Design for Additive Manufacturing

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Outlook

1. What is design?
2. Why design for Additive Manufacturing DFAM?
3. Conclusions
Additive Manufacturing

General term for those technologies that based on geometrical representation create physical objects by successive addition of material.

While 3D printing refers to technologies which requires printing head, nozzle or another printer technology.

Usually refers to low end technologies.

ISO/ASTM 52900:2015
What is design?

Think about shapes

a) Etley point
b) Kings corner notched point
c) Graham cave point

Source: http://associations.missouristate.edu/mas/identification.html
What is design?

Think About Materials

a) Obsidian
b) Bronze
c) Bone
d) Wood
e) Steel

http://www.metmuseum.org
http://www.knivesbynick.co.uk
http://www.alltribes.com
http://www.historymuseum.ca
What is design?

Think about process

Forge arrowhead
Source: Youtube

Sculpt Arrowhead
Source: Youtube

Craft arrowhead
Source: Framepool.com
Think about performance

a) Firebox head: It was used to cause fires in cities, fortresses, ships, etc. from distance.

b) Bodkin head: Perfect to pierce cuirasses and chain mails.

c) Barbed head: Used on large game such as boar or deer. Used in war to hurt enemy horses.

d) Broadhead: Their function is to deliver a wide cutting edge so as to kill as quickly as possible.
What is design?

The engineering design process is a formulation to assist in creating a something.

The engineering design is defined as component, or process to meet desired needs.

It is a decision making process (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective.

Tayal, S. P. Engineering design process. of Computer Science and Communication Engineering (2013).
What is design?

More design process less manufacturing worries

Relatively early in the design activity the decisions taken will commit the operation to cost which will be incurred later.

What is design?

Design For “X”
DFX research emphasizes the consideration of all design goals and related constraints in the early design stage. Includes:

- Design for assembly
- Design for manufacture
- Design for disassembly and design for recyclability
- Design for environment
- Design for life-cycle
- Design for quality
- Design for maintainability
- Design for reliability

Design for manufacture and design for ‘X’: concepts, applications, and perspectives, Kuo TC, Huang SH, Zhang HC, Comput Ind Eng, 2001
1. What is design?

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Additive manufacturing has unique capabilities:

- **Design flexibility**: AM enables the creation of almost any complex geometric shape.

- **Cost of geometric complexity**: When employing AM, this complexity comes at no additional cost, as there is no need for additional tooling, re-fixturing, increased operator expertise, or even fabrication time.
- **Reduce need of assemblage:** AM processes enable the production of geometric shapes that would otherwise require assembly of multiple parts.

- **Reduce material waste:** Creating products layer-by-layer is inherently less wasteful than traditional subtractive methods of production.

- **Customized unique items:** Current embodiments of AM technologies are suitable for fabrication of products that feature customized features.
DFAM

- **Immediate availability of CAD models**: Designs in the form of digital files can be easily shared, facilitating the modification and customisation of components and products.

- **Reconfigured value chains**: Shorter and simpler supply chains, more localised production, innovative distribution models, and new collaborations.

*Source: The Economist, 2009*
DFAM

- **Time and cost efficiency in production run**: While AM processes are significantly slower than injection molding for fabricating components, they are better suited for low part quantities as there is no startup tooling required for production.

- **On-demand and on-location AM production**: can lower inventory costs and potentially reduce costs associated with supply chain and delivery.

- **Small batches**: It’s very costly to create molds and production lines for small batches by traditional techniques.
There are some issues that AM should overcoming:

- **Dimensional accuracy**: There is an increased need for establishing industrial dimensional accuracy standards for AM.

- **Surface quality**: The quality of a printed part’s surface is mainly determined by the thickness of each printed layer.
● Limited amount of materials: While consumer goods are comprised of a wide variety of materials that render different behaviors and functionalities, the material selection of AM systems is quite limited.

● Size: Some of the building size of AM technologies is less than traditional processes (injection, milling, etc.)
- **Mechanical Performance**: Unfortunately the strength and the stiffness of components built by these technologies are not particularly high and, furthermore, they are difficult to be defined due to their internal structures can exhibit one or more of the next important features:

  - Heterogeneity
  - Anisotropy
  - Discontinuity

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"By controlling the architecture of a microstructure, we can create materials with previously unobtainable properties in the bulk form."

Chris Spadaccini
Mechanical properties performance of materials used in A.M.

Mechanical properties of metallic materials – minimum values from data sheets. SOURCE: Metal AM magazine 2017.
Mechanical properties performance of materials used in A.M.

Building orientation.

The bed building is a horizontal surface where the first layer is attached, the piece is manufactured in the Z axis whereas the shape is patterned in the XY plane.

To manufacture the piece it is necessary to set what side will be the initial layer, the piece will increase from that layer.
DFAM

Zhang Yicha, 2016
Interdependence of mechanical properties, microstructural characteristics and selective melting

SOURCE: Metal AM: The "Materials" ALM & Mechanical Properties: It's All About Powder Metallurgy! (1/25
a) Dependency of the structure on the procedural parameters;
b) Procedure of the powder laser scanning.

I. No melting.
II. Partial melting.
III. Melting with the balling phenomenon.
IV. Complete melting.

Different result when varying parameters (raster angle and air gap) for thin and thick filaments in FDM

Six different organizations participated in a interlaboratory study to quantify the **variability in the tensile properties** of Inconel 625 specimens manufactured using laser powder bed fusion-additive (LPBF) manufacturing machines. Different machine settings that may have affected the mechanical properties of the tensile specimens and thus affected the variability of the results.

**What is post-processing?**

Post-processing is the final stage of additive manufacturing. It’s the last step in the manufacturing process, where parts receive finishing touches such as: post-curing, smoothing, painting, post-hardening, Hot Isostatic Pressing, etc.

Why is post-processing important?

Post-processing improves the quality of parts and ensures that they meet their design specifications. The finishing process can enhance a part’s surface characteristics, geometric accuracy, aesthetics, mechanical properties, and more. For samples and prototypes, this can mean the difference between a sale or a loss. For production parts, finishing creates a part that is ready to use.

## DFAM, Post-processing

<table>
<thead>
<tr>
<th>Electron Beam Melting (EBM)</th>
<th>Direct Metal Laser Sintering (DMLS)</th>
<th>Selective Laser Sintering (SLS)</th>
<th>Fused Deposition Modeling (FDM)</th>
<th>Polyjet</th>
<th>SLA</th>
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The impact of post-processing

PRIMARY ISSUES
- Energy
- Time
- Cost

SECONDARY ISSUES
- Quality
- Staffing
- Facilities
- Safety
Hybrid Manufacturing

Hybrid manufacturing = Additive Manufacturing + Subtractive process and / or Forming process

What is the performance of the final part for a defined geometry? 
Tensile strength, Young’s modulus, hardness, flexural strength, etc.

Uncertainty caused by process and material variables

Process variables: 
Layer thickness, raster width, laser power, scan velocity, chamber temperature, orientation part, etc.

Material variables: 
Density, heat capacity, Tg, critical exposure, depth of penetration, etc.
There is a strong relationship between geometry and performance of a part of a device. Determination of this geometry is one of the cores into the design process.

Like in the traditional design process, in design for AM final shapes of a device and its parts are strongly tied with their application and function.
Together with process and material employed to make the part, geometry generate an specific structure with specific properties.
Finally, performance of structure is determined by the external stimuli (e.g. loads) and the conditions of uses (e.g. temperature)
Thanks to the AM process now is possible manufacture parts and devices with complex geometries if is needed to accomplish the function requirements.

Topology optimization is a numerical tool that allow from a given predefined design domain, some given supports in connection to the design domain, some given external loads, and a given material to be used, designing an optimal structure to carry the given loads. This should be done by finding the optimal subdomain, of the given design domain, to fill with material.
DFAM
The objective might be to minimize the total weight of the structure subject to constraints on displacements and stresses in the structure under the given loads.

Topology Optimization from existing design

Source: www.linkedin.com
Lattices and AM: The concept of designed lattice structures is motivated by the desire to put material only where it is needed for a specific application. From a mechanical engineering viewpoint, a key advantage offered by lattices is high strength accompanied by a relatively low mass.

Lattice structures tend to have complex geometry variations in three dimensions, which by traditional processes is hard to make or impossible.

Numerical and analytic methods has been employed to characterize parts made by AM, however unlike what traditional process exhibit, parts made by AM process with same material and geometry as former show internal structures with complex geometries. Therefore is necessary add this features in the analysis.

Imágenes mediante SEM de la superficie de fractura de piezas hechas a) por inyección b) mediante FDM sometidas a tensión. Dawulid et al. 2016
Finite element method allow simulate physical mechanical test, tying specific features that presents in AM processes: heterogeneity, discontinuity and anisotropy.
Non-Destructive tests

Non-destructive tests are techniques for inspection and quality assurance. To analyze the integrity of material, components or structures*.

In Additive Manufacturing allow to inspect the inner microstructure maintaining its shape.

A commonly tool is Computer Tomography to inspect this kind of pieces.

Computed Tomography has been widely used to inspect inner features in AM pieces like microcracks and porosities*

In Material Extrusión is used to analyze the rasters and how they come together^.
DFAM

CT Pore Analysis a) FDM, b) Polyjet, c) SLA
Standard tensile tests method is used to determine mechanical properties from the curve Strain - Deformation as a function of the build and raster orientation [*].

Differents build orientations gives a different values in their mechanical properties such as their Young’s Modulus. The common analysed orientation are: Flat, Edge and UpRight[^].

The test pieces are design based on the ASTM norm D638 [+].


Piece builded in Edge orientation shows the better values in tensile test*.

Pieces builded in Flat and UpRight orientation shows similar mechanical properties*.

Raster angle also affects the mechanical properties, surface roughness and process cost*.
How to achieve a more energy-saving additive manufacturing?

**DFAM**

- **Energy consumption** (J/m³, J/kg)
- **Material and process: parameters, physical and chemical properties**
- **Peripheral elements:** Chamber, rollers, drivers, coolers, etc.
- **Performance (mechanical, electrical, optical, thermal, etc. properties)**
GE Aviation recently challenged the additive manufacturing community to redesign a titanium aircraft engine bracket and received hundreds of entries from 56 countries. The winning part designed by M Arie Kurniawan is shown above. The original bracket weighed 2033 grams (4.48 pounds), but Kurniawan was able to slash its weight by nearly 84% to just 327 grams (0.72 pounds) (Courtesy GrabCad).

SOURCE: www.geaviation.com
Outlook

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Conclusions

DFAM guidelines are not yet ready but has two major directions:

- Using of opportunities allowed by AM
- Integrating the restrictions inherent in AM

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