Materialeigenschaften von SLM-gefertigten Bauteilen aus Nickelbasis-Superlegierungen (In 718) mit quasi-einkristallinen Strukturen

SLM® is a registered trademark of SLM Solutions GmbH

Dr. Dieter Schwarze
2013

- DPE invests in SLM Solutions
- Production capacity enlarged to approx. 1000 m²
- 79 employees per 31.12.2013

2014

- May 9
  IPO of SLM Solutions Group AG
- 150 employees per 31.12.2014
- Machine sales > factor 2 compared to 2013
SLM Solutions – a deep rooted 3D printing heritage

Since 1970

Development of SLM technology with Fraunhofer Institute/ F&S

1998 - 2002

Focus on rapid prototyping

First company to process Aluminum and Titanium on SLM machines
Launch of first Fibre Laser technology with the SLM 250

2003

Launch of the SLM 100 as entry model

2006

Launch of SLM 250HL

2007

Launch of the 400 Watt technology

2009

Launch of the new SLM 250HL

2011

Launch of SLM 125HL and SLM 280HL machines with hull and core technology
Launch of automated powder handling devices

2013

SLM 500HL

2014 onwards

Drive industrial application of 3D metal printing technology

Note: History of SLM Solutions and its predecessors
Source: Company information
SLM Solutions – a leader in metal 3D printing

Key products

A leading metal 3D printing company

- Historical origins in rapid prototyping technology
- Paved the way for today’s primary focus: 3D printing for industrial volume production and prototyping
- A leader in selective laser melting technology
- Installed base of 133 SLM systems as per 31-Dec-13
- 26 SLM machines sold in 2013
Fishbone diagramm of the SLM process variables

Quelle: Projektarbeit, A. Wiesner
Main SLM variables

- $L$: laser power
- $v$: scan velocity
- $\Delta y$: hatch distance
- $\Delta z$: layer thickness

- **Energy Density** $E = \frac{L}{v \times \Delta y \times \Delta z}$

- **Build Rate**: $V = v \times \Delta y \times \Delta z$

Example for aluminium with one laser:
$v \approx 1000 \text{ mm/s}, \Delta y \approx 0.2 \text{ mm}, \Delta z = 0.05 \text{ mm}$

$\rightarrow V = \text{theoretical build rate } \approx 35 \text{ cm}^3/\text{h}$

- without delays and recoating time
- good accordance with reality for parts with large volume

Conclusion: The four main variables are strong levers for productivity increase
Qualified materials

- Titanium (Ti cp, TiAl6Nb7, TiAl6V4)
- Aluminium (AlSi12, AlSi10Mg, AlSi7Mg, Al7075 ...)
- Cobalt Chrome (ASTM F75)
- Steels (1.2709, 1.2344 (H13), M333, 1.4404 (316L), 1.4410, 1.4542 (17-4PH))
- Inconel (e.g. 625, 718, 939, 738)
- Hastelloy X
- CuSn10 Bronze
- ...

Spezifications:

- spherical particles
- 10 µm < Ø < 45 – 63 µm
- good flowability
- dryness
- pureness (chemistry)
Inconel

- Inconel is a trademark of Special Metals Corporation
- Inconel is a family of austenite nickel-chromium-based superalloys
- The predominant alloying ingredient is typically the metal nickel
- Inconel is used in extreme environments subjected to pressure and heat
- IN 718: high yield tensile and creep-rupture properties @ T up to 704 °C and oxidation resistance to 982 °C, used for parts for jet engines and high speed airframe parts such as wheels, buckets, spacers and high temperature bolts and fasteners.

Source: Special Metals Corporation / Wikipedia
Co-Authors

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Dr. Thomas Niendorf, Institut für Werkstofftechnik (IWT), TU Bergakademie Freiberg
Inconel 718

Example: Application in Turbine Blades


**Major Chemical Composition:**

<table>
<thead>
<tr>
<th>Element</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>Al</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gew.-%</td>
<td>Bal.</td>
<td>19.0</td>
<td>3.0</td>
<td>5.1</td>
<td>0.5</td>
<td>0.9</td>
<td>18.5</td>
</tr>
</tbody>
</table>

- **Mo, Nb:** Solid Solution Hardening
- **Nb, Al, Ti:** Precipitation Hardening
- **Cr, Al:** Good Corrosion and Oxidation Resistance
- **Fe:** Good Workability and Weldability → Low Costs

Source: Julia Hopfenmüller, Master Thesis, Allgemeine Werkstoffeigenschaften (WW1), Universität Erlangen-Nürnberg
SLM 280<sup>HL</sup> / PSH 100

- build envelope 280 x 280 x 350 [mm]
- 2 fiber lasers: 400 W + 1000 W
- 2 focus diameters 100 µm + 700 µm
- Layer thickness 30 µm – 150 µm
- new optic design (without F-Theta)
- short recoating time
- highly efficient fume exhaustion
- argon gas circulation
- optical layer control system
- substrate plate preheating 200° C
- real-time melt pool temperature monitoring
- inline laser power measurement
- ...

Details / Options
Hull – Core + Double – Beam Technology

- 400 W and 1000 W fiber laser with different focus diameter for hull and core
- fine focus (100 µm) with Gaussian beam profile for hull and larger focus (700 µm) with top-hat profile for core
- scan lengths reduction by factors
- economic production of large volume parts with AM
- reduced spatter emission with 1kW laser in the core
- build rate increase ≈ Faktor 5 possible without loss of surface quality

Source: FhG ILT Aachen
Core Microstructure Design

The productivity gain is not all of the story.

The unique double-beam technology of SLM Solutions is perfectly suited to create a microstructure that can be very beneficial e.g. for high temperature applications.

The quasi single crystal microstructure was found in stainless steel as well as in Inconel, Hastelloy X and Cocr ...

Density core experiments

Core density cubes with edge length of 13mm, hull 1.5 mm, rest core

- Experiments were carried out for layer thickness 100µm and 150µm
- The cubes are arranged diagonal, so that mutual influencing is excluded.
Core density results with 1kw laser

Test cubes built using core parameters

<table>
<thead>
<tr>
<th>Test Cube #</th>
<th>Layer thickness</th>
<th>Build-up rate [mm³/s]</th>
<th>Achieved density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100µm</td>
<td>13,6</td>
<td>99,57%</td>
</tr>
<tr>
<td>2</td>
<td>100µm</td>
<td>16</td>
<td>99,81%</td>
</tr>
<tr>
<td>3</td>
<td>150µm</td>
<td>10,2</td>
<td>99,61%</td>
</tr>
<tr>
<td>4</td>
<td>150µm</td>
<td>12</td>
<td>99,44%</td>
</tr>
<tr>
<td>5</td>
<td>150µm</td>
<td>13,8</td>
<td>99,48%</td>
</tr>
<tr>
<td>6</td>
<td>150µm</td>
<td>14,25</td>
<td>99,76%</td>
</tr>
<tr>
<td>7</td>
<td>150µm</td>
<td>16,2</td>
<td>99,57%</td>
</tr>
</tbody>
</table>

Source: FhG ILT Aachen
IN718 – Core Microstructure

IN718 As-built

- Highly anisotropic
- Coarse columnar grains
- Epitaxial growth
- <001> texture, highest intensities in BD

Microstructure directly tailored for optimized performance at high temperatures !?!

Courtesy of A. Taube
IN718 – Core Thermal stability

- No significant changes in microstructure
- No driving force for recrystallization

Standard heat treatment procedures can be employed for aging

Courtesy of A. Taube
IN718 – Core Thermal stability

Heat treated @ 500 °C

- Hardness following aging seems hardly be affected by previous solutionizing
- Hardness increase in as-built

Evolution of hardness

Vickers Microhardness, HV

Temperature, °C

Effect of aging

Solutionized

After aging

Heat treatment may be even simplified

Cost reduction!

Courtesy of A. Taube
Test results of hull experiments

- Conventionally Forged Material

- Selective Laser Melting Material

Source: Julia Hopfenmüller, Master Thesis, Allgemeine Werkstoffeigenschaften (WW1), Universität Erlangen-Nürnberg
IN718 – Mechanical properties

IN718

- Aging induces increase in strength
- Can be correlated to evolution in hardness

Precipitation of phases well-known in IN718

Effect of aging

Tensile tests at RT

Courtesy of A. Taube
IN718 – Creep performance

IN718, Standard Parameter 400 W

- Significantly smaller grains
- Relatively weak texture

As-built, 400 W Laser

Reference material

Courtesy of M.E. Aydinöz
IN718 – Creep performance

IN718, Standard Parameter 400 W

- Significantly smaller grains
- Relatively weak texture

→ Reference material

Superior creep properties for IN718 following SLM!

Courtesy of J. Hopfenmüller
IN718 – Stress rupture performance

Stress Rupture Test AMS 5662 at 650 °C
Axial Stress 100 ksi = 690 MPas
Life, largely exceeded min. spec of 23 h
Elongation, % - 5 also exceeded
Thank you very much for your attention!