by layer at the overhang portions causing deformations of the part are explained in order to propose a new concept of the support structures to limit deformations and geometric defects. This support structure is based on the adding support at the front of the part end. Experimental results show a good enhancement at the quality of the manufactured overhang part with proposed support structure. Indeed, we can conclude that the main role of support structure is to maintain the overhang portion during the build to avoid any deformation caused by thermal phenomena. Future works will be focus on the improvement of the new concept of support structures and their extension to complex-shaped components.

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