Study of Energy Absorption in micro-Strut Lattice Structure Produced by Selective Laser Melting

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Faculty of Mechanical Engineering
BUT

Brno, 28th March 2019
Motivation

To increase the passengers safety in transport area using SLM lattice structures

Metal foam

- 32% of produced metal foams will use in transport industries
- Irregular shape of the structure
- Increase of the impact absorption and protection
- Base material is usually aluminium alloys
Motivation

To increase the passengers safety in transport using SLM lattice structures

SLM lattice structures

- Graded density of lattice structure
- Custom defined lattice structures geometry
- Numerical simulation as the tool for design

Zhenyu L. et al., 2018

Lijun X. et al., 2018

Vrana et al., 2018
Motivation

To increase the passengers safety in transport using SLM lattice structures

SLM lattice structures

- Imperfections of SLM technology
- Numerical model which include them
State of the Art

**Numerical model of impact loading**
- Definition of a bi-linear material model
- Creation of a numerical model
- Finding of equal ideal strut diameter
- Implementation of the elliptic cross-section

**Study of the SLM produced lattice structures material**
- Experimental devices
- Software for evaluation of mechanical properties
- Dynamic mechanical properties of the lattice structures

**Study of energy absorption in lattice structures**
- Quasi-static mechanical properties
- Study of shape and geometry accuracy
- Study of inner porosity formation
- Development of the novel SLM contour strategy

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State of the Art

Experimental devices

- Devices with impact velocity above 50 m/s
- Devices with impact velocity under 50 m/s
- Energy absorption parameters

- Shen et al. (2013)
  - Vertical „tower“ configuration
  - HSC velocity measurement
  - Strain gauge force measurement

- Yahaya et al. (2015)
  - Horizontal configuration
  - Projectile accelerated using nitrogen gas
State of the Art

Study of energy absorption

- Devices with impact velocity above 50 m/s
- Devices with impact velocity below 50 m/s
- Energy absorption parameters

- Main parameter describing absorption
  - $F(x)$ curve
  - Densification of absorber
  - Amount of absorbed energy $E_{\text{abs}}$

Ashby et al., 2016
State of the Art

Lattice structures phenomena - Shape

- Dimensional inaccuracies
- High surface roughness
- Internal porosity

- Qiu et al. (2015)
- Influence of the main SLM process parameters on lattice structure diameter

Numerical simulation

Study of the SLM produced lattice structures

Study of energy absorption

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State of the Art

Lattice structures phenomena - Roughness

- Dimensional inaccuracies
- High surface roughness
- Internal porosity

- Leary et al. (2016); Yan et al. (2014)
  - High surface roughness on the down-skin
  - Due to the orientation of the struts
  - Accumulation of heat energy
  - Sintering of surrounding powder
State of the Art

Lattice structures phenomena – Internal porosity

- Dimensional inaccuracies
- High surface roughness
- Internal porosity

- Delroisse et al. (2017)
  - Higher level of porosity in down-skin part of the struts – usually gas pores
  - Heterogenous microstructure of the struts
  - Due to accumulation of heat energy

- Qiu et al. (2015)
  - Influence of the main SLM process parameters on porosity formation
State of the Art

Lattice structures phenomena – Internal porosity

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Study of energy absorption → Study of the SLM produced lattice structures → Numerical simulation
State of the Art

Lattice structures phenomena – Mechanical properties

- Dimensional inaccuracies
- High surface roughness
- Internal porosity

- Tsopanos et al. (2010)
  - 316L wires as the specimens for mechanical testing
  - The mechanical properties were lower about 50% compared to Di-cast material

- Dong et al. (2018)
  - Influence of the strut size on mechanical properties
  - Higher internal porosity in smaller struts
  - Smaller struts were more brittle than bigger struts
Lattice structures phenomena – Mechanical properties

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State of the Art

Numerical model of lattice structure

- Labeas et al. (2013)
- Numerical model with real geometry
- Numerical model with homogenized geometry
- Bi-linear material model
State of the Art

Conclusion

- SLM-produced lattice structures have imperfections and inaccuracies
  - Irregular and bigger lattice structure diameter
  - High-surface roughness at the down-skin area
  - Internal porosity

- They are possible to partly manage by SLM process parameters

- Real dimensions of the lattice structures must be evaluated
  - Mechanical properties must be tested directly on lattice or strut geometry
  - Bi-linear material model is possible to use for drop-weigh impact test
  - Numerical model with real geometry better reflect the experimental results

- The numerical model which includes the imperfections of SLM technology has not been developed yet.
Aim of the Thesis

The development of the numerical model for studying deformation behaviour of the SLM produced lattice structures

To achieve the main goal of this thesis, the solution to the following sub-aims are necessary:

- Development of an experimental device
- Novel contour strategy
- Shape and dimension analysis of lattice structure
- Definition of bi-linear material model for lattice structure AlSi10Mg

Impact testing → Contour strategy → Shape and dimension analysis → Bi-linear material model → Numerical model (Explicit)
Material and Methods – Inputs and Outputs

Numerical model (Explicit)

- Boundary conditions
- Bi-linear material model
- Geometry
Material and Methods – Inputs and Outputs

1) Impact testing

\[ m, v_{in} \]

Numerical model (Explicit)

- Bi-linear material model
- Boundary conditions
- Geometry
Material and Methods – Inputs and Outputs

1) Impact testing
   \( m, v_{in} \)

2) Contour strategy

3) Shape and dimensions analysis
   \( \text{ellipse, } d_{\text{Gauss}} \)

Numerical model (Explicit)

- Bi-linear material model
- Boundary conditions
- Geometry
- Contour strategy
Material and Methods – Inputs and Outputs

1) Impact testing
   - \( m, v_{in} \)

2) Contour strategy
   - \( \text{ellipse, } d_{\text{Gauss}} \)

3) Shape and dimensions analysis
   - \( \text{ellipse, } d_{\text{Gauss}} \)

4) Mechanical testing
   - \( \sigma, \varepsilon, E, E', R_{0.2}, \varepsilon_{\text{max}} \)

Numerical model (Explicit)
- Boundary conditions
- Geometry
- Bi-linear material model

Mechanical testing

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Material and Methods – Inputs and Outputs

1) Impact testing
   - $m, v_{in}$

2) Contour strategy
   - Ellipse, $d_{Gauss}$

3) Shape and dimensions analysis

4) Mechanical testing
   - $E, E', R_{0.2}, \varepsilon_{max}$

Numerical model (Explicit)
- Bi-linear material model
- Boundary conditions
- Geometry

Impact testing
- $F(t), F(x)$

Mechanical testing
- $\sigma, \varepsilon$

Mechanical testing inputs and outputs:
- $E, E', R_{0.2}, \varepsilon_{max}$

Impact testing inputs and outputs:
- $F(t), F(x)$

Shape and dimensions analysis:
- Ellipse, $d_{Gauss}$

Contour strategy:
- $x (mm), t (s)$
Material and Methods

1) Impact testing
- The Drop-weight Impact Tester – Impactor 3.0
- Tower configuration of tester
- Strain-gauge and HS camera
- F(x) characteristic

Impact testing  →  Contour strategy  →  Shape and dimension analysis  →  BI-linear material model  →  Numerical model (Explicit)
Material and Methods

1) Impact testing – Data evaluation
   - Image analysis of the HSC record
     - Evaluation of the real impact velocity and samples deformation
     - Connection of the F(t) and x(t) characteristics

![Graphs showing force and deformation over time.](image)

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Material and Methods

1) Impact testing – Data evaluation

- **Image analysis** of the HSC record
  - Evaluation of the real impact velocity and samples deformation
  - Connection of the F(t) and x(t) characteristics

- $k_d$ – (N/mm) – dynamic stiffness
- $F_{Avg}$ – (N) – average force in plateau stress
- $x_d$ – (mm) – densification deformation
- $W$ – (J) – deformation work/absorbed energy
- $\psi$ – (J/kg) – specific energy absorption
- $P_{abs}$ – (J/s) – energy absorption power

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Material and Methods

2) Novel contour strategy

- No standard production strategy for lattice structures
- Constant OL in whole strut cross-section
- Based on the single tracks geometry
Material and Methods

2) Novel contour strategy

- No standard production strategy for lattice structures
- Constant OL in whole strut cross-section
- Based on the single tracks geometry

<table>
<thead>
<tr>
<th>d (mm)/strategy</th>
<th>0.5 mm</th>
<th>0.6 mm</th>
<th>0.7 mm</th>
<th>0.8 mm</th>
<th>0.9 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour</td>
<td><img src="image1" alt="Contour 0.5 mm" /></td>
<td><img src="image2" alt="Contour 0.6 mm" /></td>
<td><img src="image3" alt="Contour 0.7 mm" /></td>
<td><img src="image4" alt="Contour 0.8 mm" /></td>
<td><img src="image5" alt="Contour 0.9 mm" /></td>
</tr>
<tr>
<td>Standard</td>
<td><img src="image6" alt="Standard 0.5 mm" /></td>
<td><img src="image7" alt="Standard 0.6 mm" /></td>
<td><img src="image8" alt="Standard 0.7 mm" /></td>
<td><img src="image9" alt="Standard 0.8 mm" /></td>
<td><img src="image10" alt="Standard 0.9 mm" /></td>
</tr>
</tbody>
</table>

![Graph](image11)

Impact testing → Contour strategy → Shape and dimension analysis → BI-linear material model → Numerical model (Explicit)

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Material and Methods

3) Shape and dimensions analysis

- Irregular struts cross-section
- Computed tomography
- Script for evaluation of statistic values
- Measurement by fitting of cylinders

```
krok = 1
cislo=0
while (cislo<=1000):
    cislo += krok
    jmeno = "Point " + str(cislo)
    jmenoGauss = "Point " + str(cislo) + "-G"
    jmenoMaxIn = "Point " + str(cislo) + "-M"
    jmenoMinOut = "Point " + str(cislo) + "-H"
    gom.script.selection3d.select_inside_sphere(
        center=gom.app.project.inspection(jmeno),
        radius=2.50e+00)
...
```
Material and Methods

4) Mechanical testing

- To define bi-linear material model
- Special strut shape of tensile specimens
- Tensile test of the thin struts – $E, E_t, R_{p0.2}$
- Compression test of the lattice structure cubes – $\varepsilon_{\text{max}}$

![Tensile testing graph](image1)

![Compression testing graph](image2)

Impact testing ➔ Contour strategy ➔ Shape and dimensions analysis ➔ Bi-linear material model ➔ Numerical model (Explicit)

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Material and Methods

5) Numerical model (Explicit)
- ANSYS Workbench 18.2 – Explicit dynamic module
- Quarter symmetry
- Tetrahedron volumetric elements
- Circular and elliptic shape of the lattice
- Bi-linear isotropic hardening mat. model

Bi-linear material model

\[ \sigma = f(\varepsilon) \]

Impact testing → Contour strategy → Shape and dimensions analysis → Bi-linear material model → Numerical model (Explicit)

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5) Numerical model (Explicit)

- ANSYS Workbench 18.2 – Explicit dynamic module
- Quarter symmetry
- Tetrahedron volumetric elements
- Cylcicular and elliptic shape of the lattice
- Bi-linear isotropic hardening mat. model
- **EPS failure parameter**

**Bi-linear material model**

Turning off the elements
Results and Discussion

Lattice structure Internal porosity and Surface roughness

- Computed tomography analysis
- Strut shape of the samples
- Linear resolution 15 μm
- Each strut was evaluated individually
Results and Discussion

Lattice structure Internal porosity and Surface roughness

- Computed tomography analysis
- Strut shape of the samples
- Linear resolution 15 µm
- Each strut was evaluated individually
- Surface reconstruction for surface analysis
- Roughness analysis in GOM Inspect
Results and Discussion

Lattice structure **Internal porosity and Surface roughness**

- SLM laser parameters with lower linear energy
- Limit for linear energy – 0.25 J/mm
- LP in range – 225W – 300W
- LS in range – 900 mm/s – 1400 mm/s

![Surface roughness](image)

![Internal porosity](image)

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Results and Discussion

Lattice structure shape and dimension analysis

- Study of real lattice struts dimensions – $d_{\text{nom}} = 0.8$ mm
- Statistics population $N = 1000$

**Gauss cylinder**

**Nominal $d = 0.8$ mm**

- $\Delta d = 0.683$ mm

**Impact testing** → **Contour strategy** → **Shape and dimensions analysis** → **Bi-linear material model** → **Numerical model (Explicit)**

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Results and Discussion

Lattice structure shape and dimension analysis

- Study of real lattice struts dimensions – \( d_{\text{nom}} = 0.8 \) mm
- Statistics population \( N = 1000 \)

Gauss cylinder

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85</td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>150</td>
</tr>
<tr>
<td>0.95</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Nominal \( d = 0.8 \) mm

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Inscribed</th>
<th>Circumscribed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.707</td>
<td>1.390</td>
</tr>
<tr>
<td>0.9</td>
<td>0.957</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \Delta d = 0.683 \) mm

Impact testing  \( \rightarrow \) Contour strategy  \( \rightarrow \) Shape and dimension analysis  \( \rightarrow \) Bi-linear material model  \( \rightarrow \) Numerical model (Explicit)

Imput for calibration of numerical model

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Results and Discussion

Lattice structure shape and dimension analysis

- Study of Ellipticity
  - Based on the results of the real shape
  - Strut diameter $d = 0.8$ mm
  - Ellipticity parameter $e = 0.71$

- Study of Influence of Strut Orientation
  - Strut diameters from 0.2 to 1.0 mm
  - Strut inclinations from 0 – 90°
  - Manufacturing limit for AlSi10Mg – 0.45 mm
  - Dependence of the real diameter on the nominal diameter and its inclination

![Diagram of lattice structure and elliptical shape]

- Impact testing
- Contour strategy
- Shape and dimension analysis
- Bi-linear material model
- Numerical model (Explicit)

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Results and Discussion

Numerical model calibration – Strut Diameter

- Which diameter best describes the mechanical properties of lattice structures?
- Parametric calibration for \( d = 0.8 \) mm
- Input parameters
  - Range of strut diameters from inscribed to circumscribed – \( \Delta d \)

\[
\begin{array}{c|c|c}
\text{Din} & 0.957 & \text{Dout} \\
\text{Gauss} & & \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c|c|c|c|c}
\text{Force (N)} & 0 & 2000 & 4000 & 6000 & 8000 & 10000 & 12000 \\
\text{Deformation (mm)} & 0 & 2 & 4 & 6 & & & \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c|c|c|c|c}
\text{Deformation (mm)} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\text{Time (s)} & 0 & 0.6 & 0.9 & 1.2 & 1.5 & & & \\
\end{array}
\]

\( d = 0.95 \) mm

Experimental results
Numerical analysis

\( F_{\text{max}}; x_{\text{max}} \)

Impact testing → Contour strategy → Shape and dimensional analysis → Bi-linear material model → Numerical model (Explicit)

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Results and Discussion

Numerical model calibration – Strut shape

- Geometry used ideal cylindrical shape $d = 0.95$
- Geometry used elliptical shape $e = 0.71$

relative deviation in the first force peak 12 %

relative deviation in the first force peak 2 %
Results and Discussion

Numerical model calibration – Strut shape

- Geometry used ideal cylindrical shape $d = 0.95$
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Impact testing $\rightarrow$ Contour strategy $\rightarrow$ Shape and dimensions analysis $\rightarrow$ Bi-linear material model $\rightarrow$ Numerical model (Explicit)
Results and Discussion

Numerical model - Prediction

- Comparison of the Maximum force, maximum deformation and duration of the deformation

### Maximum force

<table>
<thead>
<tr>
<th>Strut (mm)</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipse cross-section</td>
<td>23%</td>
<td>2%</td>
<td>6%</td>
<td>0%</td>
</tr>
<tr>
<td>Circle cross-section</td>
<td>14%</td>
<td>14%</td>
<td>18%</td>
<td>17%</td>
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### Deformation

<table>
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<tbody>
<tr>
<td>Ellipse cross-section</td>
<td>5%</td>
<td>3%</td>
<td>12%</td>
<td>4%</td>
</tr>
<tr>
<td>Circle cross-section</td>
<td>6%</td>
<td>15%</td>
<td>17%</td>
<td>19%</td>
</tr>
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</table>
Results and Discussion

Numerical model prediction

- Elliptical geometry was applied on lattice structures diameters in range between 0.6 – 1.2 mm

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Conclusion

- **Novel contour strategy for lattice structure fabrication using SLM**
  - Managing of internal porosity and surface roughness

- **Global shape and dimension analysis of the lattice structure**
  - Large statistic population
  - Evaluation of elliptical cross-section
  - $d_{\text{Gauss}}$ the best describe the mechanical properties in numerical model

- **Bi-linear numerical model of lattice structure made of AlSi10Mg**
  - In diameter range 0.6 – 1.2 mm
  - Strut tensile specimens
  - Elongation parameter of failure

- **Numerical model of impact loading**
  - For studying of the shale and dimensions influence on the mechanical properties of lattice structures
Outcomes of PhD thesis


- *Materials MDPI* - IF 2.467, Q2
- Authors contribution 65%


- *Materials MDPI* - IF 2.467, Q2
- Authors contribution 60%
List of Publications

Topic 1 – Study of Energy Absorption


Topic 2 – Study of SLM produced lattice structures

List of Publications

Topic 2 – Study of SLM produced lattice structures


Topic 3 – Numerical Simulation


Others

Oral or poster presentation
- EURO PM2015
- WORLD PM2016
- 3Dtrends 2016
- Discussion “3Dprinting in Aerospace Industry”

Internship at RWTH Aachen University
- 6 month internship
- Establishing of cooperation
- Lattice structure contour strategy

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Thank you for your attention

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