A REVIEW ON THE FUNCTIONAL FEATURES OF PARTS PRODUCED BY ADDITIVE MANUFACTURE IN COMPARISON WITH OTHER CONVENTIONAL PROCESSES

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Abstract*. Additive Manufacture – AM – is presenting an increasing growth in the last decades regarding the production of mechanical parts, due to its outstanding characteristics in relation to conventional processes. Indeed, AM is able to produce parts with unique geometries at once, which could otherwise require a lot of different operations or processes. This work aims to describe the AM variations in the mechanical parts production and their main functional features, like mechanical resistance and dimensional tolerances, when compared to currently known processes, in order to investigate their potential and competitiveness on replacing the former usual processes. Some constraints in AM technology are also raised, showing its limitation and impracticability in some applications.*

Keywords*: Additive Manufacturing, AM, Rapid Manufacturing, Direct Manufacturing*

1. INTRODUCTION

The production processes known until some decades ago were Subtractive Manufacturing (e.g.: milling, turning, drilling) and Forming Manufacturing (e.g.: casting, forging, stamping). Additive Manufacturing (AM) also known as Layer Manufacturing (LM), is a recent computer dependent technology that has proven its success as an option for production of parts in a wide application range, but still subject to some important limitations. Its main advantages in relation to other processes are:

• AM can generate high complexity items, with shapes that could be very difficult or even impossible to be manufactured by other conventional processes. AM allows also a unique assembly that could instead require the fitting of several parts;
• Saving of material (product cost) and weight (operational costs) are allowed by design topological optimization (Marchesi et al., 2015), which configures the part shape just within the requirements of its mechanical strength. AM is able to manufacture complex geometries without restriction;
• The absence of waste material, like chips resulting from machining, is also a great AM advantage in terms of cost reduction, due to saving of energy, material, tooling and man power as well;
• Failures due to operator's errors or tool breakage, mainly at final machining stages do not exist with AM. This is also a cost benefit;
• AM allows remanufacturing of expensive parts with worn surfaces which would be discarded otherwise. Filling with layers of high strength metals recover the component original features (Brückner et al, 2015);
• The use of high fusion temperature metals and alloys is also an AM advantage, mainly regarding absence of part machining;
• No or minimum post treatment is required with AM – this fact leads to an additional cost saving;
• Expensive tooling investments (forming, machining) are not required with AM. This allows availability of functional prototypes in a very short time and with low cost;
• Due to its computer based technology, AM also presents easy application on reverse engineering to generate new parts, almost identical, by means of three-dimensional (3D) scanning of existing parts – this prevent a completely new design (Chen and Ng, 1997).
  Important limitations are inherent to AM part build principle:
• The low production due to the high part production time. Mass production is not possible;
• The part size is limited by machine compartment dimensions;
• Other specific AM features in comparison to conventional processes, demand close control and adjustments to allow part quality. These features are mainly connected to material soundness and dimensional tolerances.

All the factors listed above lead to the selection of AM in applications which present low production volumes that can be benefited of the cited advantages, depending on the case, with consideration of the process inherent constraints. Application examples where AM is advantageous are parts used in aerospace components (Brückner et al, 2015).

The scope of this work is the discussion of AM processes related to metallic parts, mainly regarding to material structure and their geometric features, in order to allow comparison with other traditional processes, as described further in this text.

2. AM WORKFLOW

AM involves several different processes and materials, but in a rough analysis, a simple generic AM workflow may be considered (Wong and Hernandez, 2012; Gebhardt, 2011; Gibson et al., 2010; Chua et al., 2003), as illustrates Fig. 1. Specific details depend on each process. Steps are described as follows.

• CAD 3D solid or surface file creation - All AM processes start with a CAD 3D design, which results in a solid or surface representation file. Almost any professional solid modeling software can be used (Gibson et al., 2010). This file can also be created by reverse engineering (Chen and Ng, 1997), through laser scanning of an existing part;

• STL file conversion - The next step is the CAD file conversion in a STL format. The STL suffix came from Stereo Lithography (Chua et al., 2003; Cooper, 2001), Standard Tessellation Language (Wong, 2012), Stereo Lithography Language or Standard Transformation Language (Gebhardt, 2011). The STL formulation defines the slicing of the part volume by means of transforming it in triangular facets (Gibson et al., 2010), which size determines the layer thickness and the resolution (accuracy) chosen by the designer for any given geometry. The greater the number of triangular facets (smaller their size), the greater is the resolution and the file size (Gebhardt, 2011). Triangular facets in an STL file must obey two rules (Huang et al., 2002):

(1) Each triangular facet must share one, and only one, edge with each of its adjacent triangles. In other words, a vertex of one triangle cannot lie on the side of another;

(2) The orientation of the facet is specified in two ways, which must be consistent. First, the direction of the normal vector is outward. Second, the vertices are listed in a counterclockwise order when looking at the object from the outside.

After software conversion is ready, some adjustments are needed for triangles vertices adjustment. This is done by specific algorithms (Huang et al., 2002). Additional correction is done manually (Gibson et al., 2010). Since 1990, several studies have been developed to improve the STEP-NC (a machine control tool language). It mainly describes procedures to remove material (Rauch et al., 2014). Several researchers are working towards an integration of AM with the open platform STEP-NC (Xiao et al., 2015).

• Part build - The STL file, after refinement, is transferred to the AM machine. Generally, the machine software allows part visualization. The operator can reposition the part or change its orientation to permit building of more than one item or improve part surface resolution. Some software allows scaling and segmentation of STL files to make possible building of parts larger than machines compartment (Gibson et al., 2010). A simple or more complex machine setup is needed depending on the equipment. The first build is generally semi-automated for operator's adjustment and then fully automated. A cleanup or further tasks are required after removal of the part;

• Finishing - This process stage is very application-specific. A post-processing is necessary depending on the case, which could include heat/pressure treatments, sandpapering, polishing or application of coatings.
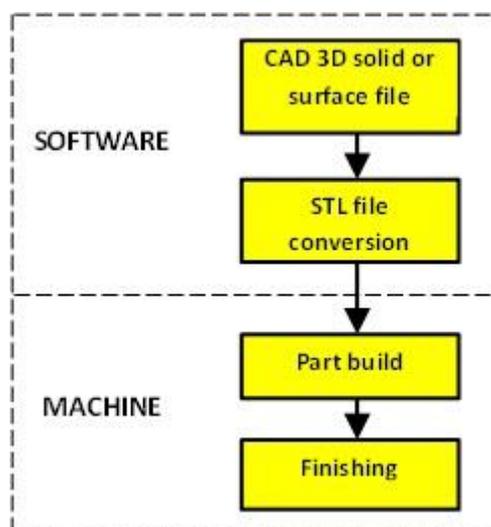

Figure 1 – AM generic flow

3. AM PROCESSES

As its name indicates, AM comprehends all processes that adds material during a part build, making it difficult to enumerate all of them. In this work, only the processes related to material layer addition – Layer Manufacturing (LM) of metals are considered and are following described. Liquid and powder based processes of non-metallic materials like plastics, as well as Laminated Object Manufacturing (LOM), will not be described in this work due to its objective. An overview on the AM processes can be found in (Wong and Hernandez, 2012). A comprehensive explanation on AM processes is found in (Gebhardt, 2011; Gibson et al., 2010; Chua et al., 2003; Cooper, 2001).

LM processes considers few basic steps (see Fig. 2):

(1) Material is fused, sintered or bound over a support surface depending on the process type. The material can be already laying in the surface (powder) or can be projected over it (powder, binder, extrusion), mainly by a beam fashion way and then hatched over the surface following an external contour defined by part's horizontal slice, or layer, geometry;

(2) After the first layer is ready, the support platform is lowered by a device at a distance equal to the layer thickness and the material deposition follows the same procedure of the preceding layer, including the support surface lowering;

(3) When the last layer is ready, the process is finished and the part is removed from machine compartment. This process condition is called "as fabricated" (AF);

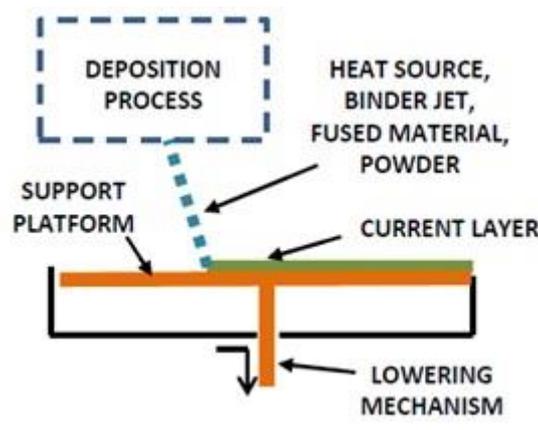(4) Depending on the process and other requirements, post processing is performed before part delivery.

Figure 2 – Generic LM Process device arrangement

3.1. Important properties of metals in part build

Materials can be classified as either crystalline or non-crystalline (or amorphous) (Kridli, 2006):

• Crystalline structures are organized structures in which atoms and molecules of solids arrange themselves in a regular and repeating manner that is called lattice. Metals present different crystalline structures depending on the position of their atoms that are most commonly of the types Body-centered cubic -BCC (such as in iron), Face-centered cubic - FCC (such as in aluminum), and Hexagonal close-packed - HCP (such as in magnesium).

• On the other hand, amorphous structures have some level of local order relative to their neighbors, but globally, they do not have an ordered structure like crystalline materials. Amorphous structures are generally observed in glass and plastic materials, even though some plastics also have a semi-crystalline structure, which is a combination of crystalline and amorphous structures.

Metals possess several properties which can be used for design specification and inspection evaluation for conformity and comparison among different material types. The most common and important properties are the yield strength (maximum stress that can be applied without causing plastic, or permanent, deformation), ultimate tensile strength (maximum stress that can be applied without causing necking), stiffness (resistance to deformation or deflection), electrical and thermal conductivities, toughness (ability to absorb energy without fracture) and hardness (resistance to deformation by indentation).

These properties, however, depend on the quality and condition of the material crystalline structure, which can affect their values:

• Homogeneity – condition where the properties are the same at ever portion in the material structure. Defects like inclusions, voids and cracks make the material non-homogeneous;

• Isotropy is the property of being directionally independent. An anisotropic material implies in different properties in different directions.

Different processing of the same metal or metal alloy can lead to different properties, which can jeopardize its application requirements. The major challenge on comparing AM with other production processes, like casting and forming, is that if the built part will have the material properties according to the ones needed and specified in the design. In other words, how different are the same material properties when it is AM processed or subject to other conventional processes?

Some works deal with the certification issue involving AM (Seifi et al, 2016). Standards are being proposed for this intent.

3.2 AM Processes for building metal parts

As already mentioned, AM processes vary according to different materials. This text treats only with metallic materials and their main AM processes are briefly described in their basic aspects, since several variants and registered names (not cited) are used by different manufacturers. AM terminology was also agreed and standardized by ISO and ASTM (ISO/ASTM 52900, 2015). It is convenient to separate them in two classes (Lewandowski and Seifi, 2016). :

3.2.1. Powder Bed Fusion (PBF)

In this class, the material is supplied in form of powder lying in a surface. The following types follow this class:

- **Laser Sintering (LS) or Selective Laser Sintering (SLS)** - In LS or SLS a powder is sintered by a carbon dioxide laser beam. To allow operation with a lower laser power, the machine chamber containing the powder is heated near the material melting point, making the powder surface to fuse with a small temperature differential. The chamber is also flooded with a shielding gas, to prevent oxidation (Gebhardt, 2011). A laser scanning device is provided to reach all points of the work surface. After part completion, it needs cooling down and cleaning up for powder removal.

- **Laser Melting (LM), Laser Beam Melting (LBM) or Selective Laser Melting (SLM)** - These are basically the LS/SLS processes, where sintering is replaced by a locally fully molten material. Materials are only metals, carbon steel, titanium, aluminum and alloys are examples. Equipment differences in relation to LS and SLS include a fiber laser beam and different shielding gases (Gebhardt, 2011).

- **Electron Beam Melting (EBM)** – EBM is an AM powder based process where electron beam is used instead of the laser. For this, the laser source, lenses and mirrors are replaced by an anode and electromagnetic focus and deflection wire coils. This set up is also used for process preheating and the shielding gas is also replaced by a highly sealed vacuum chamber. EBM, due to its nature, is a very fast process and operates at high temperatures (Gebhardt, 2011).

3.2.2. Directed Energy Deposition (DED)

In this class the metal in form powder or wire is ejected/fed by a nozzle and is melt by an energy beam at a work surface point. The molten metal solidifies when it is cooled down. The DED process is also known as Laser Metal Deposition (LMD) and provides a high built rates and larger built volumes than LBM ones (Herzog et al, 2016). To prevent oxidation, an argon inert atmosphere is provided at a sealed work chamber (Wong and Hernandez, 2012). One example of DED process is Laser Engineered Net Shaping (LENS).

4. FEATURES OF PARTS BUILT BY AM IN COMPARISON TO CONVENTIONAL PROCESSES

4.1. Mechanical Properties

The AM fabricated material characteristics depends greatly on the bulk material and the sintering/melting process. During metal AM, a defined volume element of the material is usually subjected to a complex thermal cycle, which involves a rapid heating above melting temperature due to the absorption of the energy of the laser or electron beam and its transformation into heat, a rapid solidification of the molten material after the heat source has moved on, and numerous re-heating and re-cooling processes when the following layers are welded and the volume element is still exposed to heat. The complex thermal histories that are associated with AM processes strongly influence the microstructure, as each discrete volume of a component deposited by an AM technique may have a thermal history that differs significantly relative to the adjacent volume (e.g., near edges). AM microstructure is therefore a result of the above described thermal cycle. Irrespective of the material, a fine-grained structure has usually been observed for AM in comparison to other processes, e.g. casting (Herzog, 2016; Collins, 2016).

According to Collins et al (2016), the influence of powder characteristics still remains an unexplored aspect of simulations, despite the efforts on predicting the evolution of material in both powder bed and powder-blown approaches. Metal powder is produced by different methods, which imply in different powder characteristics such as

particle morphology, particle size and chemical composition. These characteristics affect the final AM material, which process requires good flow properties in order to achieve homogeneous spreading of the powder as well as good packing characteristics for the formation of a layer with high relative density. The powder particles must be as spherical, finer and oxygen free as possible for a good AM result. Powder characteristics impact the bulk material properties of the fabricated component such as its density and porosity. The majority of metal powders are typically produced using methods such as water, gas or plasma atomization. Especially in the field of Ti and Ti alloys, electrolytic methods, metallothermic processes and the hydride-dehydride process are under development or already used for cost-effective metal powder production. The most simple and low-cost atomization process is water atomization, where liquid metal is atomized by water jets when free falling through the atomization chamber, but due to the high cooling rate the particles adopt an irregular shape during solidification, leading to an irregular and asymmetric particle shape, which is at a disadvantage of high packing density and so are not preferred for the use in AM. Also, water atomization powder particles present high oxygen content, causing the formation of oxide layers with undesired effects as they not only influence the powder flow behavior but also impact the melt pool and consequently change the bulk material composition and the parts mechanical properties. Gas atomization is usually used for producing feedstock for AM to prevent water atomization limitations. The risk of oxidation is reduced by using an inert gas, such as argon or nitrogen, for atomization of the melt and thus gas atomization is the preferred method for reactive materials such as Ti, however the method may also be used for non-reactive materials such as steel. The particular choice of inert gas influences the development of the microstructure of the particles and consequently does also affect the microstructure of the parts manufactured via AM. Due to cooling in an inert gas atmosphere, heat conduction between the metal and the surrounding gas allows formation of spherical powder particles, ideal for AM build (Herzog et. al, 2016).

Other processes used for production of spherical metal powders are plasma melting inert gas atomization as well as induction plasma spheroidization, both well known for Ti powder production. While in plasma atomization the raw material is a wire that is melted and atomized using plasma torches and an inert gas, e.g. argon, the feedstock in the spheroidization process is an irregular, non-spherical metal powder that is melted by inductively coupled plasma. Compared to other atomization processes the solidified powder particles are finer and feature an average particle size of 40 μm. Spherical particles favor the desired flow ability and apparent density for AM (Herzog et al, 2016).

Following this explanation, the main mechanical and geometric properties of AM are resumed in this section.

4.1.1. Static Strength

In general, the static strength depends on the density of the parts, as well as on the microstructure formed during AM. As compared to parts which are fabricated by other processes (e.g. casting), the microstructure of AM fabricated parts is finer. The Hall–Petch relation predicts that as the grain size decreases, the yield strength increases and therefore reveals a higher static strength. So, in general, AM fabricated parts present higher yield strength compared to other processes (Herzog et al, 2016).

4.1.2. Tensile Properties

AM parts, due to their building nature, present an anisotropic structure with regard to the build direction. Consequently, the tensile properties are also anisotropic and strongly depend on the orientation and the tensile strength and the strain to failure in as-fabricated (AF) parts are higher in build direction than orthogonal to it. AM fabricated steels and aluminum alloys often meet the ASTM standard specifications even in the AF state. Grain refinement leads to a considerable increase in both yield and ultimate tensile strength. Regarding titanium alloys, they are probably the most investigated AM materials and in general show increased tensile strength compared to cast or wrought material (e.g. Ti-6Al-4V). All AM techniques meet or exceed yield and ultimate tensile strengths of ASTM specifications for cast and wrought materials usually applied in industry, except in the case of little elongation for the LBM AF state. Microstructure images and detailed comparative tables are referred in Herzog (2016) and Lewandowski (2016).

4.1.3. Fatigue Strength

The AM processes, due to their build characteristics, in general present factors that reduce the fatigue strength in comparison with other production processes. The fatigue strength of metallic materials primarily depends on their microstructure, as occur with the static strength. However, process-inherent properties such as surface roughness and material defects strongly influence the fatigue performance of AM fabricated parts. Coarser surface roughness causes increased stress concentration and early failure of AM parts under fatigue loading in AF condition. Mechanical surface treatments (e.g. polishing) improve the fatigue behavior. However, material defects such as porosity and insufficient layer bonding affect negatively the fatigue properties. Control of these defects by adequate process real time monitoring (Brückner, 2015) and densifying the material by hot-isostatic pressing (HIP) (e.g. by maintaining a part of Ti alloy for 4 h at 920 °C and 103 MPa) in order to relieve stresses and to reduce any remaining porosity. Results found in Herzog (2016) show improved fatigue properties and values comparable to cast and wrought materials.

4.2. Geometric Properties

The accuracy prediction in AM processes is still an open issue, only few indications relating the dimensional deviations exist. Analysis of the subject literature also indicates two observations:
(1) The absence of an appropriate consideration on error correction methods, involving repetitive errors (geometric) and non-repetitive errors (caused by secondary causes, as heat and force deformations, wear and vibration - or random - errors) (Nakazawa, 1994);
(2) The lack of a systematic analysis regarding production processes, like Process Statistical Control (PSC) on verifying measured values bias. According to Liu et al. (1998a), LM produced parts accuracy depends on an error propagation mechanism, i.e., the resulting error is an effect of individual error accumulation. Some researchers presented benchmarking studies by Quality Function Deployment (QFD) to analyze relationship strength among several accuracy influencing factors (Dimitrov et al., 2006).

Prior to discussing the sources of dimensional and surface inaccuracies in the AM processes, let us revisit the theoretical LM process approach:
(1) Each layer is hatched in the x - y directions by a radiation beam or/and a material ejection nozzle scanning, following a CAD contour in a plane;
(2) The next layer is hatched over the former ready layer in the z direction.

Sources of inaccuracies can be studied separately:

4.2.1 Design/ Software related inaccuracies

The first consideration must be made between the x - y CAD model theoretical exact dimension and the process beam/nozzle position, regardless of process type or material being used. As the CAD scanning (hatching) software considers the center line of the beam as the layer contour, a theoretical error, one half of beam diameter, can be present, as illustrates Fig. 3. So, in principle, a compensation of half of the tolerance zone must be considered for all CAD designs when LM is intended as fabrication process. The designer must know the process to be used and its beam diameter prior to deliver the CAD file (Gebhardt, 2011).
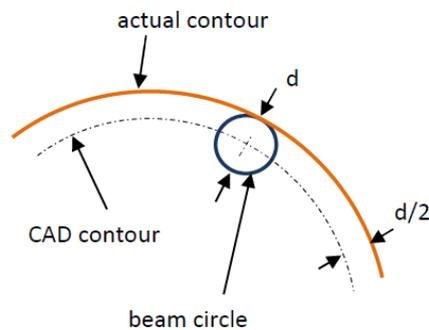

Fig. 3. CAD/Process contour variation

The second geometric inaccuracy concern observed in AM manufacturing, in the z direction, is related to its primitive building concept, that is, the layer contour generates a staircase effect on part surface (Liu et al., 1998b; Hope et al., 1997; Dolenc and Mäkelä, 1994). This feature causes an inherent roughness that, when removed by finishing processes (e.g.: sand papering or grinding), reduce outside dimensions as shown in Fig. 4. Kaji and Barari (2015) proposed a more realistic model for the staircase effect - a step cusp profile - based on 3D topography microscope images. Material adding processes can also be considered with the due considerations. Posttreatment is particularly important when the surface is functional, that is, it will be assembled with other parts. Layer thickness is resulting of the AM process type, but the smaller the layer thickness the greater the number of layers and consequently greater is the building time. Layer thickness depends also on the material characteristics.

One way of dealing with this concern is to consider different layer thicknesses (adaptive slicing) in the same material adding process. This procedure was proposed by Kulkarni and Dutta (1996). For example, vertical surfaces may consider as great as possible layer thickness, so speeding up the process time. Surfaces subject to dimensional constraints may be made with thinner layer height, allowing less post-processing.

Other design dependent LM inaccuracy factor refers to the hatching style considered, which can jeopardize part geometry, mainly if it is intended for tooling production (hatching can be understood as a pattern of parallel movement of the beam/nozzle on building a layer). According to Onuh and Hon (2001), when layers are scanned (hatched) in just one direction, different part distortions can occur, like post cooling shrinkage, swelling, cantilever curl distortion,

vertical wall distortion and horizontal slab distortion. In order to prevent these inaccuracies, different strategies on hatching subsequent layers (alternate exposure) are suggested, as divergent star weave (DSW) and diagonal divergent star weave (DDSW). These strategies are based on the hypothesis that alternate exposure of layers homogenizes the residual stress structures when they start from the middle of the part. The alternate hatching between layers makes the stresses uniformly distributed and normalizes the residual stress (Onuh and Hon, 2001). Another software related problem can occur during STL file slicing, causing non-manifold facets, cracks, incorrect facets normal and overlapping facets. Algorithms were proposed to prevent these occurrences (Huang et al., 2002; Leong et al., 1996a,b). Other algorithms to save computation memory and improving slicing were also proposed (Choi and Kwok, 2002).
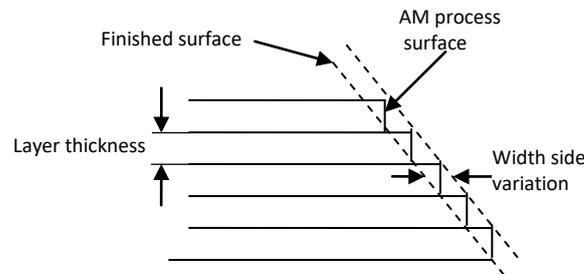
Figure 4. Surface stair effect due to layer stacking

4.2.2 Process related inaccuracies

Process related geometry errors are mainly caused by the equipment. According to Brøtan (2014), there were found accuracy differences in parts produced between machines from the same brand and model. A variety of errors can be split in two major groups:
(1) x - y layer plane ones;
(2) z direction ones.

The layer building errors are mainly caused either by the scanning machine device precision (e.g.: laser mirrors position calibration) or by repositioning the workpiece on support surface after an intermediate operation, when applicable (Brøtan, 2014). The positioning direction of the workpiece on the building platform also affects the part side geometry (Paul and Anand, 2011; Pandey et al., 2007; Ahn et al., 2007). For example, if a cylinder is built with its central axis parallel to x direction, the stepped side surface will be quite different from that if the part is positioned in a inclined direction between x and y, leading to greater surface roughness and subsequent post processing. The z axis errors are affected by the workpiece lowering device (Brøtan, 2014).

A big constraint regarding LM processes concerns heat dissipation to allow adequate molten metal solidification, and supports must be dimensioned for thermal dissipation (Vayre et al., 2012). An important factor concerning process is that the speed and acceleration of the deposition nozzle (or radiation beam) must respect material's melting or sintering characteristics to prevent variations on layer height (Vayre et al., 2012).

4.2.3 Material related inaccuracies

Material inaccuracies depend on material accommodation after cooling, which can produce:
(1) shrinking, which magnitude depends on the material type and also cooling time, and
(2) warping, caused by the same effects seen in shrinking (Brøtan, 2014).

Shape problems may also vary according to materials: stainless steel seems to add extra height in the z direction at sharp edges, which affects the whole built (Brøtan, 2014). When metals are added by melting, post thermal treatment for stress relieving must be considered for functional parts and this can lead to part warping (Ponche et al., 2014).

4.3 General features comparison

Although a general comparison among subtractive and additive manufacturing could lead to a meaningless result due to the several different factors involving very dissimilar processes, an attempt was considered in this work just for a coarse comparison between material removal and material addition processes regarding metals, as illustrate Tab. 1. Surface finishing processes, like reaming, grinding, honing and lapping were not considered, since they can be also used as a post processing for AM.

AM tolerances values are not often found in the AM related literature and few indications available are generally conflicting with each other (Boschetto and Bottini, 2014). Surface quality depends on the layer thickness and, when

applicable, on the powder particle size – comparison values would lead to a wrong interpretation. Accuracy values are referred only for one AM process, extracted from a machine manufacturer specification. The difficulty on reporting geometrical errors is due to their dependence of part shrinking and warping, rather than from the process itself. Tab. 2 shows a comparison among metals produced with conventional processes in their wrought condition and AM ones (Herzog et al., 2016).

Table 1. Comparison among conventional machining processes and AM processes regarding general features.

Feature	Machining processes [1]					AM
	Turning/ Boring	Milling	Planning/ Shaping	Drilling	Broaching	SLS/LBM/LMD
Production rates per hour	1-60 manual 10-1000 automatic	1-100	1-50	10-500	< 400	Very low [7]
Material utilization [2]	Poor/ moderate	Poor	Poor	Very poor	Poor	Very high
Flexibility [3]	High – manual Low – automatic	High	High	High	High	High
Production volumes [4]	-- >1000 automatic	Low	Low	Low/ moderate	Very high	Very low
Tooling costs	Low – manual Moderate/high – automatic	Moderate/high	Low	Low	High	No
Direct labor costs [5]	High – manual Low/moderate – automatic	Moderate/high	Moderate/ high	Low/ moderate	Low/ moderate	Low
Finishing costs	Low	Low	Moderate	Low	Low	No or very low
Tolerances [6] ±mm/ 10 mm ±mm/100mm	0.007 to 0.030 0.02 to 0.070	0.03 to 0.20 0.07 to 0.45	0.02 to 0.09 0.05 to 0.30	0.04 to 0.20 0.1 to 0.5	0.003 to 0.009 0.007 to 0.02	±0.05 [8] ±0.05 [8]
Surface roughness µm Ra [6]	0.05 to 25	0.2 to 25	0.4 to 25	0.4 to 12.5	0.4 to 6.3	--

[1] All machining data obtained from Swift and Booker, 2003.
[2] Poor material utilization means large quantities of chips.
[3] Low flexibility means high changeover and setup times and/or dedicated tooling.
[4] Production volumes refer to economical quantities.
[5] Skilled operators lead to higher labor costs.
[6] Usual figures for average conditions.
[7] Depends on part size, but cannot be compared with machining processes.
[8] SLS - EOSINT M250 Machine spec. (Chua et al., 2003).

Table 2. Comparison among conventional and AM processes mechanical properties.

Material/ Property (9)	Conventional (Wrought) [10]	AM		
		LBM	LMD	EBM
Stainless Steel 316 L	ASTM A276 (AN-A)			
YS (MPa)	170	528 ± 4 [12]	410 ± 5 [11]	--
UTS (MPa)	485	659 ± 3 [12]	640 ± 20 [11]	--
EL (%)	40	16.6 ± 0.4 [12]	36 ± 4 [11]	--
Aluminum	EN 1706 (AF)			
YS (MPa)	140	260 [11]	--	321 ± 26 [12]
UTS (MPa)	240	380 [11]	--	430 ± 8 [12]
EL (%)	1	3 [11]	--	--
Titanium Ti-6Al-4V	ASTM F1472			
YS (MPa)	860	900 ± 5 [12]	960 ± 26 [12]	899 ± 4.7 [12]
UTS (MPa)	930	990 ± 5 [12]	1063 ± 20 [12]	978 ± 3.2 [12]
EL (%)	>10	15.5 ± 2 [12]	13.3 ± 1.8 [12]	9.5 ± 1.2 [12]

[9] YS = yield strength; UTS = ultimate tensile strength; EL = elongation;
[10] AF = as fabricated; AN = annealed condition; A = austenite;
[11] In build (x-y) direction;
[12] Orthogonal to build direction (z).

5. CONCLUSION

Additive Manufacturing has shown a great success in the three last decades due to its outstanding features in comparison to traditional manufacturing processes. Its major concern is the slow production time, which turns it non-competitive regarding other ones, but positive points like need of no tooling makes it very useful in the fabrication of prototypes, either functional or not, due to very short lead times, and in the production of very specialized parts, which materials and shape are unfeasible in other ways. Other great advantages of AM are the processing of very special metals that cannot be processed otherwise and the ability of building the same part with different materials as well. The fabrication of tooling for shaping processes is also a positive point, since with AM, there is no concern about failures in their machining processes, caused by human errors or other causes –generally tooling do not allow reworking - which can lead to serious time schedule and cost penalties. Unlike machining and shaping processes, which selection depends on the part shape or surface geometry, AM processes have no restriction in this case. Literature data have shown that AM resistance properties are better than their equivalent obtained through conventional processes. As surface roughness and material homogeneity are worse as compared to other manufacturing processes, the fatigue strength is negatively affected in AM. Although dimensional tolerances data are not easily found in the reference literature, AM has shown a negative trend with respect to accuracy, due to its anisotropic process characteristic and to part deformation. These features must be taken in consideration when choosing the process, but even so, AM can be very advantageous when these factors are not a stringent exigence.

This work approaches the mechanical and geometrical features of AM of metallic parts in relation to usual production processes and, by means of a review in the up-to-date literature, identifies conformity of its built materials with applicable standards. Post treatments, like in other processes, must be necessary for attainment of technical features – a special one is the hot-isostatic pressing (HIP) – to obtain an almost fully dense and sound material. AM, due to its exclusive material and geometric features, can be competitive in terms of cost for specialized industrial and aerospace components.

6. ACKNOWLEDGEMENTS

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