Design for Additive Manufacturing

Uncover New Design Rules

Moscow – Vladimir Workshop
November 14-19, 2016

Laboratoire G-SCOP/Université Grenoble Alpes - Grenoble INP
Design Process

Needs, contraintes

Solution search, Synthesis

Possible solutions

Evaluation, Analysis
Design for Additive Manufacturing

- New design rules
- New forms
- Functional Materials

Form opportunities

Solution search, Synthesis

Needs, contraintes

Possible solutions

Evaluation, Analysis

Prototyping opportunities
New Design Rules

Form freedom

… Also induced constraints
New Design Rules

Molded parts design rules

Cracks formation

Good design

Formation de retassure

Good design
<table>
<thead>
<tr>
<th>Structure</th>
<th>Unfavourable</th>
<th>Favourable</th>
<th>Explanation</th>
<th>Restrictions and Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td>- part size must consider substrate plate dimensions</td>
<td>max. part dimensions incl. substrate plate: x = ca. 250 mm, y = ca. 250 mm, z = ca. 215 mm</td>
</tr>
<tr>
<td>General part size</td>
<td><img src="image3.png" alt="Diagram" /></td>
<td><img src="image4.png" alt="Diagram" /></td>
<td>- integration of substrate platform into part possible</td>
<td>(see machine manufacturers for more information; larger machines available)</td>
</tr>
<tr>
<td>Inclusion of substrate</td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
<td>- reduction of manufacturing time and costs</td>
<td></td>
</tr>
<tr>
<td>Platform</td>
<td><img src="image7.png" alt="Diagram" /></td>
<td><img src="image8.png" alt="Diagram" /></td>
<td>- hybrid manufacturing approach</td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td><img src="image9.png" alt="Diagram" /></td>
<td><img src="image10.png" alt="Diagram" /></td>
<td>- radii at the interface part / substrate platform prevent part strip off during manufacturing process</td>
<td>the larger the interfaces layer, the larger the radius should be</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>r = 3-5 mm suitable for TiAl6V4</td>
</tr>
<tr>
<td>Integration of materials</td>
<td><img src="image11.png" alt="Diagram" /></td>
<td><img src="image12.png" alt="Diagram" /></td>
<td>- part height in build up direction should equal multiple layer thicknesses</td>
<td>layer thickness: 20 - 50 μm</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>TiAl6V4: 30 μm (see manufacturing machine documentation)</td>
</tr>
<tr>
<td>Cavity</td>
<td><img src="image13.png" alt="Diagram" /></td>
<td><img src="image14.png" alt="Diagram" /></td>
<td>- prefer integral part design</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- reduction of manufacturing time</td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td><img src="image15.png" alt="Diagram" /></td>
<td><img src="image16.png" alt="Diagram" /></td>
<td>- use cavities in order to reduce the part volume to be exposed</td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>- reduction of manufacturing time and cost</td>
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<td></td>
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<td></td>
<td>- avoid powder nesting by designing simple cavity geometries</td>
<td></td>
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<tr>
<td>structure</td>
<td>unfavourable</td>
<td>favourable</td>
<td>explanation</td>
<td>restrictions and recommendations</td>
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<td>------------------</td>
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<td>-----------------------------------------------------------------------------</td>
<td>---------------------------------</td>
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<tr>
<td>cavities</td>
<td></td>
<td></td>
<td>- consider at least one opening</td>
<td>3 – 5 mm suitable for TiAl6V4</td>
</tr>
<tr>
<td>powder removal</td>
<td></td>
<td></td>
<td>- the larger the opening, the more easy the powder removal is</td>
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<tr>
<td>accumulations</td>
<td></td>
<td></td>
<td>- use multiple openings at complex parts</td>
<td></td>
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<tr>
<td>horizontal</td>
<td></td>
<td></td>
<td>- avoid material accumulation</td>
<td></td>
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<tr>
<td>segments</td>
<td></td>
<td></td>
<td>- reduction of part volume reduces manufacturing time and costs</td>
<td></td>
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<tr>
<td>material</td>
<td></td>
<td></td>
<td>- avoid horizontally positioned part segments</td>
<td></td>
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<tr>
<td>distribution</td>
<td></td>
<td></td>
<td>- highest thermally induced stresses</td>
<td></td>
</tr>
<tr>
<td>walls</td>
<td></td>
<td></td>
<td>- focal diameter of laser limits resolution in manufacturing plane</td>
<td></td>
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<tr>
<td>sharp corners /</td>
<td></td>
<td></td>
<td>- worst surface quality</td>
<td></td>
</tr>
<tr>
<td>edges</td>
<td></td>
<td></td>
<td>- sharp corners / edges not manufacturable</td>
<td></td>
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<tr>
<td>not manufacturable</td>
<td></td>
<td></td>
<td>- thermally induced stresses can lead to part failure during build process</td>
<td></td>
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<tr>
<td>material</td>
<td></td>
<td></td>
<td>- avoid notches in part design</td>
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<tr>
<td>transitions</td>
<td></td>
<td></td>
<td>- prefer round material transitions</td>
<td></td>
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<tr>
<td>Structure</td>
<td>Unfavourable</td>
<td>Favourable</td>
<td>Explanation</td>
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<tr>
<td>gen. g</td>
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<td>• consider massive supports for optimized heat flux and reduced part deformation during build up</td>
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<tr>
<td>supports</td>
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<td></td>
<td>• consider breakage points for easy removal</td>
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<td>massive</td>
<td></td>
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<tr>
<td>supports</td>
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<td>• consider adequate allowances in CAD design</td>
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<tr>
<td>allowance</td>
<td></td>
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<td>• necessary allowance highly depending on final machining</td>
<td></td>
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<tr>
<td>general</td>
<td></td>
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<tr>
<td>position</td>
<td></td>
<td></td>
<td>• surfaces to be final machined should be lift from surrounding part</td>
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<td>• surfaces to be machined should be placed in one plane</td>
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<tr>
<td>tooling</td>
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<tr>
<td>points</td>
<td></td>
<td></td>
<td>• span and positioning points should be incorporated in part design allowing safe spanning for final machining and low part deformation</td>
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<tr>
<td></td>
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<td></td>
<td>• place location bores in reference planes</td>
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<tr>
<td>turning/milling</td>
<td></td>
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<td></td>
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<td></td>
<td>• consider tooling run-outs and ensure accessibility as well as clearness</td>
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<tr>
<td>milling</td>
<td></td>
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<td></td>
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<td></td>
<td>• prefer perpendicular alignment of planes to be final machined</td>
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<tr>
<td>drilling</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>• design bore diameters smaller than necessary and drill out during final machining if high accuracy is needed</td>
<td></td>
</tr>
</tbody>
</table>
## New Design Rules

### Other design rules examples

<table>
<thead>
<tr>
<th>Group</th>
<th>Typ</th>
<th>Attribute</th>
<th>Description</th>
<th>Design for manufacturing</th>
<th>LS</th>
<th>LM</th>
<th>FDM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Element transitions</td>
<td>Firmly bonded elements</td>
<td>Thickness</td>
<td>Element transitions' thicknesses can be chosen freely as they do not influence element's form accuracies.</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
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<tr>
<td></td>
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<td></td>
<td>Element transitions' thicknesses should be chosen so that the cross sectional areas in the building plane remain of the same size or become smaller.</td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
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<tr>
<td>Edge</td>
<td></td>
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<td></td>
<td>Sharp (outer and inner) edges should be avoided. In order to receive better form accuracies edges should be rounded. The rounding radii correlate with the outer radii of simple-curved elements.</td>
<td><img src="image6" alt="Diagram" /></td>
<td><img src="image7" alt="Diagram" /></td>
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<td></td>
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<td></td>
<td>Edges that form vertical extreme points should be blunted parallel to the building plane. The dimensions of the blunted areas should be larger than non-curved elements' thicknesses.</td>
<td><img src="image8" alt="Diagram" /></td>
<td><img src="image9" alt="Diagram" /></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>Typ</td>
<td>Attribute</td>
<td>Description</td>
<td>LS</td>
<td>LM</td>
<td>FDM</td>
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</tr>
<tr>
<td>Element transitions</td>
<td>Non-bonded elements</td>
<td>Gap width</td>
<td>If accessibility to the gap is given along the complete width, the gap width can be chosen freely.</td>
<td></td>
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<td>X</td>
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<td></td>
<td></td>
<td></td>
<td><strong>Gap length</strong></td>
<td></td>
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<td></td>
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<td></td>
<td>Gaps’ lengths need to be short enough to enable a robust removal of disperse support structures which are contained inside the gaps.</td>
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<td></td>
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<td></td>
<td>LS: ( l_g \leq 8.0 \text{ mm} )  ( h_G = 1.2 \text{ mm} )</td>
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<td></td>
<td></td>
<td></td>
<td>( l_g \leq 30.0 \text{ mm} ) ( h_G = 1.8 \text{ mm} )</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( l_g \leq 50.0 \text{ mm} ) ( h_G = 2.4 \text{ mm} ) (max. tested length)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>LM: ( l_g \leq 50.0 \text{ mm} ) ( h_G = 0.2 \text{ mm} ) (max. tested length)</td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>Gaps’ lengths can be chosen freely because no disperse support structures are contained inside the gaps.</td>
<td></td>
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</tr>
<tr>
<td>Aggregated structures</td>
<td>Overhang</td>
<td>Length</td>
<td>Overhangs’ lengths can be selected freely because required stabilizations of the overhangs are provided by the disperse support structures.</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
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<td></td>
<td>Overhangs’ lengths should be short enough to ensure a robust manufacturability given by part layers that do not bent out of the building plane (LM) or filaments that do not “fall off” their nominal positions (FDM).</td>
<td></td>
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<td></td>
<td>LM: ( l_{oh} \leq 2.0 \text{ mm} )</td>
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<td></td>
<td></td>
<td></td>
<td>FDM: ( l_{oh} \leq 1.8 \text{ mm} )</td>
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</tbody>
</table>
New Design Rules
Optimized Forms

Think Out of the box…

Psychological inertia:

- “we have always done like that”
- “we are not allowed to to that”
- “I usually do like that”
- “in this company we do it that way” …
Optimized Forms

Solution 1: rely on experts knowledge

But they also have there cognitive limits …

Machined, Aluminium 7075, 52g

EBM, TA6V, 49g
Optimized Forms

Solution 2: Topological optimisation

Machined, Aluminium 7075, 52g
Optimized Forms

Solution 2: Topological optimisation

- Need a rebuild phase, verification, parametric optimisation …
- May be manufactured as is, but difficult to be accepted by people (psychological inertia again…)

EBM, TA6V, 29g !
Optimized Forms

Optimisation

• **General principles**
  • To minimise a function (mass, cost, …) = objective function
  • Problem variables (and limit values). Dimensions for example
  • Constraintes = limitations of certain functions or its variables (s_{vm} < 200 MPa, T_{max} < 50°C…)

• **Mechanical example**
  • Minimise mass = f(b,h) = r.L.b.h
  • 2 variables b [10 - 30mm] et h [15 - 25mm]
  • d_{max} = 1 mm = g(b,h)
Optimized Forms

Parametric Optimisation vs. Topological Optimisation
Topological Optimisation

- Variable -> material density \( \rho \) in each element of a FEM mesh

- Objective function ->
  - Minimise mass -> \( \int_v \rho \cdot dV \)
  - Minimise compliance = energy -> \( \int_v \sigma \cdot \epsilon \cdot dV \)
  - Compliance is expressed as a function of density: for example -> \( E = E_0 + \rho^n E_1 \)
Example of a formulation of a topological optimisation problem

- Minimise compliance $\int_V \sigma \cdot \varepsilon(\rho) \, dV$
  - With $\rho \in [0,1]$ for each element except BC where $\rho=1$
    - $\int_V \rho \cdot dV$
    - $\nabla \sigma + F = 0$
    - $\sigma = C.\varepsilon$
    - Plus design constraints
Optimized Forms

Find minimum compliance

- Principle: example with 2 elements

\[ \int_V \sigma \varepsilon(\rho) \, dV \]

Contrainte

\[ \int_V \rho \, dV \leq V_{limite} \]

Contrainte

\[ \sigma_{VM max} \leq \sigma_{limite} \]
• Method to find the optimum material distribution in a given design space
Topology Optimization Process in Altair OptiStruct

Mesh generation, definition of loads and boundary conditions

Casting Direction

Stiffness

Mass

Setup of optimization problem, definition of design constraints

Computation

Interpretation of results

Definition of available package space

CAD Design

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Manufacturing Constraints: Minimum Member Size Control

- Input: approximate minimum diameter $d$ in two dimensions (SI units)
- Works in 2D and 3D
- Controls the size of small structural features
- Controls "checkerboarding"
- Easier interpretation of the resulting layout
- Higher computation cost

Without min member size
- Difficult to manufacture due to micro structures
- Results are mesh dependent

$d = 6$

$d = 9$
Manufacturing Constraints: Maximum Member Size Control

- Definition of maximum allowable structural member size
- Eliminates material concentrations
- Mesh considerations
  - Shell and solid elements
  - Tetrahedral and hexhedral
  - Min member > 3 X mesh size
  - Max member > 2 X min size
Manufacturing Constraints: Symmetry

- Load independent
- Mesh independent
- Geometry independent
Manufacturing Constraints: Pattern Repetition

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>5 Repetitions</th>
<th>20 Repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Symmetry</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Symmetry</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>
**Draw Direction Constraint**

*Example: Optimum Rib Pattern of a Control Arm*

- **Without Draw Direction**
- **With Draw Direction**
Optimized Forms

• Can we print directly an SO result?
  – Yes… but not relevant most of the time

• Simplification and cleaning is often necessary…

• …And some verification/modification as well.
  – Will the final shape acceptable by the client?
  – Shall we be able to remove the supports?
  – Shall we be able to remove all the unused powder?
  – Will there be some weak points?
Optimized Forms

Design example

Topology optimisation

Non through-hole areas
Rugged shape
Too thin areas

Reconstruction 3D

Free design space

Powder recovery
Smooth surfaces
Manufacturable thicknesses
Aesthetics

Mechanical problem

Controlled design space

Minimum thickness
Shape allocation
Powder recovery

Reconstruction 3D

Powder recovery

Mechanical behaviour
Fillets
Machining
Aesthetics

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4 criteria to select AM candidates (Klahn et al. 2014)

1- «Integrated design»
Identify groups of parts that can be combined in one single part

<table>
<thead>
<tr>
<th></th>
<th>Original Design</th>
<th>Bionic Design</th>
<th>Integrated Design*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bracket Weight</strong></td>
<td>330 g</td>
<td>195 g</td>
<td>0 g</td>
</tr>
<tr>
<td><strong>Assembly Weight</strong></td>
<td>1.400 g (incl. fiber mount and HiLocks)</td>
<td>1.265 g (incl. fiber mount and HiLocks)</td>
<td>300 g</td>
</tr>
<tr>
<td><strong>Dimensioning Load Case</strong></td>
<td>35 kN</td>
<td>35 kN</td>
<td>35 kN</td>
</tr>
<tr>
<td><strong>Weight Saving</strong></td>
<td></td>
<td>135 g (-41%)</td>
<td>1.100 g (-80%)</td>
</tr>
</tbody>
</table>

Example (Emmelmann et al. 2012)
4 criteria to select AM candidates (Klahn et al. 2014)
4 criteria to select AM candidates (Klahn et al. 2014)

2- « Individualization »: Complex part with high variability (often interface parts)
4 criteria to select AM candidates (Klahn et al. 2014)

3 - « Lightweight Design » : Complex mobile parts

Bracket Airbus A380 (EOS)
4 criteria to select AM candidates (Klahn et al. 2014)

4 - « Efficient Design » : Part participating to mass, energy transmission or conversion
4 criteria to select AM candidates (Klahn et al. 2014)

1. « Integrated design » : Identify groups of parts that can be combined in one single part
2. « Individualization » : Complex part with high variability (often interface parts)
3. « Lightweight Design » : Complex mobile parts
4. « Efficient Design » : Part participating to mass, energy transmission or conversion
Materials Dimension

The Materials in Additive Manufacturing

• The material is « built » at the same time as the part
  => Tight connexion product-material-process

• Multi materials opportunities

  => alternate, and blend materials and filament

credit: NASA-JPL/Caltech
Materials Dimension

Architectured materials

- Best ratio mass/resistance

343 Mpa, 7.2 g

328 Mpa, 6.1 g
Materials Dimension

Architectured material

- Specific and «designed» properties
- Complex behavior (negative Poisson ratio)
Materials Dimension

Architectured materials

Lighten structures

Porosity gradient

Scaffolds for Bones development

Credit SIMAP - Grenoble

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Materials Dimension

Lattice structures
Materials Dimension

Insert lattice structures in blind zones of topology optimisation

http://www.3ders.org/articles/20140915-futurist-christopher-barnatt-report-london-2014-3d-printshow.html
Materials Dimension
Design FOR Additive Manufacturing

New design rules
New forms
Functional Materials

Form opportunities

Solution search, Synthesis

Needs, contraintes

Possible solutions
Evaluation, Analysis

Prototyping opportunities
Some Manufacturing Issues

Complexity of numerical simulation

- Material modeling
- Importance of CL
- Geometric Singularities
- Many details
- Geometric uncertainties …
Some Manufacturing Issues

Architectured materials
Do we build what we calculate?

1mm strut
Circular cross-section

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How far from the ideal?
Some Manufacturing Issues

Geometry correction

Alignement of neutral axis of strut with vertical

Projection of pixel along the strut.

Inscribed cylinder: circular cylinder of same area than the inscribed surface

Inscribed cylinder $\rightarrow$ Mechanical properties

$R_{EQ}^{GEOM} = \text{radius of inscribed cylinder}$

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Some Manufacturing Issues

Equivalent diameter
Influence of orientation (EBM)

<table>
<thead>
<tr>
<th>Build orientation</th>
<th>$\frac{R_{\text{EQ}}^{\text{NUM}}}{R_{\text{CAD}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal strut</td>
<td>71%</td>
</tr>
<tr>
<td>No change</td>
<td>58.1%</td>
</tr>
<tr>
<td>No change</td>
<td>57.6%</td>
</tr>
</tbody>
</table>

- Horizontal strut:
  - Larger cross-section due to over-melting $\rightarrow$ Higher stiffness
- No change in stiffness for vertical and 45° strut

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Some Manufacturing Issues

Equivalent diameter structures

\( R_{\text{EQ}} \) depends on:
- fabrication direction
- CAD size
- Process parameter

Different orientations
Conclusion

Take advantage of the form freedom offered by AM:

- Uncover new design rules
- Topological optimisation used
  - Optimisation require expertise
- Topological optimisation + architectured materials = promising results
- Rapid access to prototyping even when simulation is complex
Design FOR Additive Manufacturing

New design rules

New forms

Functional Materials

Form opportunities

Solution search, Synthesis

Needs, contraintes

Possible solutions

Evaluation, Analysis

Prototyping opportunities
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