Additive Manufacturing – next generation

AMnx

Study results by Roland Berger

Eindhoven, March 15th, 2017
Photo: FIT AG
Roland Berger is a trusted advisor for Additive Manufacturing (AM) in the Engineered Products & High Tech industry

AMnx @

51 offices in 36 countries – 2,400 employees

> Founded in 1969 as a one-man business, we now have successful operations in all major international markets
> Largest consulting firm with European/German roots
> Among the top 3 players for strategy consulting in Europe, number 1 for mechanical & plant engineering
> Team of 2,400 employees worldwide, of whom 180 are partners

Source: Brand Eins; Roland Berger

Engineered Products & High Tech Competence Center

Aerospace & defense
Energy equipment
Long lifecycle products
Digital technologies
B2B electronics

> Additive Manufacturing is part of our digitization initiative
> Roland Berger published two AM studies in 2013 and 2016 available on our homepage
> Relevant project experience ever since forms the basis for the updated study at hand
> Our consulting services for AM range from business development to operational excellence
AM has seen strong development in the recent past and achieved production readiness – What's next (AMnx)?

Emergence of Additive Manufacturing

- **1985**: Foundation of EOS by Dr. Langer and Dr. Steinbichler
- **1990**: Extrude Hone (now ExOne) becomes exclusive licensee of the binder jetting process for metal parts and tooling
- **1995**: Arcam commercializes PBF by electron beam technology, launching first production model
- **1996**: The "basic ILT" SLM patent which describes metal PBF by laser is filed
- **1997**: First metal PBF by laser machine is introduced by F&S Stereolithografietechnik (Fockele & Schwarze)
- **1999**: Optomec delivers first commercial directed energy deposition (DED) System (LENS 3D Printer)
- **2000**: First PBF 4-laser concept introduced by EOS
- **2002**: Trumpf introduces its first lines of metal PBF by laser machines (TrumaForm LF)
- **2003**: MCP Tooling Technologies (later MTT Technologies Group) introduces PBF by laser machine SLM Realizer 100
- **2005**: EOS introduces EOSINT M 250
- **2010**: First AM-produced part for use in a jet engine by GE, receives FAA approval
- **2013**: FDA approval (510(k)) for the first patient specific cranial device by OPM granted
- **2015**: First PBF 4-laser concept introduced by EOS
- **2016**: GE announces take over of Concept Laser and Arcam; Oerlikon announces the acquisition of Citim
- **2017**: DMG MORI presents PBF machine in cooperation with Realizer

**Today**
- Series production readiness achieved; Up to 4 lasers simultaneously creating one part; Build area up to 800 mm in length; Automation concepts available

**Next generation**
- **2011**: AM growth in medical, e.g. dentistry, is picking up traction
- **2011**: ASTM approves first non-terminology AM standard
- **2013**: Arcam commercializes PBF by electron beam technology, launching first production model
- **2015**: First AM-produced part for use in a jet engine by GE, receives FAA approval

Source: Company websites; European Patent Office; Wohlers Associates; Roland Berger
Our recognized study AMnx gives a comprehensive overview about different aspects of the metal AM industry

"Additive Manufacturing – next generation (AMnx)" – our latest study

1) (Partly) not included in published study

Source: Roland Berger
A. Engineering & software
For future applications a seamless software suite needs to cover the entire AM value chain including e.g. machining and documentation.

Seamless AM software suite – schematic

**Seamless software integration**

**Software**
- Design
- Optimization
- Production planning
- Print file generation
- CNC programming

**Hardware**
- Printer controller
- Oven controller
- Machine controller 1
- Machine controller 2
- Machine controller 3
- Machine controller 4

**Production step**
- CAD
- Optimization
- Production planning
- Additive Manufacturing
- Heat treatment
- Support structure removal
- Machining
- Surface treatment
- Quality control

**Equipment**
- Printer
- Oven
- 5-axis CNC/EDM
- 5-axis CNC
- e.g. MMP
- Test rig, CMM etc.

Source: Roland Berger
Additive Industries addresses already the integration of several process steps in its modular machine concept

Integration concept

- Multiple (1-4) full field laser and optics positions preventing the need for stitching
- Effective build volume: 420x420x400 mm³
- Strong reproducibility caused by robust thermal machine design and smart calibration strategies
- Integrated post processing (heat treatment) increases process predictability and product quality
- High productivity by continuous production (2 build chambers)
- Instant switching between multiple materials gives a high flexibility
- Automated handling by integrated robot, enclosure design and filter solution results in high operator safety
- >112 h unmanned multi-job operation prevents multiple shift operations

Source: Additive Industries; Roland Berger
B. Materials

Photo: AIRBUS APWORKS GmbH
Amorphous metals offer a unique combination of material properties due to their atomic structure

**Amorphous metals: Introduction**

**Metallurgical process**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Melt</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass-transition temperature</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Amorphous 
- Crystalline

**Mechanical properties**

<table>
<thead>
<tr>
<th>Strength (GPa)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-based amorphous metals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zr-based amorphous metals</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Plastics</td>
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</tr>
</tbody>
</table>

**Temperature**

- Melting temperature
- Glass-transition temperature

**Log (time)**

- Crystallization started
- Crystallization finished

- Strength (GPa)
- Elasticity (%)

**> Alloy with suitable **glass-forming ability** needed to produce amorphous metals, e.g. Fe-, Zr- or Ti-based**

**> High cooling rates lead to amorphous (non-crystalline, i.e. disordered) atomic structure**

**> Achievable cooling rate limits **maximum material thickness** with traditional manufacturing methods, e.g. casting**

**> The amorphous atomic structure determines specific material characteristics**

**> Amorphous metals combine **high strength and high elasticity****

**> They offer high hardness, corrosion resistance, conductibility, biocompatibility and self-sharpening properties**

**> Ductility and fatigue strength** are typically below that of crystalline metal – research has shown that fatigue strength can be improved by reinforcing amorphous matrix with nanocrystals

**> Ferromagnetic amorphous alloys furthermore offer **high magnetic susceptibility with low coercivity** and high electrical resistance**

Source: Exmet; Roland Berger
C. Machines
Current AM systems utilize multiple lasers to increase productivity and reduce manufacturing time

Multi-laser concept – The current state-of-the-art solution

**Principle**

- AM production time depends on the layer-by-layer laser exposure time, lowering of the chamber platform and powder-bed distribution time
- Using multiple independent lasers, different areas can be manufactured in parallel with direct impact on exposure time
  - E.g. dual-laser systems halve the exposure time leading to an overall productivity increase by a factor of 1.8

**Realization**

<table>
<thead>
<tr>
<th># of laser spots</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Commercial systems available with up to 4 laser systems

**Result**

- A higher number of laser spots yields a direct increase in manufacturing speed
- Nevertheless, multi-laser technology faces some problems, e.g.:
  - The laser system is the system's most complex and expensive component
  - Heat and fume creation scales with the number of laser spots and limits the manufacturing process
- Limited advantage of multi-laser technology: scaling of the system with the most complex and expensive component fundamentally limits the method's cost advantage

Image of the manufacturing chamber of SLM Solution's SLM 500HL system capable of using 4 independent lasers and scanner systems simultaneously

Source: SLM Solutions; Roland Berger
ILT's multi-spot system represents a conceptually new approach –
Direct advantages in process speed and system cost

Multi-spot array concept – Next generation technology

**Principle**

- A 5-spot laser array is mounted on a single printer-like processing head
- 5 diode lasers are coupled to the processing head via an optical fiber system
- The processing head moves over the powder bed similarly to a paper printer head
- A local shielding gas and fume removal system is mounted directly on the processing head
- Melt pool control is achieved by laser intensity modulation while the processing head moves over the powder bed (see figure below)

**Realization**

- Picture of the enclosed ready-to-use PBF multi-spot system
- View of the processing head: a five-spot array is mounted on a single scanning head

**Result**

- Good scalability in terms of manufacturing speed and chamber size:
  - Increased manufacturing speed due to a wider area of optical illumination
  - Chamber size is not limited by the optical system
  - Local shielding gas and fume removal system for ideal processing conditions independent of chamber size
- Reduced system cost due to a low-complexity optical system

System currently in research stage, part quality to be evaluated – potential drawbacks vs. beam-steering approach for small structures

Source: Fraunhofer Institute for Laser Technology (ILT); Roland Berger
ExOne has developed a fully automatic production line for silica sand cores using soluble glass as binder

Full line concept for serial production by ExOne

Working principle

> The new machine concept by ExOne addresses the cost effective production of silica sand cores, which are difficult or impossible to manufacture by alternative processes due to their geometric complexity
> ExOne provides a full line concept for serial production including one or more Exerial 3D printers (1), a curing and drying microwave station (2) and a desanding station with an unloading robot (3). The printer is equipped with two job boxes (2,200 x 1,200 x 700 mm³), which are moved by a conveyor system from station to station. Multiple configurations of the different elements are possible
> The drying and curing of the environmentally friendly soluble glass binder material takes place in a microwave furnace
> The build speed is in the range of 300-400 l/h, max. resolution of 0.1 mm and layer thicknesses from 0.28 to 0.5 mm
> The current print head has a width of 600 mm, which means two runs to fully print the 1200 mm wide job box. A 1200 mm print head is expected to become available in 2016, which would boost the efficiency of the overall system close to the cost level of conventional automotive serial production
E. Services

Additive World

Photo: Siemens
"Mobile" applications of AM on large container ships, aircraft carriers or for military vehicle repair are gaining more and more relevance

Example – AM for mobile repair services

- Maersk ship line is investigating the use of printers on their merchant vessel fleet
- The US Navy has installed first printers on the combat ships like the aircraft carrier USS Essex
- Mobile print centers in containers for the ground troops are under investigation by several armies
- First real application show relatively robust FDM printers, which are used by the maintenance staff for printing of assembly tools, bending tools or relatively simple plastic replacement parts
- The use of metal printing in mobile applications is more difficult due to the sensitivity against vibrations. FDM printer, mostly used, are more robust

Source: Roland Berger
European defense organizations are also preparing for mobile AM solutions – First project tender published

Project target of a European tender for a containerized AM solution

> Identify opportunities and weaknesses for AM in the European defense sector

> Highlight elements delaying or preventing European defense forces from using AM technology

> Demonstrate the feasibility and operational utility of a containerized AM solution during an air-born maneuver

> Raise the military awareness of AM and its potential in defense

> Exemplify how AM could change today's ways of operations, logistic support or maintenance of platforms

> Discuss the possible economic impact on defense capability

Source: Call for Tenders; Roland Berger
Fleet operators, OEMs, Tier Xs and PLM providers need to set up a completely new infrastructure for efficient fleet data management.

Data management challenges:

- **OEM**
  - Production, e.g. production drawings, process descriptions, test specification, etc.

- **Tier 1 Engine**
  - Financial aspects, e.g. reimbursement, license agreements, etc.

- **Tier 2 Waterpump**
  - Legal aspects, e.g. IP, warranty, copyright, patents, CE, etc.

- **Tier 3 Pumpwheel**
  - Data management, e.g. CAD data, 3D models, specification, material data, etc.

Source: Roland Berger
H. Stock market
The global AM market is expected to grow significantly until 2020 – High variability of growth expectations

Global AM market

- Compared to the machine tool market, the 2015 metal AM system market is still relatively small (less than 1%)
- For the period 2004 to 2015, the overall AM market showed an annual growth rate (CAGR) of c.20%, while from 2010 to 2015 the growth rate was higher than 30%
- Based on different, actual estimates the market is expected to multiply by a factor of two to four until 2020

Source: VDW; Bloomberg Business Week; Canalys; MarketsAndMarkets; Wohlers Associates; Roland Berger

1) World production excl. parts/accessories  2) Including aftermarket products
The first printed gun and the ensuing stock rally led to a media hype about Additive Manufacturing in 2013 and 2014

Key events in 3D printing

Google searches for “3D printing”

Stock of Arcam AB [USD]

Stock of Voxeljet AG [USD]

Stock of 3D Systems, Inc. [USD]

First major announcement of Additive Manufacturing
> GE starts industrial use of AM for its jet engines

Biggest hype
> 1st 3D printed gun is unveiled (May 3, 2013)
> News media all around the world start covering the 3D printing industry

Highest stock valuation
> IPO of the small German 3D printing company Voxeljet AG
> Stock prices reach all-time high after five-month rally

1) Highest search volume = 100 points

Source: Bloomberg; Google Trends; Roland Berger
Although stock prices of established AM companies declined over the last years, analyst grades indicate hold or buy positions

**Stock prices [USD]**

- **3D Systems**
  - IPO: 1989
  - Focus on PBF (plastic)
  - Daily trading volume since 2015 stabilizing at approx. 3.1 m stocks
  - 3D Systems is the AM pioneer – first system sold in 1988
  - 52 acquisitions since 2009; cumulative acquisitions in 2014 total USD 345 m
  - New technology enables jetting of three different base materials

- **Stratasys**
  - IPO: 1994
  - Focus on material extrusion
  - Daily trading volume approx. 1.3 m

- **Voxeljet**
  - IPO: 2000
  - GE acquired 76% of Arcam in 11/2016
  - Focus on PBF by electron beam (inventor of the technology)
  - Daily trading volume approx. 128 k stocks
  - New technology enables jetting of three different base materials

- **SLM Solutions**
  - IPO: 2013
  - Focus on binder jetting
  - Daily trading volume approx. 1.8 k stocks, tending upwards
  - Developed new phenolic binder in 2014 enabling higher resolution, precision and powder recyclability rate
  - Opened new service facility in the US in 2015

- **GE**
  - IPO: 2014
  - GE bid on SLM in 09/2016 – Stopped after Elliott stepped in
  - Focus on PBF by laser (metal)
  - Versatile systems due to open architecture – most metal powders applicable
Overvalued AM stocks are approaching fair valuation – Stock profits are likely to be appropriate and stable in the medium term

Price/earnings ratios of listed AM suppliers

Source: Bloomberg; Capital IQ; Nasdaq; Roland Berger
Please contact us if you have any further questions

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