Additive Manufacturing of Hard Biomaterials

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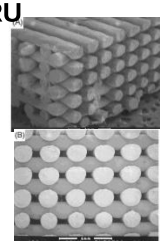
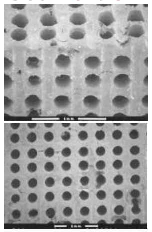
From 1995 to 2016 – AM of Hard Materials

Materials and structures

1995 – FDC - Direct ceramic processing @ RU

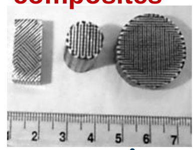


1998 – Indirect FDM – Bone tissue engineering scaffolds

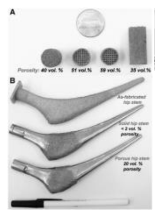


2000 – CT Scan to Ceramic Bone Graft

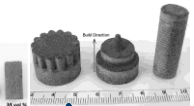
2001 – AM of metal-ceramic composites



2005 – AM of porous metal implants and coatings

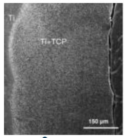


Direct ceramics via LENS

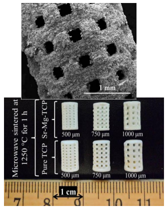


2007 – Patient matched implants

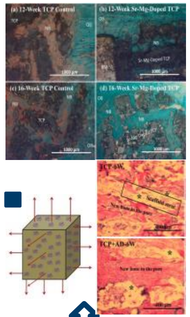
Biocomp-atible coatings



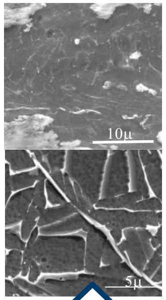
2008 – Controlled resorption rate ceramic scaffolds



2009 – Drug delivery and dopants induced angiogenesis, osteogenesis in bone tissue engineering



2012 – Composite coatings for articulating surfaces



AM technology

- 1995 – Fused Deposition, Stratasys
- 2005 – LENS, Optomec
- 2008 – 3D Printing, ExOne

Financial Support

- NIH R01 grants (NIBIB and NIAMS)
- NSF (CMMI), ONR
- LSDF (WA State)
- W. M. Keck Foundation
- M. J. Murdoch Charitable Trust
- Industry sponsored research

Publications

- Book: Additive Manufacturing, CRC Press (2015).
- Over 150 journal papers

Relevant Patents

- 14 issued US patents
- 7 US patents pending

Research collaborators

- Over 60 graduate students
- Another 40+ collaborators

Materials systems

Metals: Ti and alloys, CoCrMo, Ta, Bulk amorphous alloys (BAA), Al alloys, Inconel, NiTi, Different stainless steels, bimetallic compositions.

Ceramics: Calcium phosphates, Al_2O_3, zirconia, TiO_2, SiO_2, PZT, vanadium carbide, niobium carbide.

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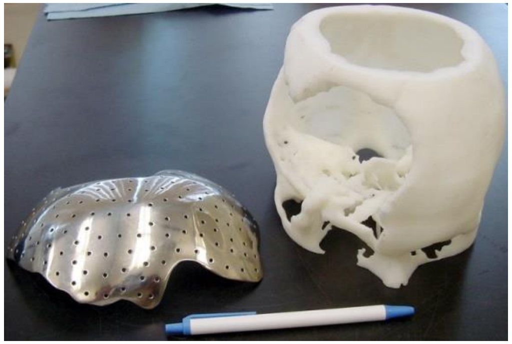
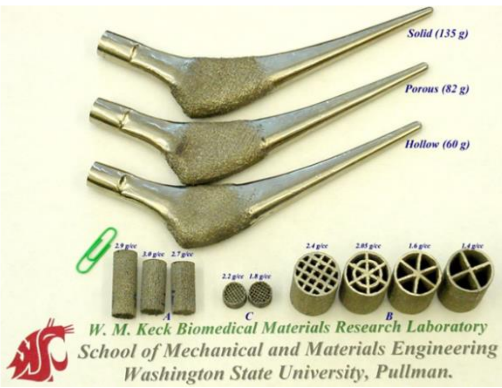
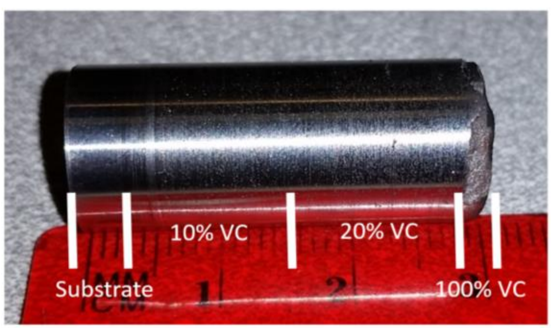
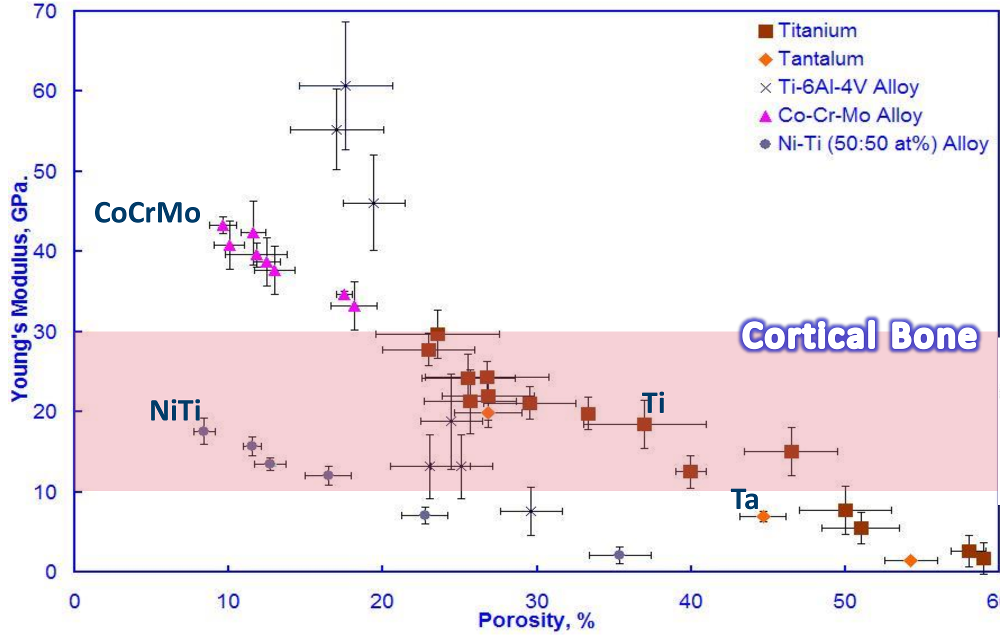
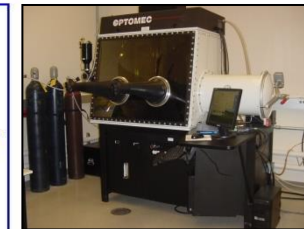
Additive Manufacturing of Metals

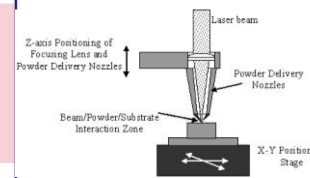




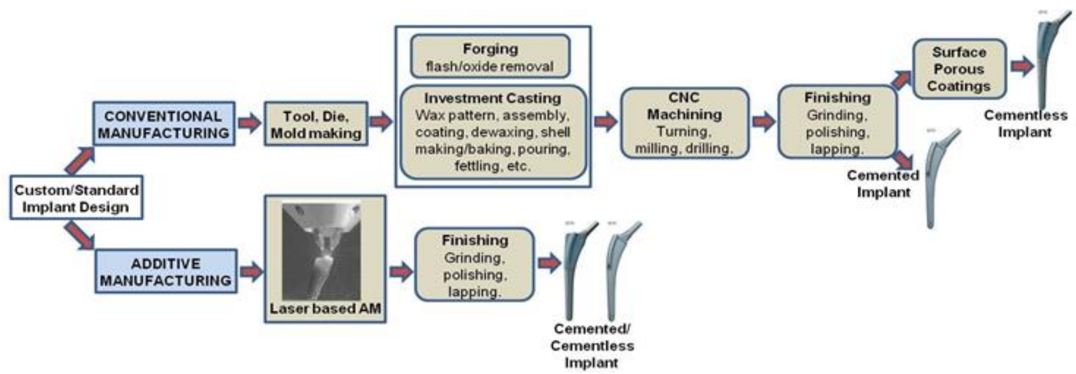








- Porosity between 10 and 40% resulted in modulus close to human cortical bone.[1]



For AM of metals, our work is focused on Laser Engineered Net Shaping (LENS) of ceramics, metals and metal-ceramic composites.

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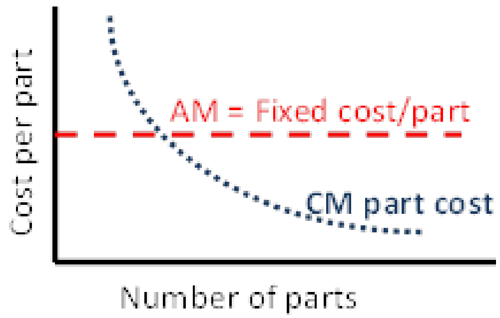
[1]Bandyopadhyay, A, Bose, S (2016) "Bone replacement materials," US 11/675,006 (Claims approved, USPTO).

AM of Metals: Advantages and Challenges

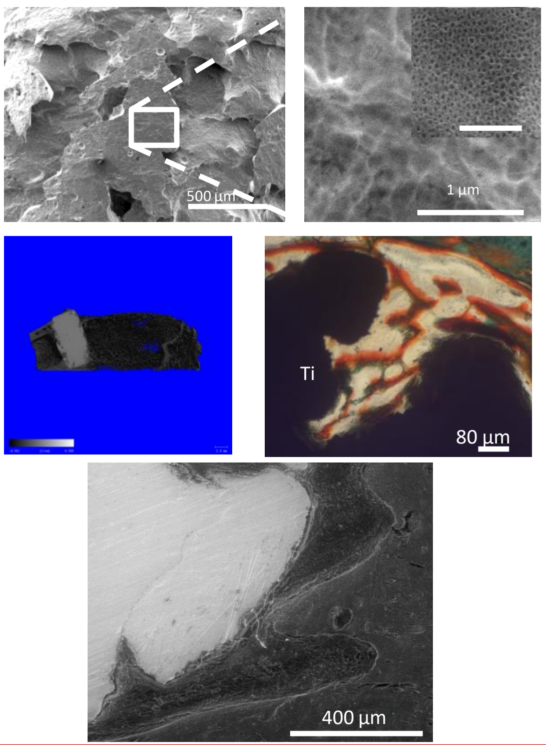
Advantages (Direct Manufacturing from a CAD file)

1. Manufacturing of patient matched implants, one of kind implants
2. Biomedical devices with structural gradients such as porosity
3. Manufacturing of parts with compositional variations
4. On-demand manufacturing
5. Site specific operation on finished products such as coatings



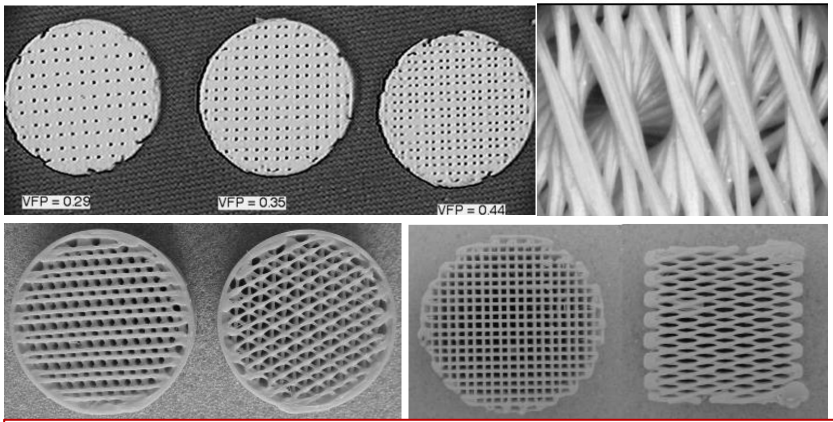
Challenges

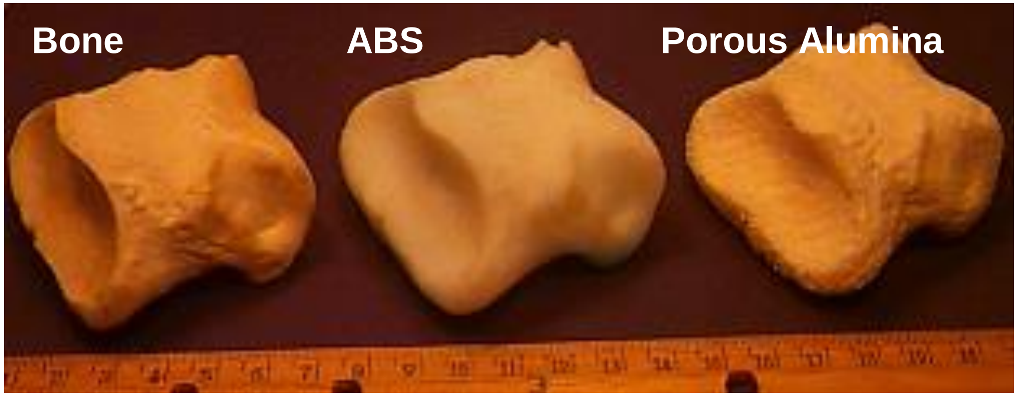
1. Reliability and reproducibility – from machine to machine, and within one machine due to variation in processing parameters.
2. Post processing may be required for many processes.
3. Part quality – still an active research topic for some.
4. Processing environment and resultant variation in material properties.
5. Variations in starting powders particle size, shape and distribution.
6. Cost of machines.



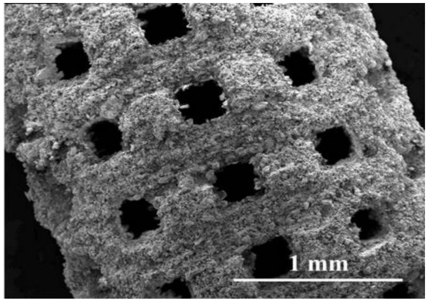
LENS processed porous metal implants show excellent bone tissue integration within 4 weeks after implantation in rat distal femur model. Pore size varied between 200 and 500 mm.

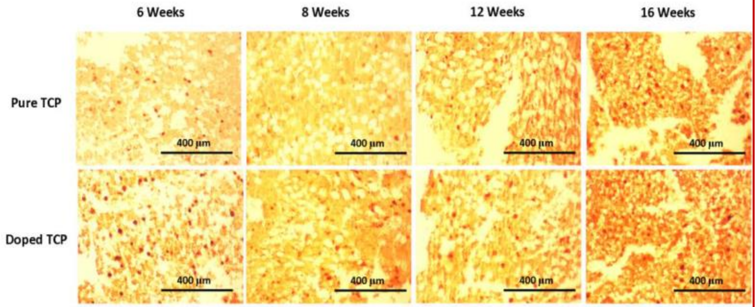
Additive Manufacturing of Ceramics



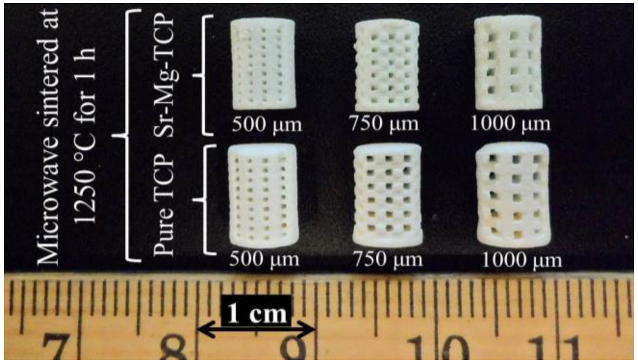


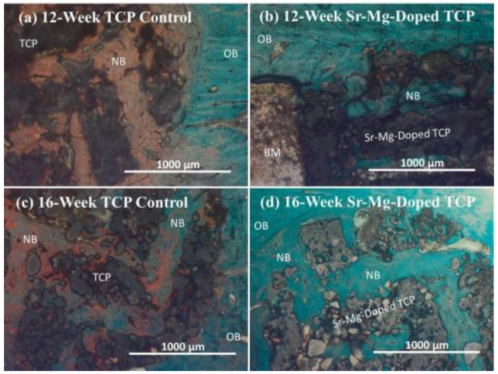
Porous ceramics (alumina, TCP, HA) and ceramic-polymer composites can be directly or indirectly processed via AM with varying pore size, pore shape and pore-pore inter-connectivity. Porous ceramic scaffolds can also be fabricated using a CT scan image of a bone (1998-2002).





- Calcium phosphate ceramics scaffolds for bone tissue engineering with controlled resorption kinetics due to variation in dopant chemistry and concentration. [1]
- Dopant chemistry can influence both angiogenesis and osteo-genesis *in vivo*, these scaffolds also used in drug-delivery.



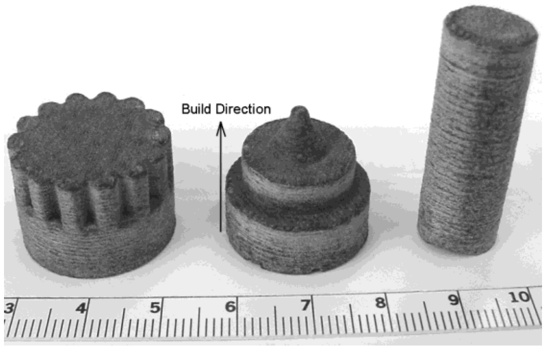


Bose, S, Bandyopadhyay, A (2015), "Resorbable ceramics with controlled strength loss rates," US Patent # 9,028,871.

AM of Ceramics : Advantages and Challenges

Advantages (Direct Manufacturing from a CAD file)

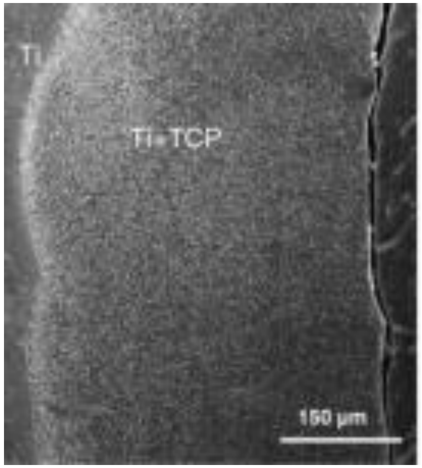
1. Manufacturing of patient matched scaffolds
2. Tailored porosity scaffolds for bone tissue engineering
3. Manufacturing of site specific ceramic coatings on implants
4. Manufacturing ceramic-polymer or ceramic-metal composites
5. On-demand manufacturing



Melt cast direct ceramic structures via Laser Engineered Net Shaping

Challenges

1. Reliability and reproducibility – Most ceramic powders are very sensitive to humidity / moisture. Reliable processing of ceramic parts throughout the year needs better understanding of starting materials.
2. Post processing – Most AM of ceramics require significant post processing. Optimization of post processing steps can be expensive and time consuming.
3. Process optimization – Most ceramic AM approaches require significant process optimization.



Ti-CaP AM processed coating to enhance biocompatibility of Ti.[1]

[1]Bose, S, Bandyopadhyay, A, (2016), US 13/955,757 (Claims approved, USPTO).