Karlsruhe Institute of Technology

Application Driven Advances in Additive Manufacturing

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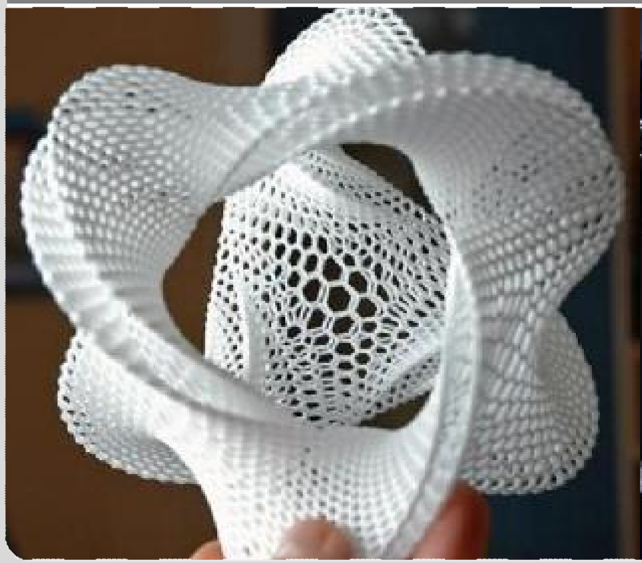
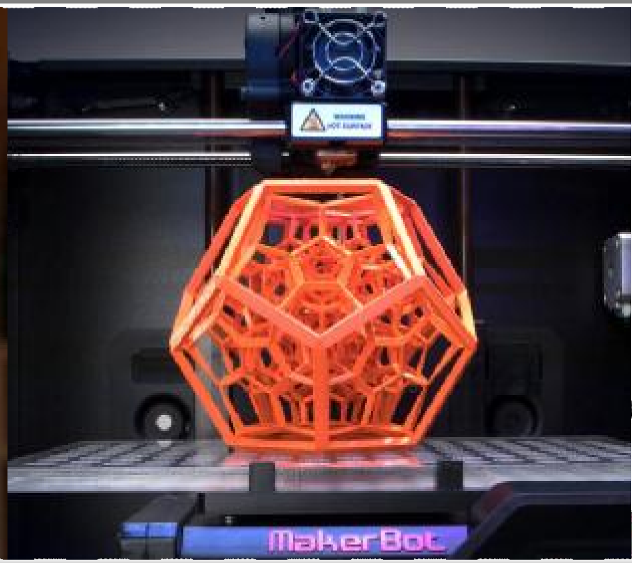
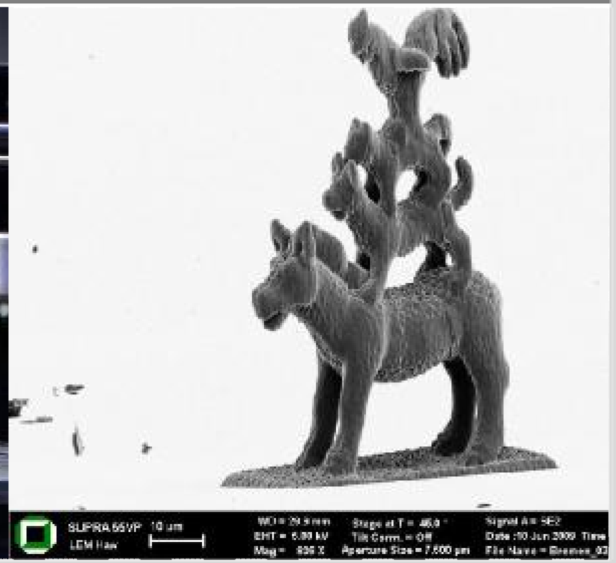
Insitute of applied computer science, Helholtz program: STN







Overview

Introduction

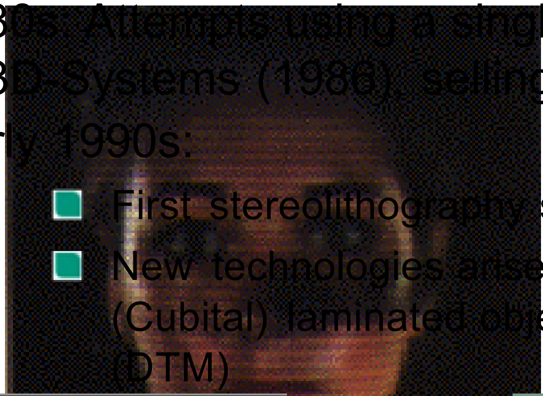
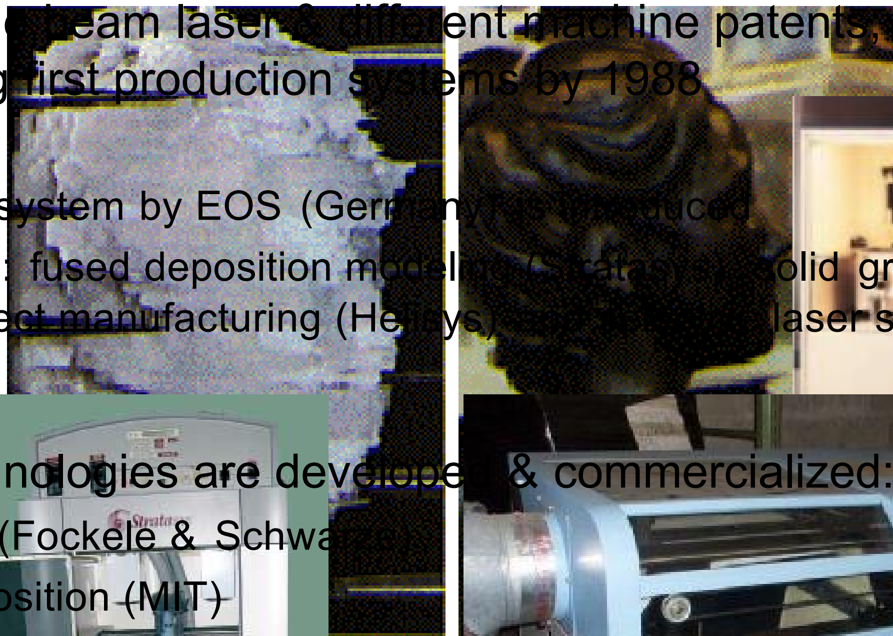
- Definiton of AM:
  - „The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining“[1]

- Typical technologies:
  - Laser/Light Polymerization (e.g. stereolithography)
  - Laser Melting (e.g. selective laser sintering, selective laser melting)
  - Extrusion processes
    (e.g. fused filament fabrication, fused deposition modeling)
  - Material jetting (e.g. inkjet printing or multijet modelling)
  - Adhesive based processes (e.g. laminated object manufacturing)
  - Electron beam manufacturing (EBM)

[1]Source: ASTM Standard. Standard terminology for additive manufacturing technologies, vol 10.04

Introduction – History of AM – Early years

- Late 1960s: First experiments in creating solid objects using photopolymers and dual beam laser technology
- 1970s: First companies dealing with 3D objects by layer techniques
- 1980s: Attempts using a single beam laser & different machine patents; foundation of 3D-Systems (1986), selling first production systems by 1988
- Early 1990s:
  - First stereolithography system by EOS (Germany) is introduced
  - New technologies arise: fused deposition modeling (Stratasys), solid ground curing (Cubital) laminated object manufacturing (Helisys) and selective laser sintering (DTM)
- 1990-2000: Several new technologies are developed & commercialized:
  - Selective laser melting (Fockele & Schwarze)
  - Inkjet liquid binder deposition (MIT)
  - Inkjet wax printing (Solidscape)
  - Paper lamination (Kira Corp.)
  - Multijet modelling (Objet)



of Soho Im

Introduction – History of AM

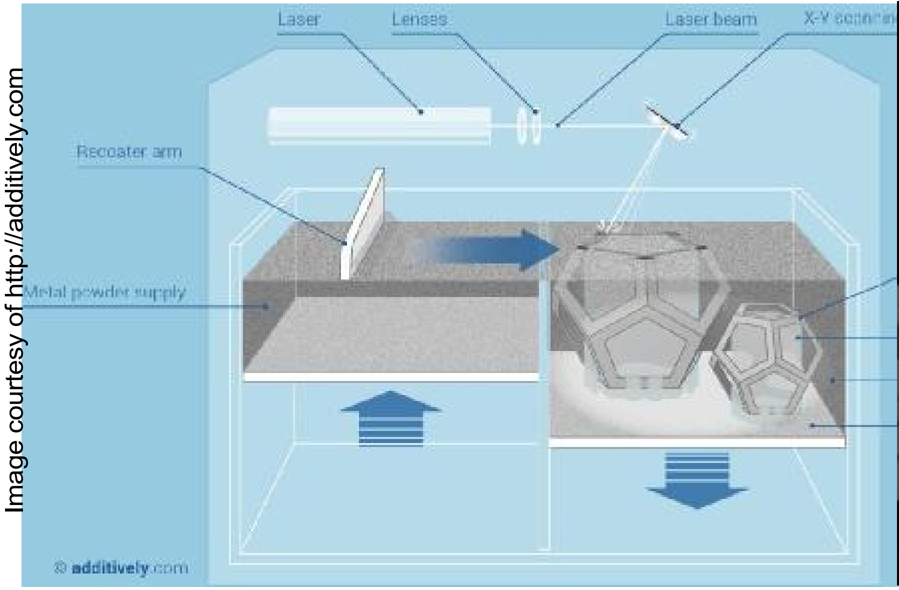
- 2000-2010:
  - Build platforms are getting bigger, resolution is getting better, building time is reduced and prices for machines start to get lower
  - New materials are available: Nanocomposites, high-elongation materials, hight temperature resistant materials, improved mechanical properties and bio-compatible materials
  - Formation of ASTM comittee for producing standards on testing, processes, materials, design and terminology in AM
  - EnvisionTec introduces first stereolithography machine using direct light processing (DLP) technique

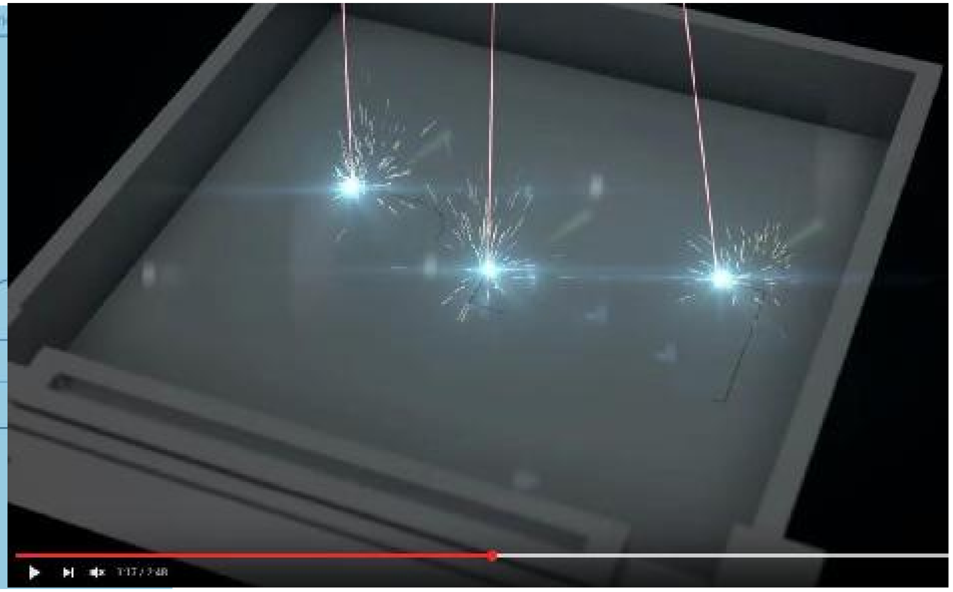
- 2010-now:
  - AM is adopted by many industries as a valid production method
  - Capabilities of machines are extended even further (materials, resolution, build sizes)
  - AM is reaching the private sector with affordable FDM, SLA and DLP printers

AM Technologies – Selective Laser Melting/ Sintering

- Thin layers of fine (metal) powder are distributed on a indexing table that is movable in the vertical (z-) axis
- Resulting powder layer is molten or sintered by a high power laser beam

Image courtesy of http://additively.com





- Advantages: High density, wide range of metals applicable
- Drawbacks: Slow process, surface finishes are limited
- Possible Materials: Stainless steels, tool steels, titanium, nickel based alloys, ceramics

AM Technologies – Fused Filament Fabrication

- Material filament ist unwound from a coil or continuously fed from strains
- Deposition of individual layers by feeding material through heated nozzle

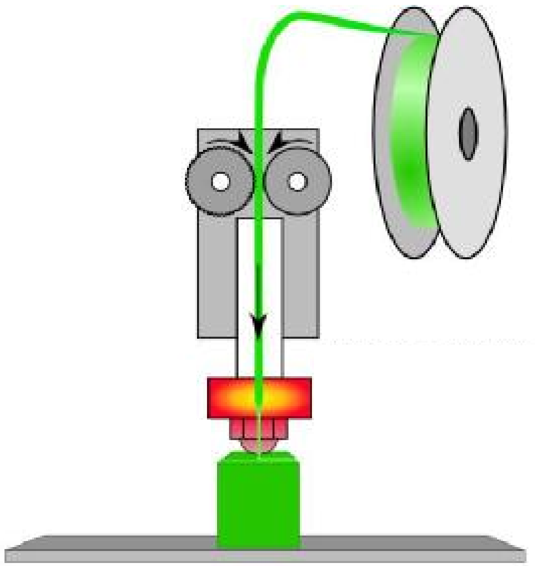


Image courtesy of http://spacediy.es/

- Advantages: Cheap, huge variety of machines available, compact size
- Drawbacks: Ribbing (visible layers), low part strength, delamination problems
- Possible Materials: ABS, PLA, PC, PPSF, PEI, materials with fillers (wood, copper)

AM Technologies – Stereolithography (SLA)

- Photocurable polymer, typically liquid resin
- Layer by layer hardening by applying focussed light or UV light

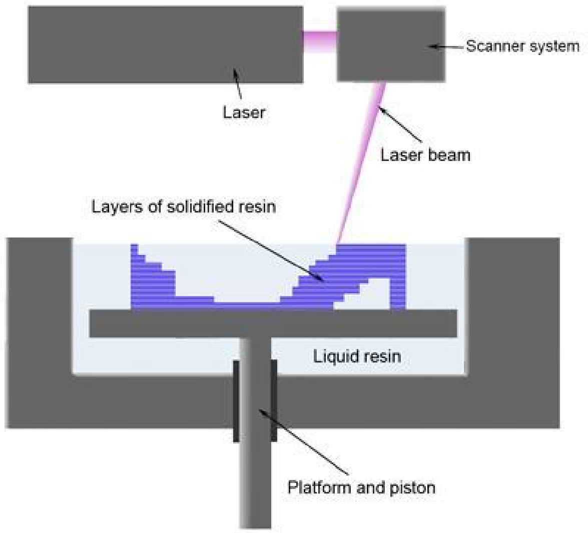


Image Courtesy of http://isambardkingdom.com/

- Advantages: High resolution, smooth surfaces, high mechanical strength
- Drawbacks: Limited material range, high printing costs compared to FFF
- Possible Materials: Epoxy based photopolymers

AM Technologies – Inkjet / Multijet printing

- Similar to classic inkjet printing small droplets are dispensed by a single or multiple printheads
- Printed layer are either cured (photopolymers) or cooled (wax)

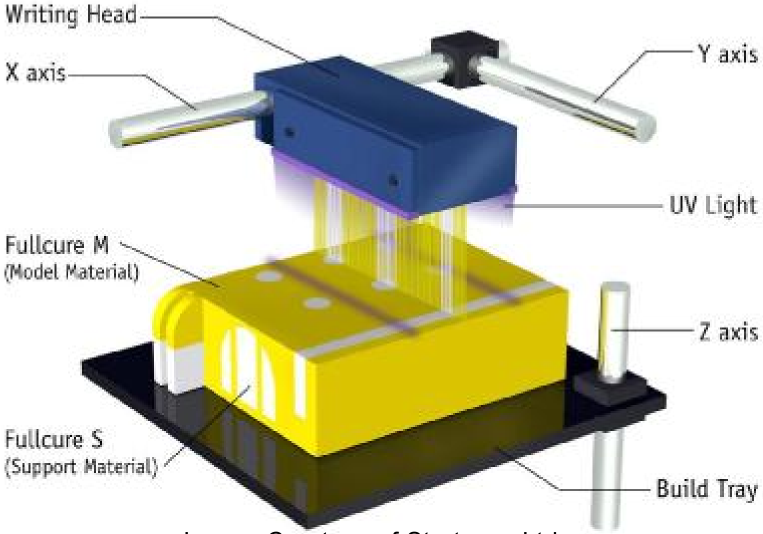


Image Courtesy of Stratasys Ltd.

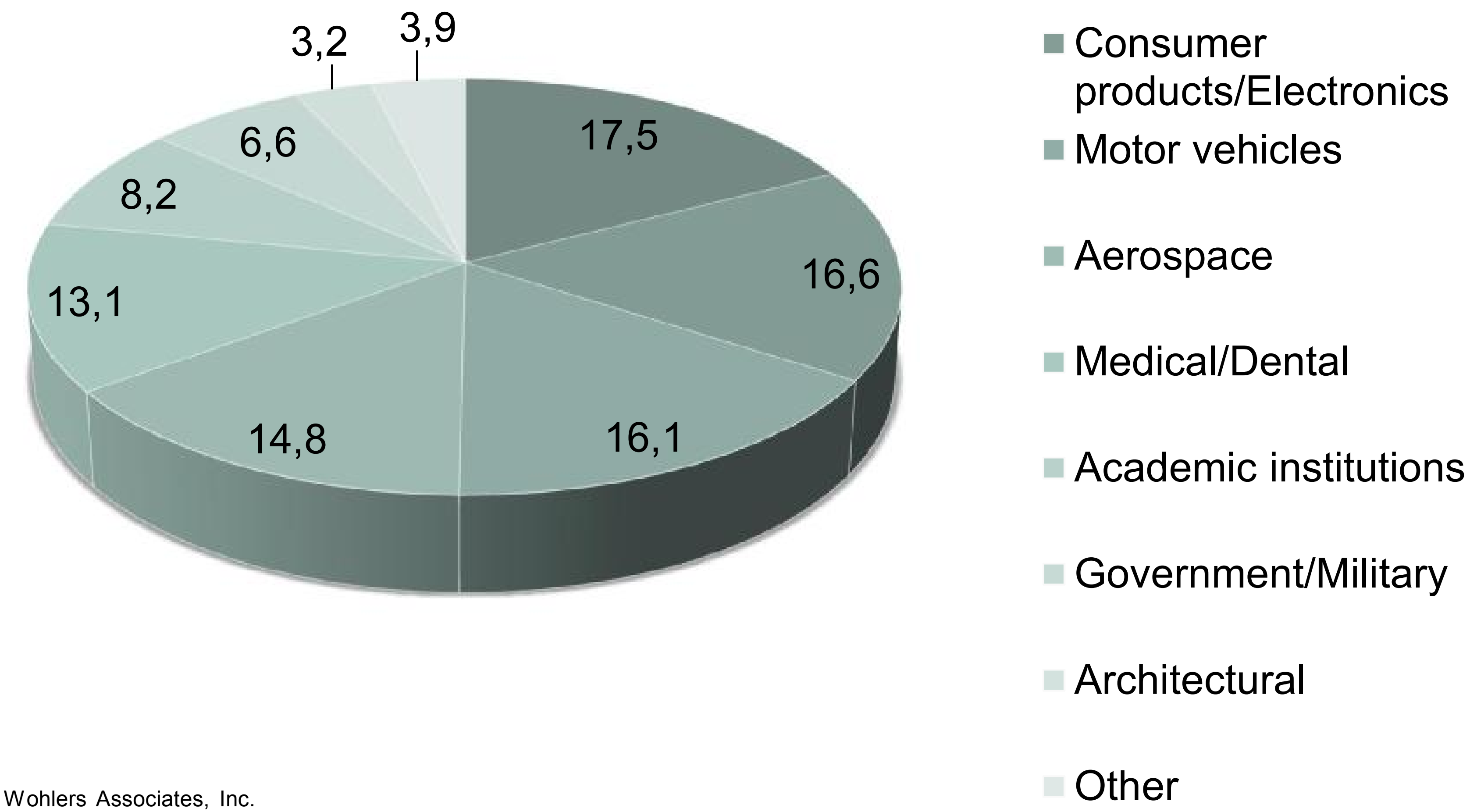
- Advantages: Very accurate, smooth surface, Quick print time (Multijet)
- Drawbacks: Separate process for melting supports, slow (Inkjet)
- Possible Materials: ABS, PA, TPE, resins

AM Technologies – Comparison

Process	Min. Resolution z-axis [µm]	Min. Resolution xy-axis [µm]	Build Platform [mm]
Fused filament fabrication (FFF)	20	> 250 (depending on nozzle size)	Up to 914 x 610 x 914
Selective laser sintering/melting (SLS/SLSM)	50	200-300	Up to 800 x 400 x 500
Stereolithography (SLA)	20	150	Up to 2100 x 700 x 800
Inkjet/Multijet printing	16	100-200	Up to 1000 x 800 x 500

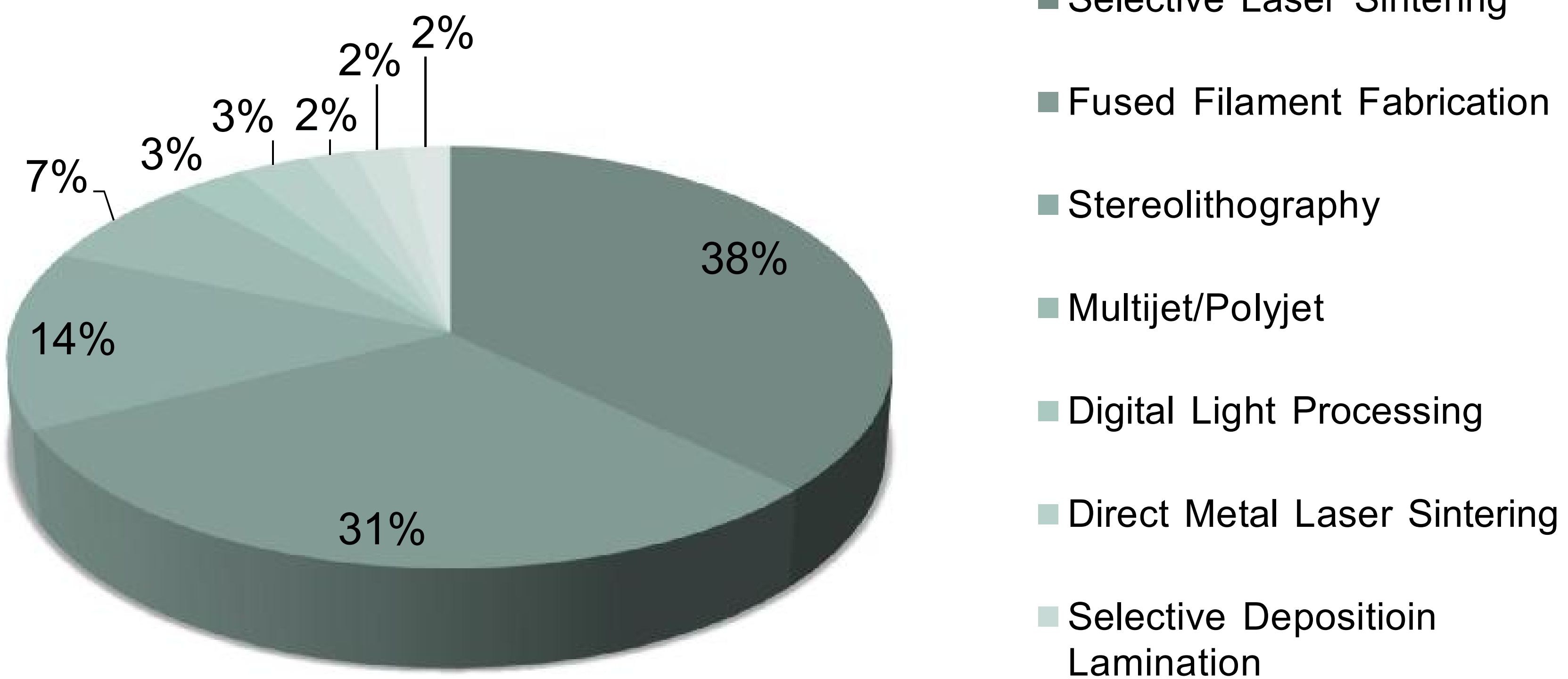
Market status - Sectors

- Sectors



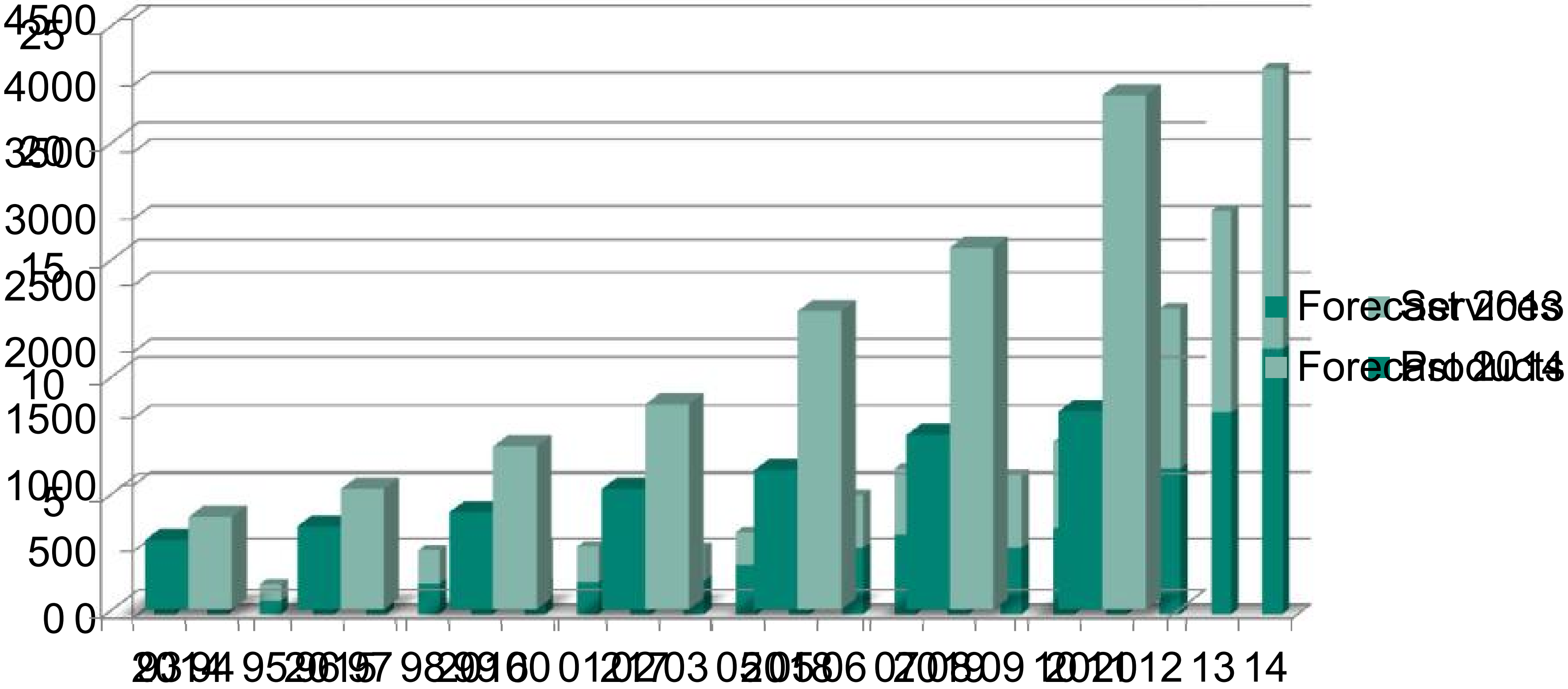
Source: Wohlers Associates, Inc.

Market status – Materials & Technologies



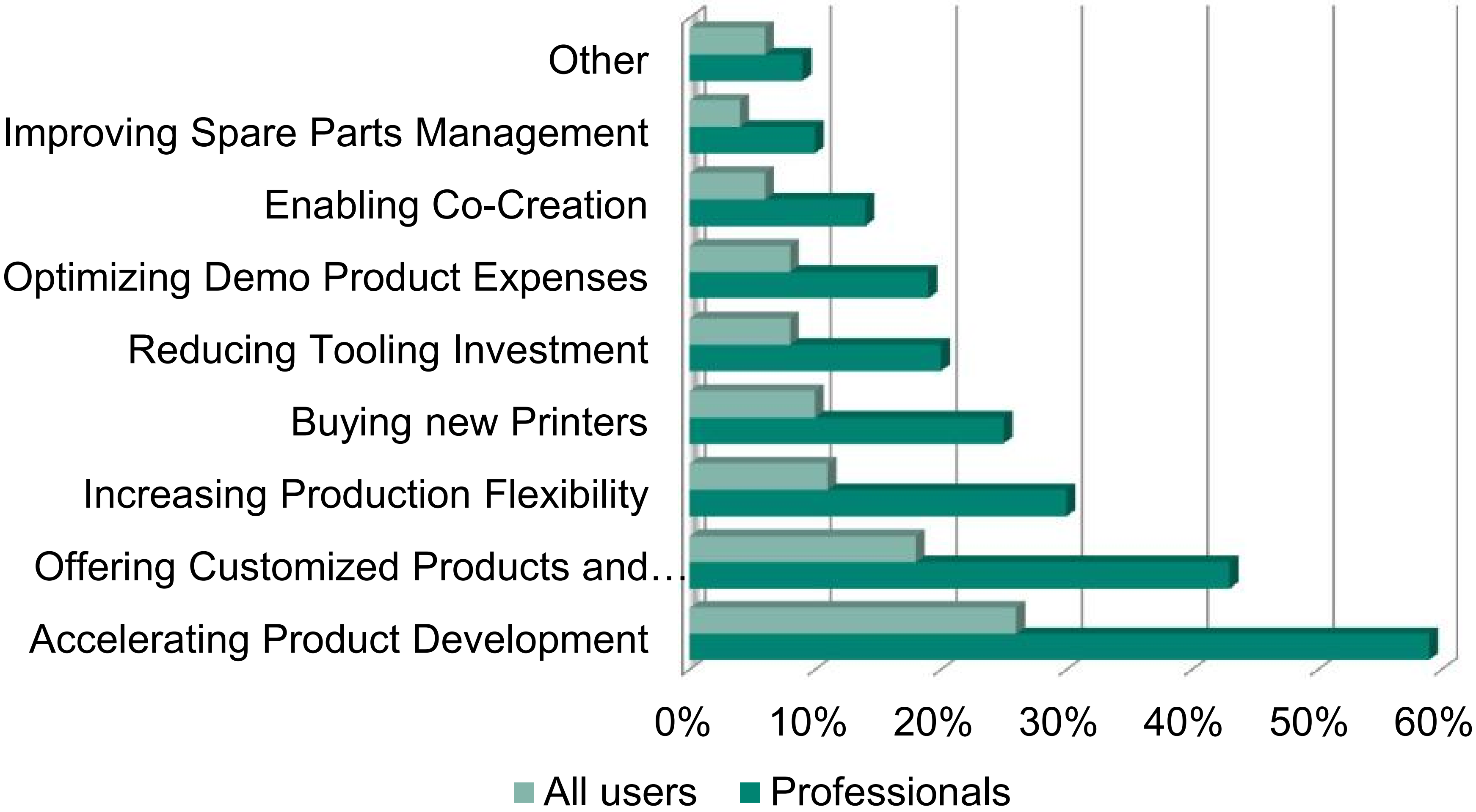
Market status – Past and future

- Average annual growth over past 26 years: 27.3%, over last 5 years: 33,8%
- Current worldwide revenue: 4.103 billion US $, being split between AM products (1.997 Billion) and AM services (2.105 billion)



Source: Wohlers Associates, Inc.

Market status – Priorities for users in 2016



Source: Sculpteo.com „The State of 3D Printing“ 2016 report

Applications – Multi-Material Printing

- Creation of parts with functionally graded materials:
  - Hardness
  - Flexibility
  - Adhesive properties
  - Stiffness
  - Color

Image Courtesy of Kiril Vidimce

Image Courtesy of Synthesis Design + Architecture

Images Courtesy of Massachusetts Institute of Technology

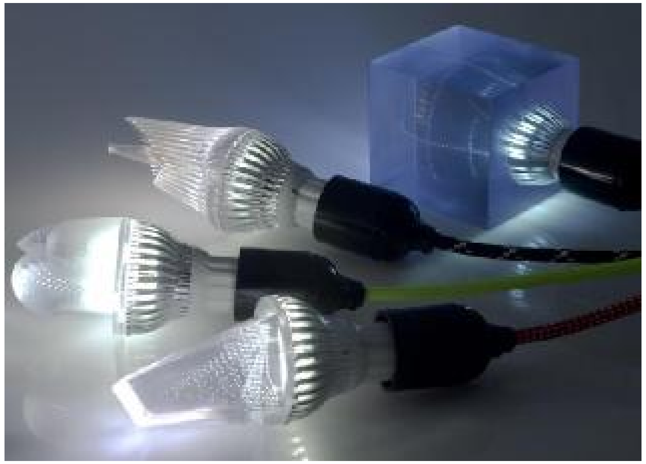
- Possible Applications:
  - Compliant joints
  - Artistic sculptures
  - Heat Dissipation

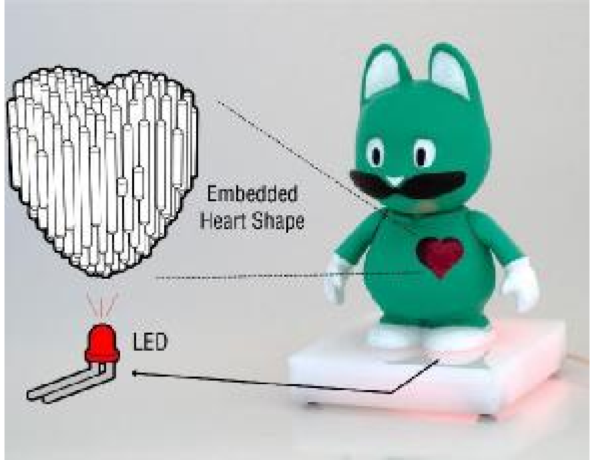
Image Courtesy of Stratasys Inc.

Applications – Embedded Components

- Objects can be embedded due to layer-by-layer build-up
  - Circuits
  - Sensors
  - Monitors
  - Threaded rods
  - Etc.

Image Courtesy of Berkeley University





Images Courtesy of Disney Research

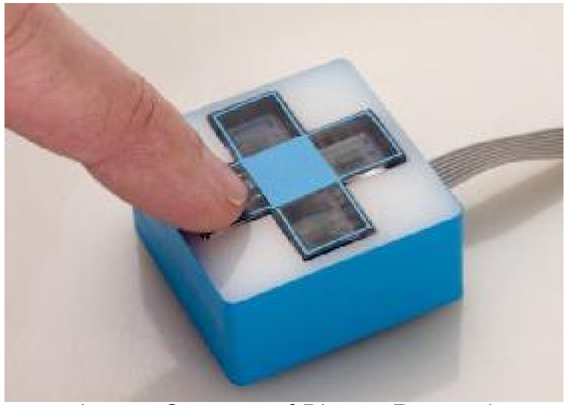


Image Courtesy of Disney Research

- Possible Applications:
  - Toys
  - Lighting devices
  - Food monitors

Applications – Printed Electronics

- Direct writing of conductive material enabling the creation of
  - Circuits
  - 3D antennas
  - Sensor (Magnetic, force, strain gauge)
  - Batteries
  - Etc.

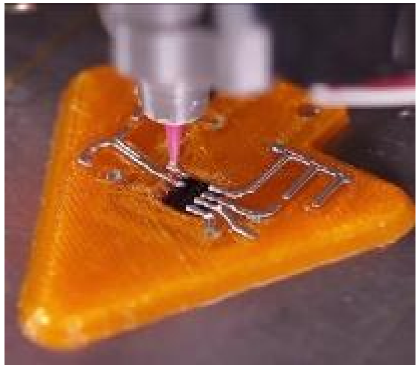


Image Courtesy of Voxel8

Image Courtesy of Neotech AMT

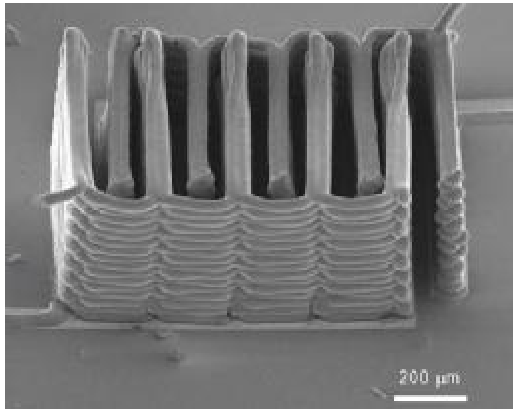


Image Courtesy of Harvard University

Image Courtesy of Harvard University

- Possible Applications:
  - Mobile communication
  - Medical devices
  - Consumer products

Applications – Printed Assemblies

- Pre-Assembled Parts directly printed
  - Use of sacrificial support material
  - Gaps of few hundreths µm between parts
  - Removal of support leaves captive assembled linkage
- Possible Applications:
  - Physical Working models
  - Locomotive robots
  - Articulated Models
  - Prosthetics

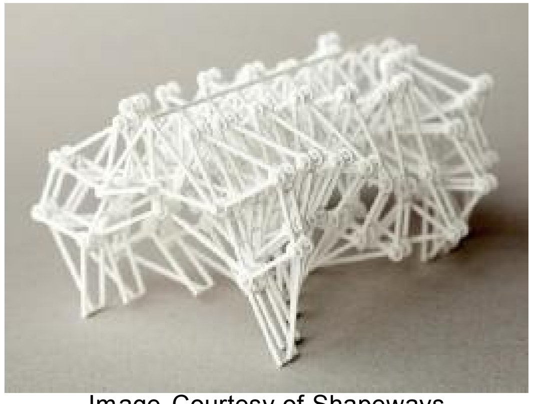
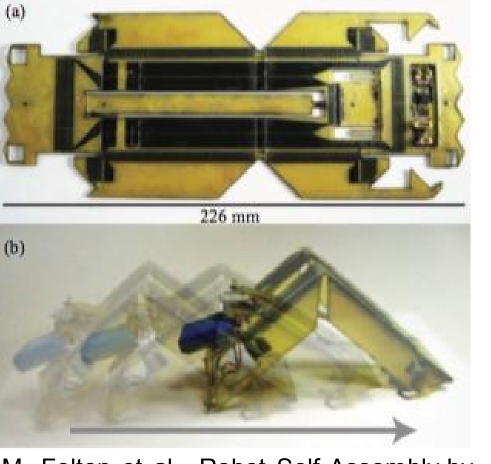


Image Courtesy of Shapeways



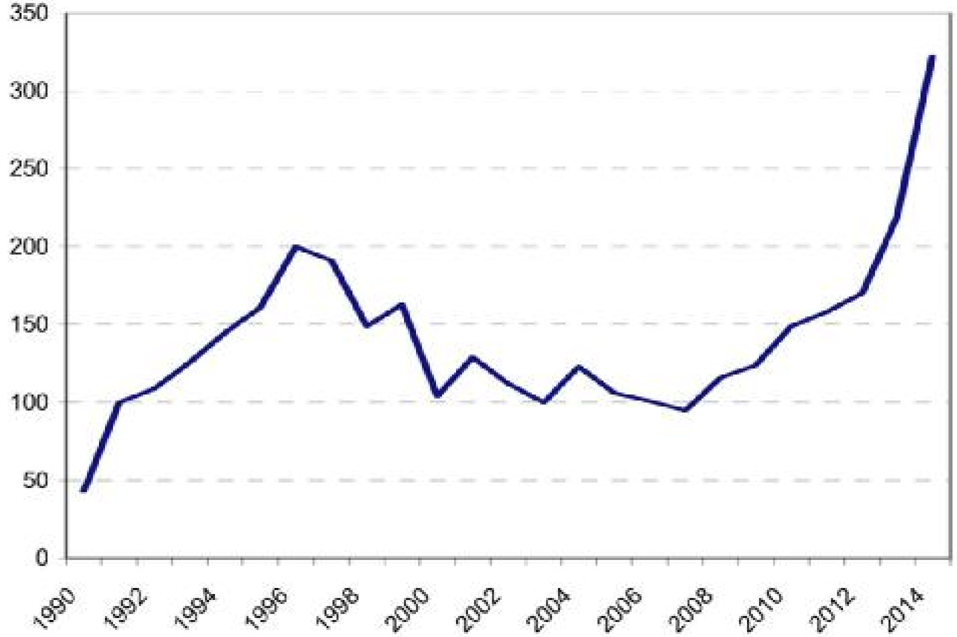
S.M. Felton et al. „Robot Self-Assembly by Folding: A Printed Inchworm Robot“, ICRA Conference 2013

M. Bächer et al. „Fabricating Articulated Characters from Skinned Meshes“, ACM Trans Graph, 31 (4), 2012

R&D – Relevant Topics

- Current drawbacks:
  - Tolerance and surface finish
  - Limited materials palette & heterogeinity
  - Limited knowledge on (mechanical) properties
  - No standard test methods and protcols → standardization needed
  - Modelling and optimization algorithms are missing

→Worldwide increase in funding and research activity



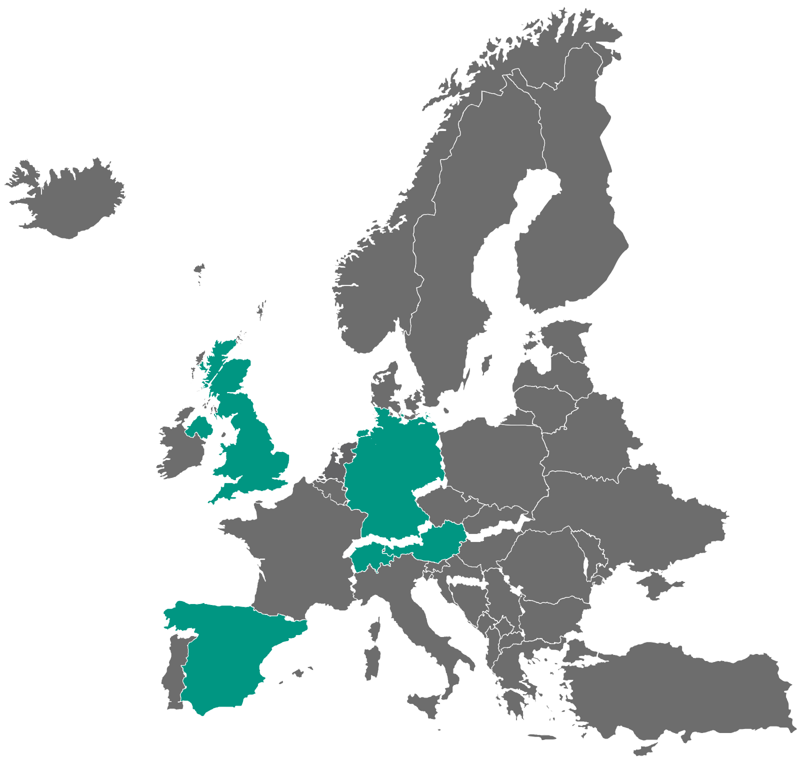
Attendance at the Solid Freeform Fabrication Symposium
(courtesy of University of Texas, Austin)

R&D – Project Examples

SMARTLAM - A Modular, Flexible, Scalable and Reconfigurable System for Manufacturing of Microsystems

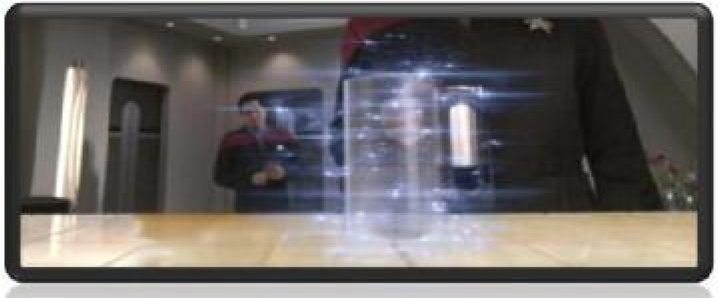
FP7 Cooperation Program Grant No. 314580

- European project in FP7 program
- 8 partners from 5 countries

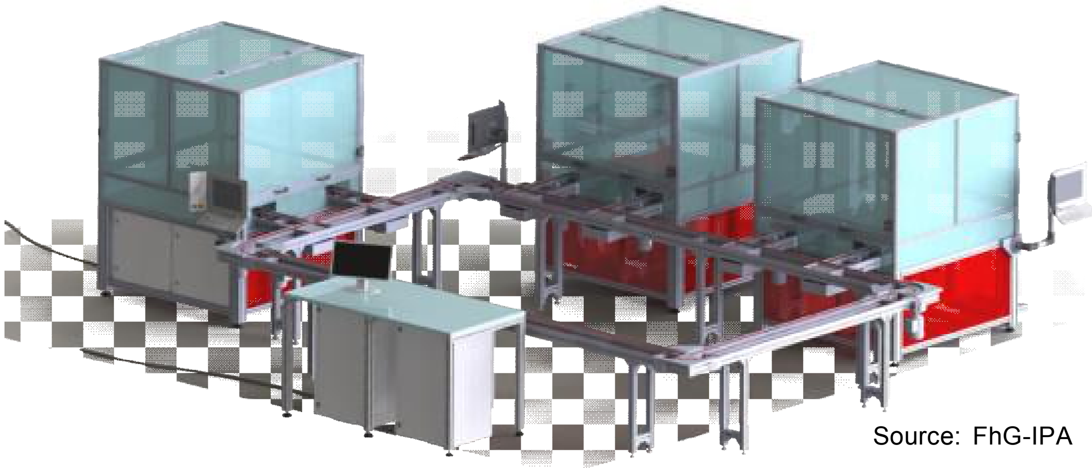


R&D – Project Examples

- Scalable, easily adaptable system
  - Flexible layout of module
  - Additional process modules
- Autonomous, connected process modules
  - Joint holding/workpiece carrier
  - Transfer system
- Module dimensions are variable
- Decentralised production

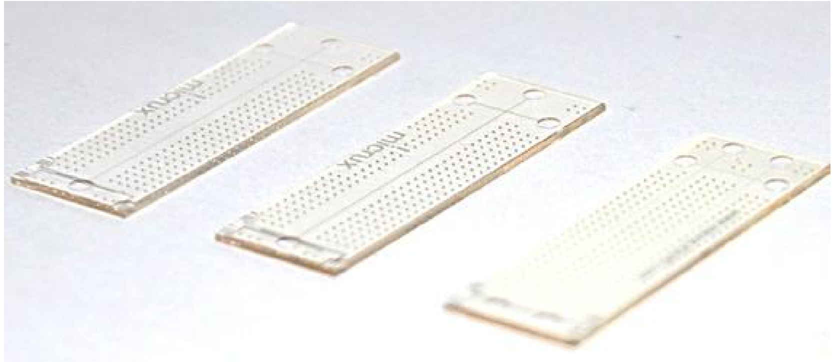


... produce complete micro systems in a „Star-trek"-like manner...



Source: FhG-IPA

R&D – Project Examples



6 Modules + Control

- Laser Structuring
- Aerosoljet Printing
- Assembly
- Lamination
- Laser Welding
- Inspection

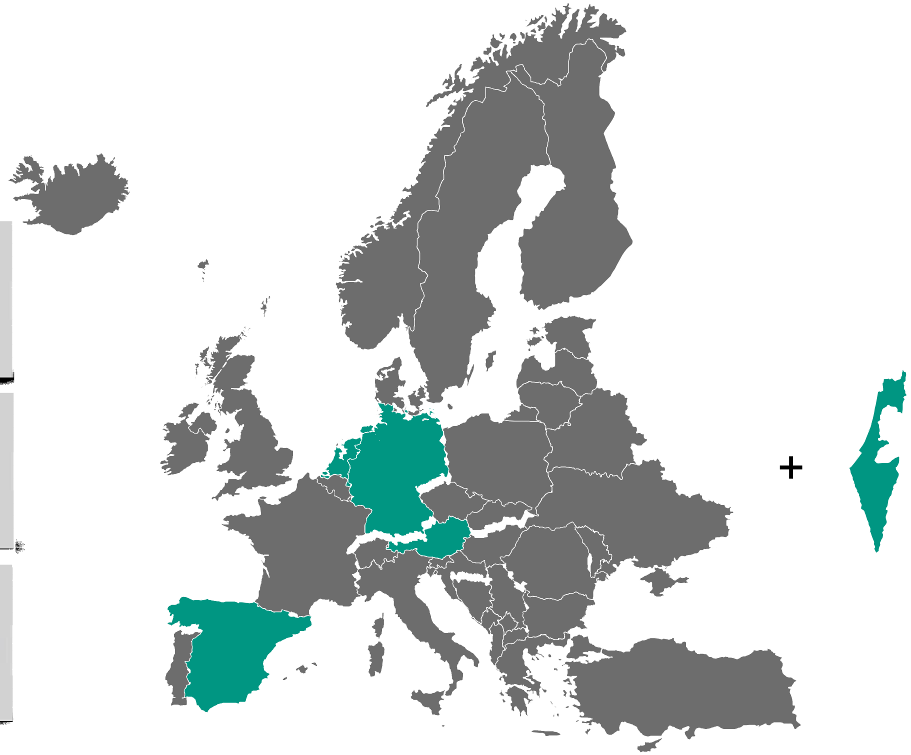
+ Central Control
+ Underlying Database

SMARTLAM

R&D – Project Examples

DIMAP – Digital Materials for 3D Printing

- European project in H2020 program
- 12 partners from 5 countries
- GA-Agreement 685937



R&D – Project Examples

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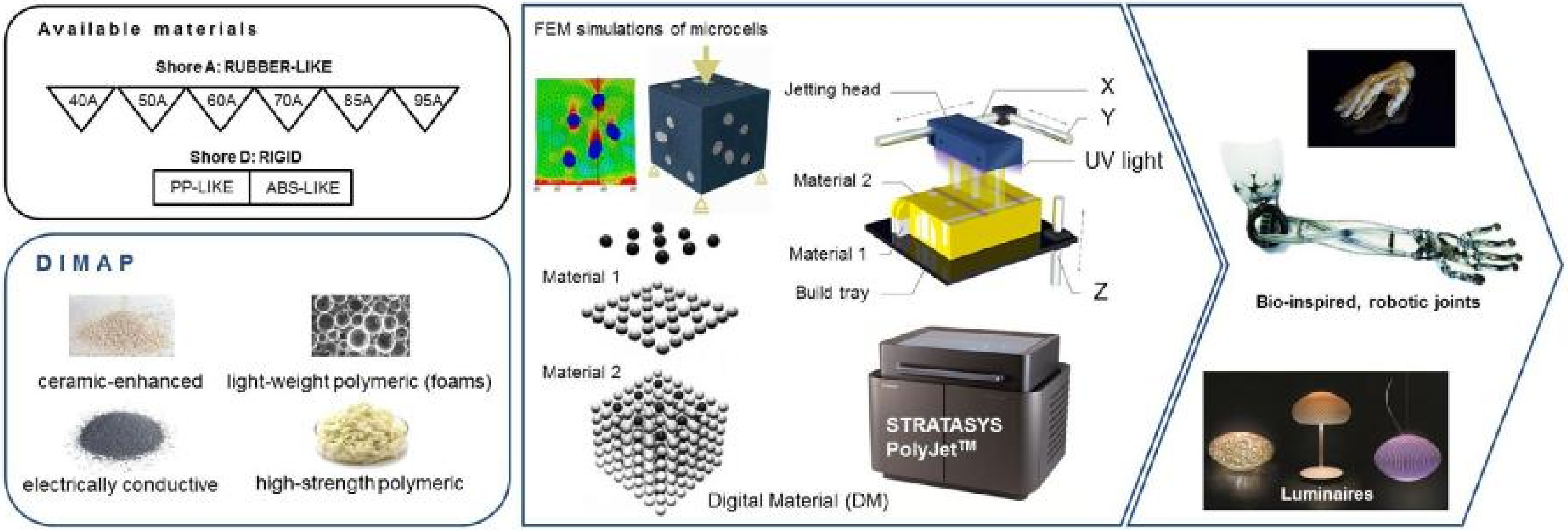

- Multijet printing of novel materials
  - Material development
  - Process development
  - Nano-Safety Management

DiMAP
DIGITAL MATERIALS FOR 3D PRINTING

R&D – Project Examples

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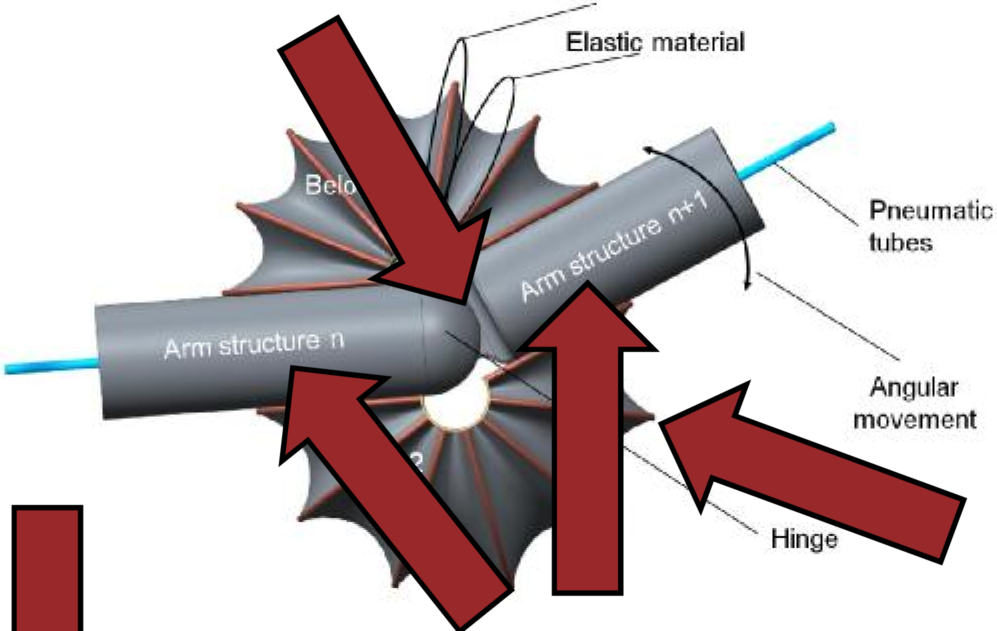
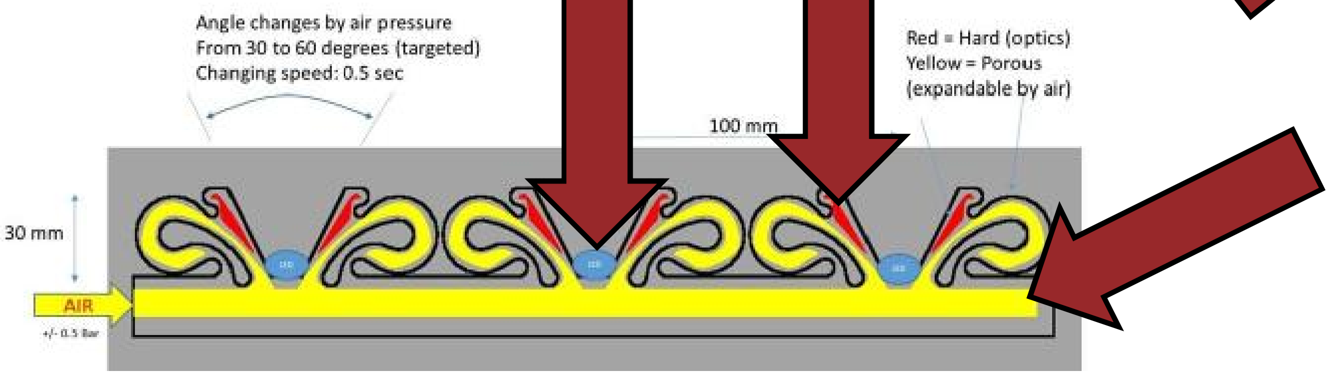
Material development

- Ceramic enhanced material
- Lightweight polymer material
- High strength polymer material
- Electrically conductive material





DiMAP
DIGITAL MATERIALS FOR 3D PRINTING

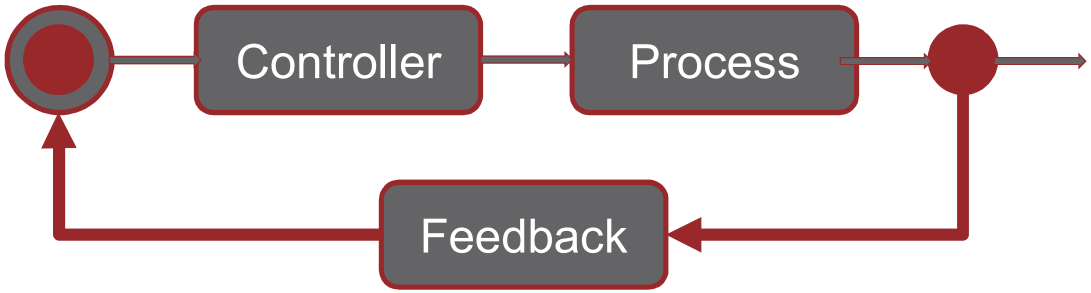
R&D – Project Examples

Material development

- Ceramic enhanced material
- Lightweight polymer material
- High strength polymer material
- Electrically conductive material

Image Courtesy of Xaar PLC

Process development

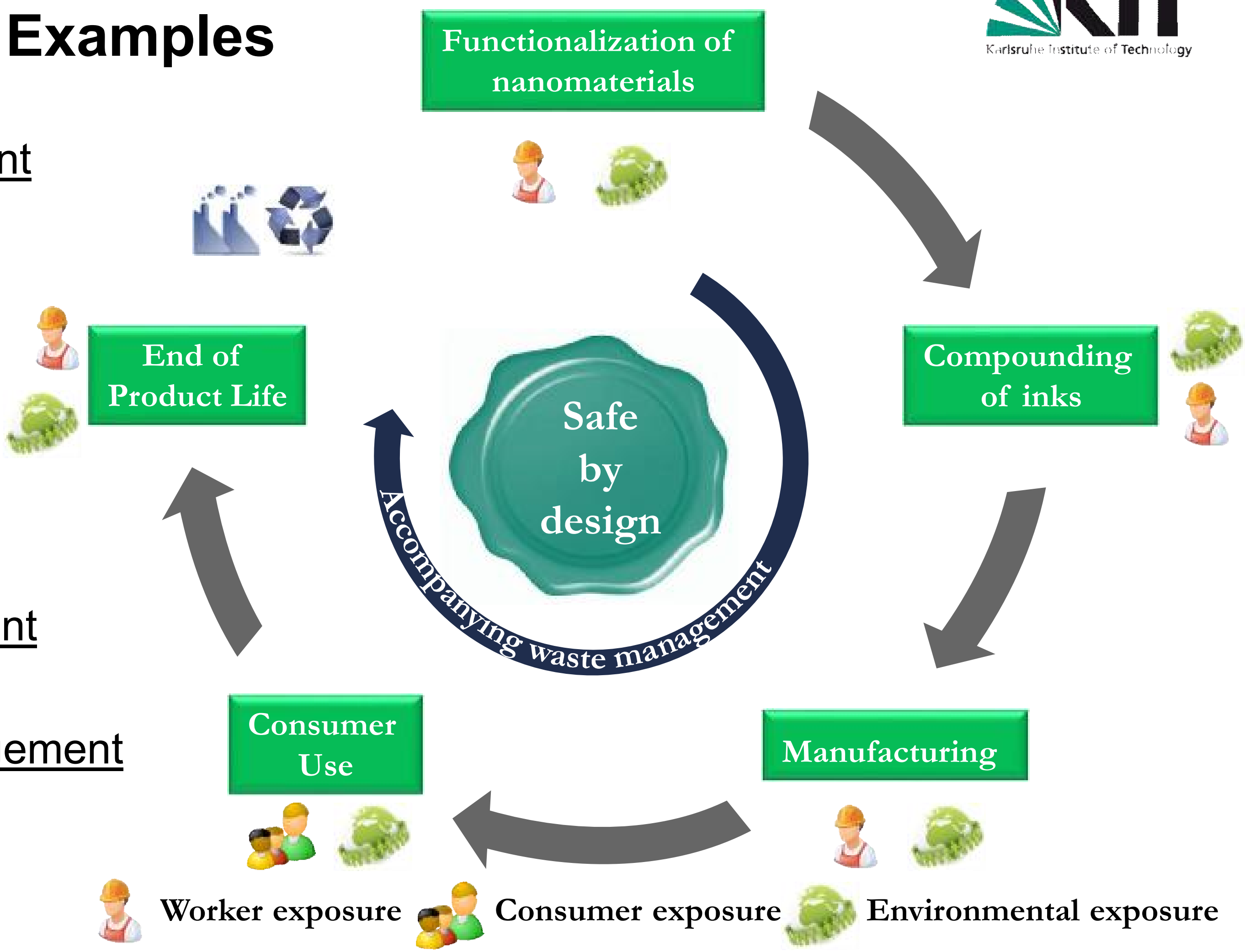


DIGITAL MATERIALS FOR 3D PRINTING

Karlsruhe Institute of Technology

R&D – Project Examples

Material development



Process development

Nano-Safety Management

DIGITAL MATERIALS FOR 3D PRINTING

<u>R</u>esource <u>E</u>fficient <u>Pro</u>duction of <u>Mag</u>nets

REProMag
Resource Efficient Production of Magnets

The objective of the REProMag project is to develop and validate an **innovative resource efficient manufacturing route for Rare-Earth magnets** that allows an economically efficient production of near net-shape magnetic parts with complex structures and geometries **using recycled Nd-Fe-B magnets in a closed material loop** and while **being 100% waste-free along the whole manufacturing chain**.

14 partners from 5 European countries

duration: 2015/01/01 – 2017/12/31

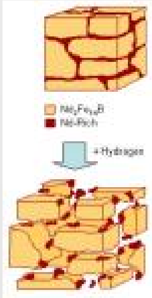
funded budget: 5.7 Mio €uro

http://www.repromag-project.eu

Resource Efficient Production of Magnets

- ✓ better mountability
- ✓ better performance
- ✓ smaller dimensions for the same power output
- ✓ higher service life
- ✓ more poles possible
- ✓ higher resolution for servomotors
- ✓ low "torque ripple"

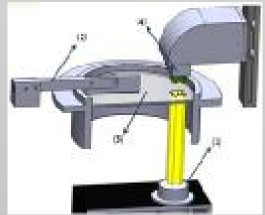
HD (hydrogen decrepitation) **process**

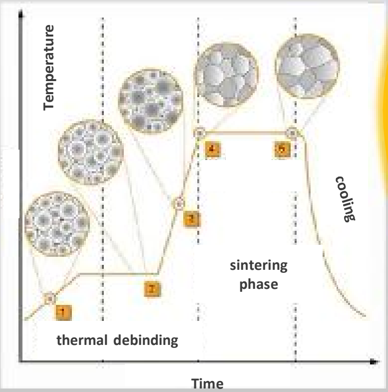


(1) MIM
(metal injection moulding)

(2) FFF
(fused filament fabrication)

(3) LAM
(lithography-based additive manufacturing)



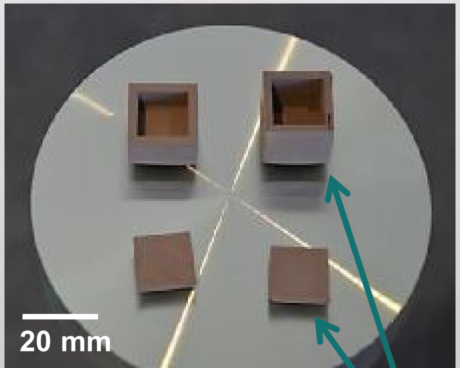


Resource Efficient Production of Magnets

REProMag
Resource Efficient Production of Magnets

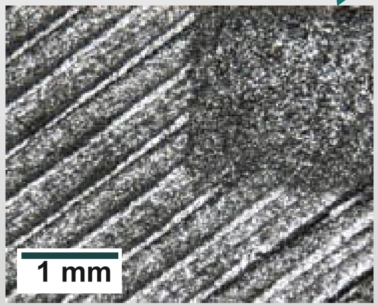
(2) FFF (fused filament fabrication)

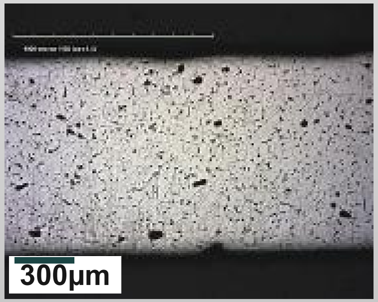
- preliminary trials with iron- and titanium-based materials
- feedstock development and filament production
- solid content amounts to ≥ 55 vol%
- design and construction of an alignment system for parallel, radial, diametrical and multiaxial alignment
- process optimization to improve the surface quality



distortion due to thermal stresses

polished in the green part state





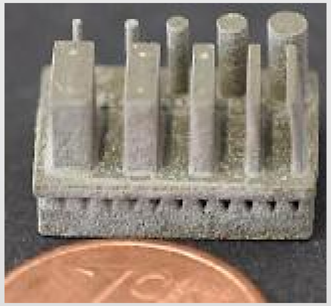
Resource Efficient Production of Magnets

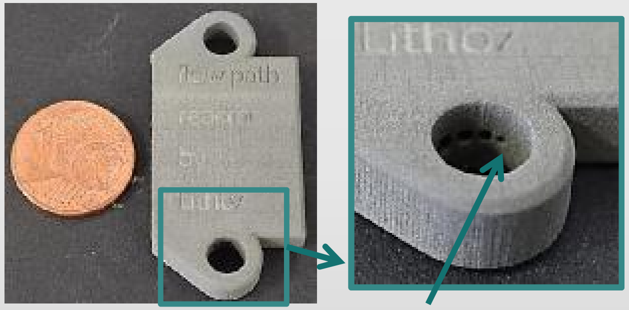
REProMag
Resource Efficient Production of Magnets

(3) LAM (lithography-based additive manufacturing)

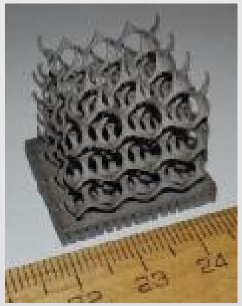
- preliminary trials with stainless steel material
- screening for optimal powder size and size distribution
  → best performing powder +10µm -31µm (gas atomized)
- development of debinding procedure

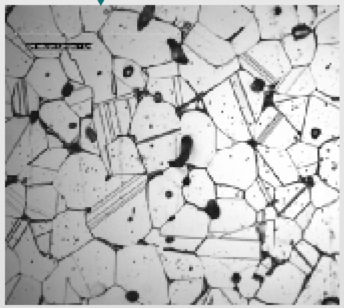
micro structure and residual porosity similar to MIM



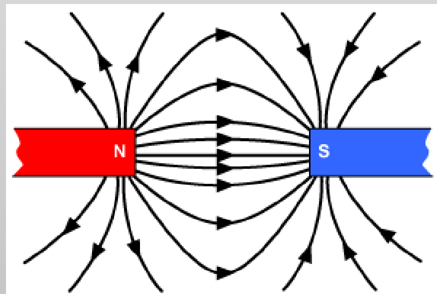


high resolution

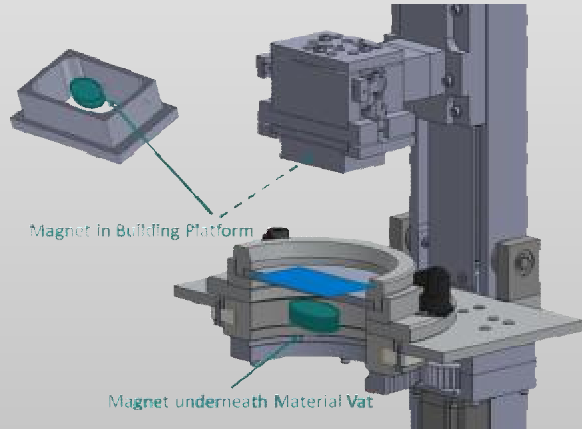




- design and construction of an alignment system



calculated alignment field
0.25 – 0.4 T



R&D – Project Examples

FoFAM – Digital Materials for 3D Printing

- European AM stakeholders and EU Member States act in a **fragmented manner**, with **gaps and inefficiencies in linking the wide range of applications, disciplines, manufacturing sectors and countries concerned.** **Europe needs a strategic approach and a common vision for AM.**
- FoFAM project takes up the **challenge of reviewing the AM ecosystem and organize it around several value chains on relevant industrial sectors.** The final aim is to put the 1st steps for a plan of action in the field by designing an **effective implementation map and facilitating interaction of players. For a complete success strategy not only technology stakeholders but also policy makers** at European level but more importantly at local level should also be involved. In this sense, the project includes the involvement of **European regions.**

Sectors tackled:

- **Medical and dental**
- **Aerospace**
- **Automotive**
- **Consumer goods/electronics**
- **Industrial equipment**

R&D – Project Examples

- 18 FoF AM related projects (completed and ongoing, projects at different levels)
- 4 more involved from call FoF-1-2016
- Results are clustered around selected sectors and value chains segments → mapping of capabilities, possible synergies and existing gaps for AM market implementation.

Nº	Acronym	Coordinator	Nº	Acronym	Coordinator
1	PHOCAM	TU Wien	10	CASSAMOBILE	Fraunhofer
2	HYPROLINE	TNO	11	ADDFACTOR	Synesis
3	AMAZE	MTC	12	MANSYS	TWI
4	SMARTLAM	KIT	13	STELLAR	Net Composites
5	3D-HiPMAS	HSG-IMAT	14	NEXTFACTORY	Fraunhofer-IPA
6	HiPR	D'Appolonia	15	BOREALIS	Primapower
7	HI-MICRO	KU Leuven	16	ToMAX	TU Wien
8	AMCOR	TWI	17	REPROMAG	OBE
9	OPTICIAN2020	Eurecat	18	Symbionica	Sintea Pustek SRL

D2.1 "Report on AM Projects": www.fofamproject.eu/images/D2_1_Report_AM_projects.pdf

R&D – Project Examples

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AM ROADMAP

Market sectors | Value chains | Specific a…

- Identification of challenges around sectors and Value chains
- Specific Technical & Non-Technical actions (education, standardisation..) for AM implementation (common vision, alignment, market focus)

STATUS: 1st draft Summer 2016
FINAL: Nov. 2016

AM FoFAM network

Creation of a stakeholder's network connected and involved in project to improve interactions, communication and exploitation around sectorial value chains (VC) for market deployment.

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GA nº 636882

AM DATABASE

…s | Regions | Players

- Competences; expertise; results on each of the sectors/VCs tackled
- Networking/ Alliances: facilitating the stakeholder's relationships.

OPEN TO ALL TO BE THERE AND TO USE IT

AVAILABLE AT AM Platform Website: www.rm-platform.com

Future Trends & Challenges

- Materials:
  - Broadening of available materials; solid loaded inks & polymers
  - Digital materials & integration of discrete parts
  - Biomaterials (tissue scaffolds, organs)
- Design:
  - Specific tool representing AM functions & interactions; simp
    designing complex shapes
- High throughput & build size
  - Multinozzle array print hea
  - Integration of additional pr g)
  - Large scale parts
- Modeling, Sensing and Proc
  - Transport phenomena, ter d
  - Access to build chamber fo
  - Integration of control algor ts of building process

Source: Stratasys, Ltd.

Image Courtesy of Shapeways

Conclusion

- Current Status:
  - Steady growth of additive manufacturing industry
  - Awareness of capabilities of AM in different sectors
  - Printers for a variety of applications available
    - Cheap printers for private households (less than 300 $)
    - High accuracy printers for professional applications
    - Larger building chambers are being developed

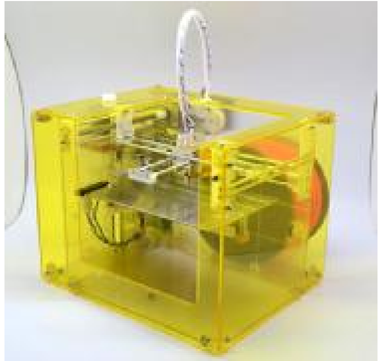

Image Courtesy of Makibox

- Still to come:
  - Wider material range
  - More process knowledge & control
  - Standardization for materials & data
  - Educational aspects

Image Courtesy of Stratasys Ltd.

Image Courtesy of Institute of Advanced Architecture of Catalonia- IAAC

Acknowledgements

Karlsruhe Institute of Technology

The author thanks all partners involved in the results presented and the European Committee for funding the projects shown.

SMARTLAM — FP7 FOF.NMP.2012-5; GA-Number 31458

DiMAP — DIGITAL MATERIALS FOR 3D PRINTING — H2020-NMP-PILOTS-2015; GA-Number 685937

REProMag — Resource Efficient Production of Magnets — H2020 FoF-02-2014; GA-Number 636881

H2020 FoF-07-2014; GA-Number 636882

Sources

Videos:

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Slide 7: Solid Concepts: https://www.youtube.com/watch?v=WHO6G67GJbM
Slide 8: Solid Concepts: https://www.youtube.com/watch?v=NM55ct5Kwil
Slide 9: Solid Concepts: https://www.youtube.com/watch?v=Som3CddHfZE