Additive Manufacturing in Power Electronics, Machines and Drives

Dr. Nick Simpson

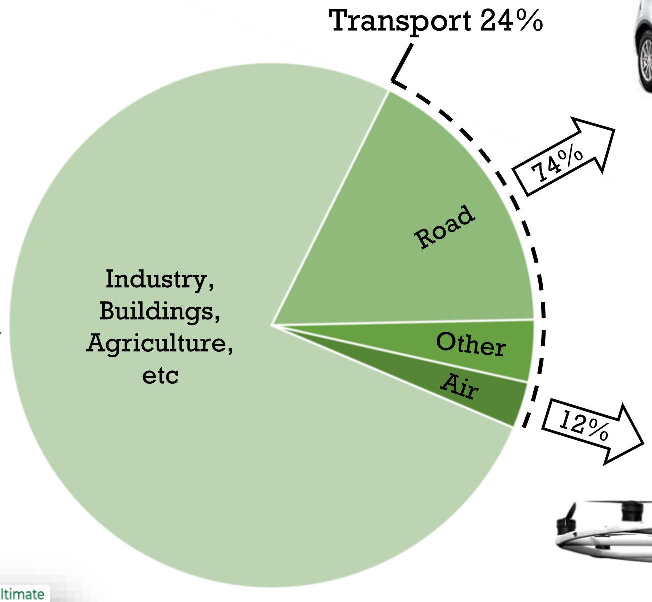
CPE Annual Conference 2022

University of BRISTOL

The Context

The Paris Agreement

UK Carbon Net Zero 2050



Global CO_2 Emissions

Road Mobility

Jaguar E-Pace

Powertrain Requirements:
- *High Efficiency*
- *Light Weight*

Urban Air Mobility

Volocopter Air Taxi

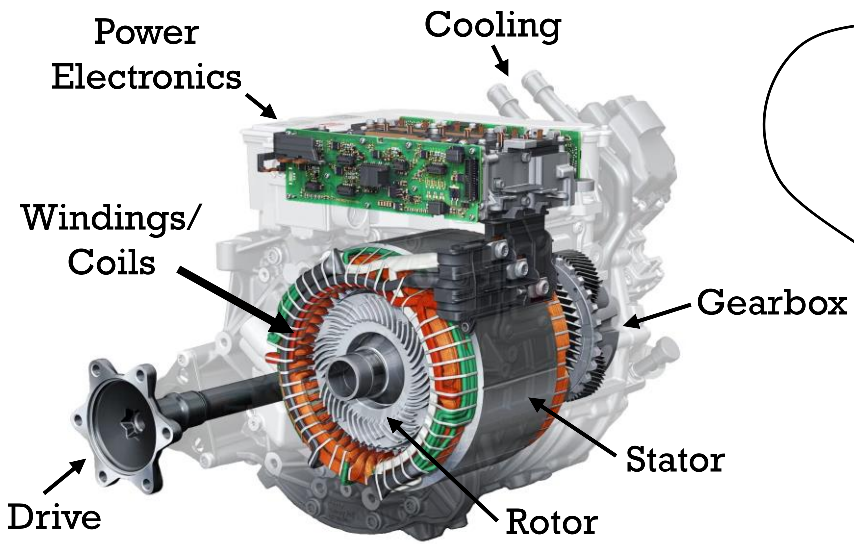
ATI Targets, March 2022		2026	2030	Ultimate Target 2050
Electric motor	Power Density (kW/kg)	13	23	25
Power electronics (Inverter)	Power Density (kW/kg)	22	40	60
Power electronics (DC-DC)	Power Density (kW/kg)	15	40	60

AEROSPACE TECHNOLOGY INSTITUTE

ADVANCED PROPULSION CENTRE UK

- Power Density 9-25 kW/kg by 2035, > 96% Efficiency
- **5 fold increase over state-of-the-art**

The Problem



Audi e-tron concept

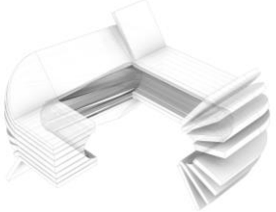
Step change in power density
→ Improve efficiency
→ Raise temperature rating
→ Enhance heat extraction

A Solution

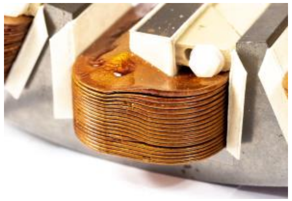
→ Additive Manufacturing (3D Printing)

Copper Winding

Aluminium Winding



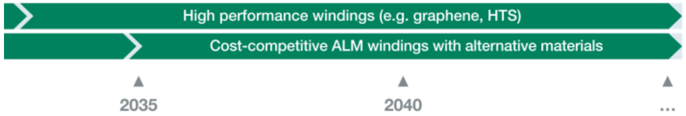
End-winding cooling



Post-manufacture Insulation

~20% reduction in loss → reduced mass

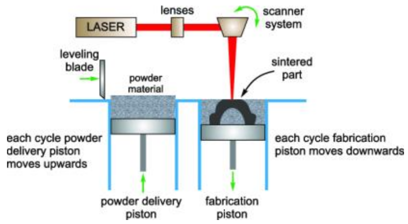
ADVANCED PROPULSION CENTRE UK



- We need new Multi-physics Design Tools, Design for AM, Material Property Studies, Post-Processes (Heat, Surface), Insulation Coatings, Cross-Discipline Academic Underpinning

The Electrical Machine Works

Metal AM Process

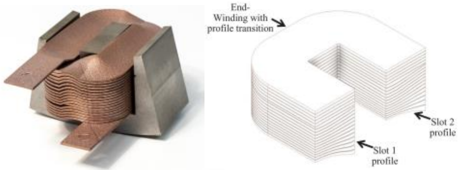


Conventional windings

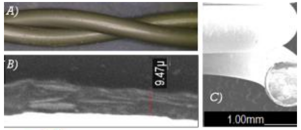
Form and performance limited by available conductor shapes and automated winding capability

Metal Additive Manufacturing Enables…

Geometric freedom



High performance insulation coatings



Integral Cooling

Integral terminals and sensors

Functionally Graded Properties

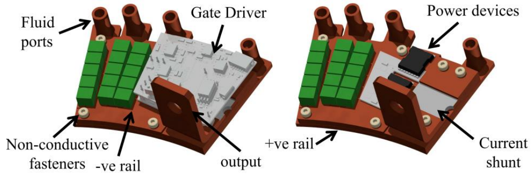
Prototyping

Conventional Manufacturing Routes

Customisation for Application

Performance tailoring

Extreme integration of power electronics



Focus on Laser Powder Bed Fusion Metal AM – discussion applicable to other materials and processes:

- Engineering Plastics
- Ceramics
- Soft Magnetics

University of Bristol · Teesside University · 3T additive manufacturing · Renishaw apply innovation™ · Motor Design Limited · Equipmake · Land Rover · Jaguar · Safran

The Electrical Machine Works Team

Piya Munagala, **PDRA**
- **Material Science**
- **Metallurgy**

George Yiannakou, **PDRA**
- **Additive Manufacturing**
- **Electromagnetic and Process modelling**

Suzie Collins, **PhD Student**
- **Electrical Machine Design**
- **Composite Materials**

Jamie Williams, **PhD Student (MDL)**
- **Electrical Machine Design**
- **Large-scale Cloud Simulation**
- **Computational Frameworks**

Harry Felton, **PDRA**
- **Additive Manufacturing**
- **Computational Design**

Dominic North, **PhD Student**
- **Electrical Machine Design**
- **Multi-physics Modelling**

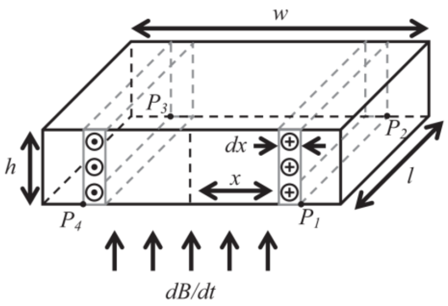
Francis Tocher, **PhD Student (GKN)**
- **CFD and Heat Transfer**
- **Mechanical Design**

Angus Cameron, **PhD Student**
- **Electrical Machine Design**
- **Integrated Power Electronics**
- **Automation and Robotics**

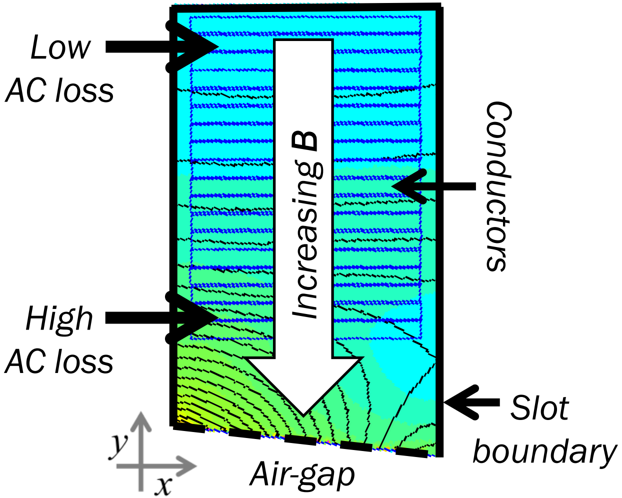
- Lead Academic, collaborating academics, 3 x Post Doctoral Researchers, 5 x PhD Students
- Expertise spanning electrical machine design and manufacture, power electronics, multi-physics analysis, additive manufacturing, material science, experimental testing, automation, computational design
- Provide support to other EEMG projects, new academics and activities.

Loss Minimisation – Shaped Profile Windings

Consider a conductor subject to an external time-varying flux:



$$P_{cond} = \frac{w^3}{6} h \sigma \left(\frac{dB}{dt}\right)^2$$

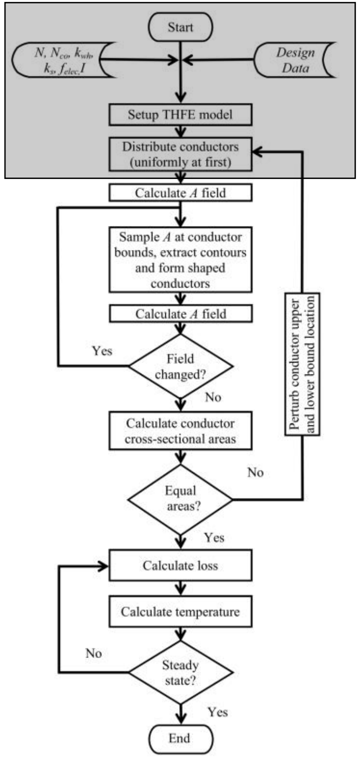


Magnetic flux within an open slot

- *Thin conductors (w << h) shaped to remain perpendicular to the external magnetic field will exhibit minimal loss*
  - Hence desirable edge-wound conductors
  - Effectively laminating the winding in the direction of flux
- Rotor effects alter the flux pattern – no longer perpendicular to slot wall
  - Particularly evident in open-slot stators

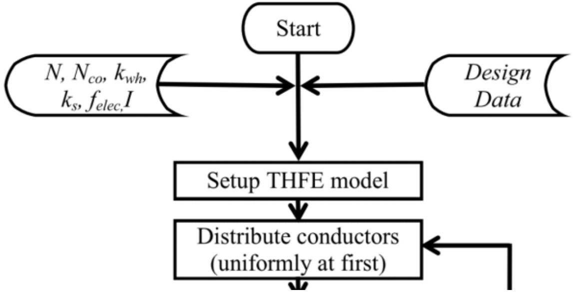
How do we shape the conductors? → Field Driven Design

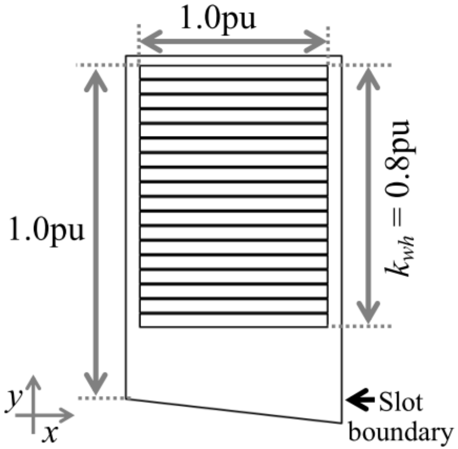
Loss Minimisation – Shaped Profile Windings



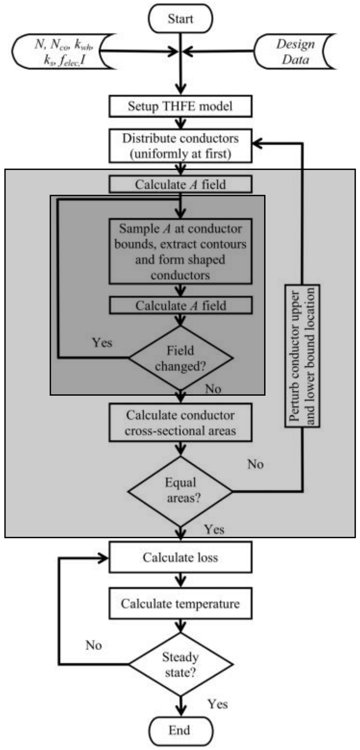
Conductor shaping algorithm

- A 2D time-harmonic finite element (THFE) model accounting for the rotor flux is used to predict the loss in arbitrary shaped conductors and provide flux vector information





Loss Minimisation – Shaped Profile Windings



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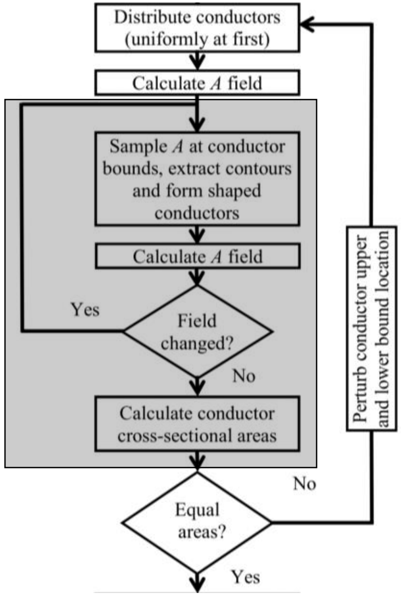

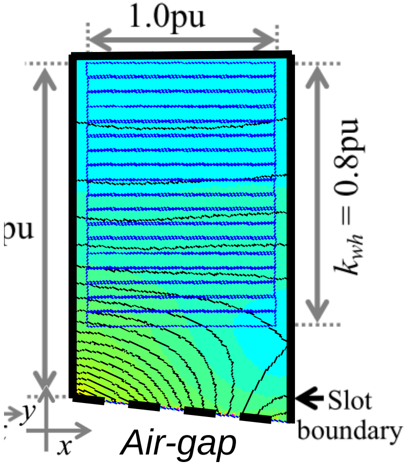

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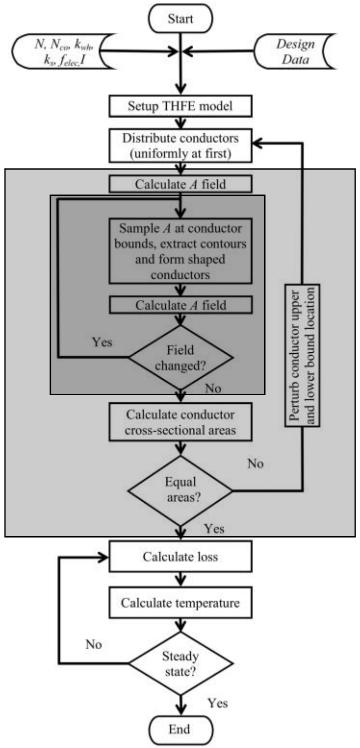

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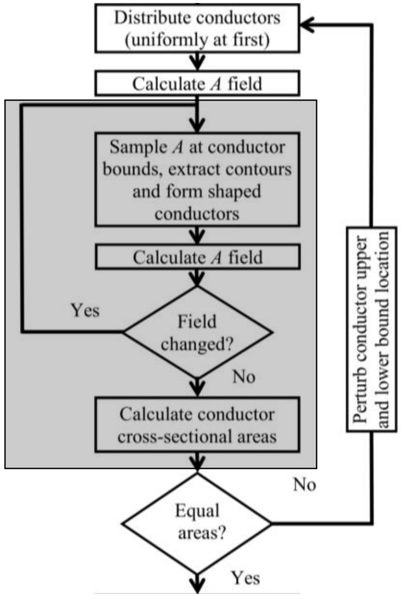

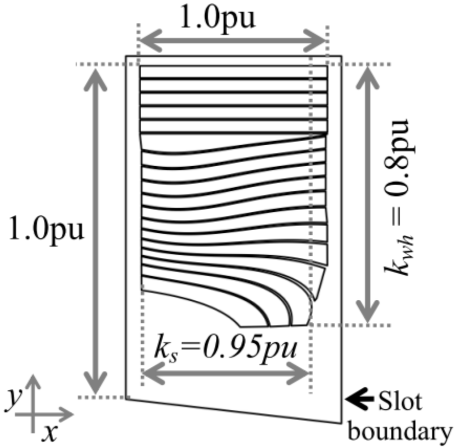

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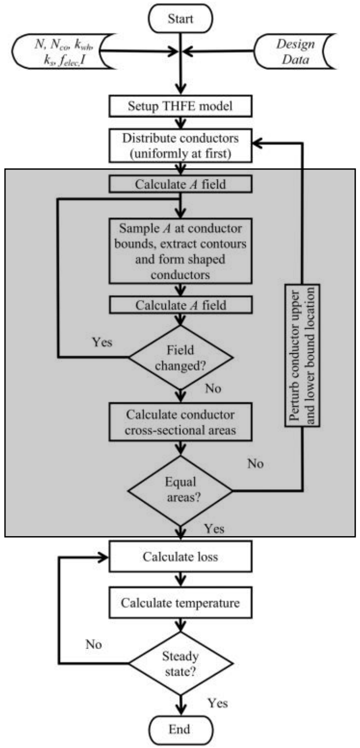

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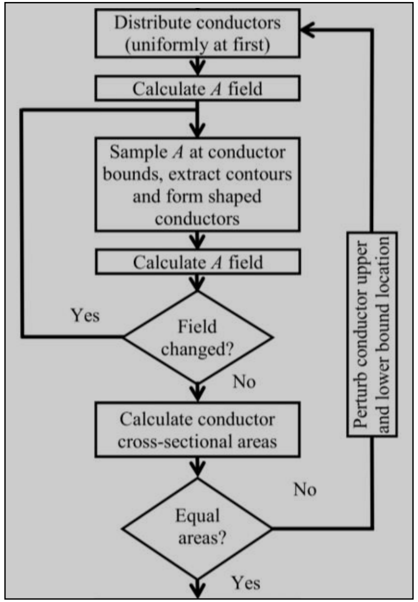
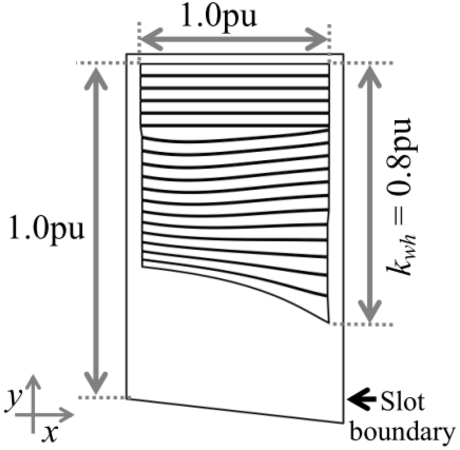
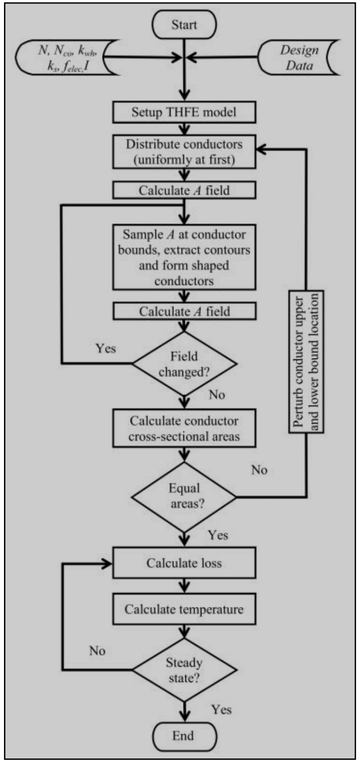


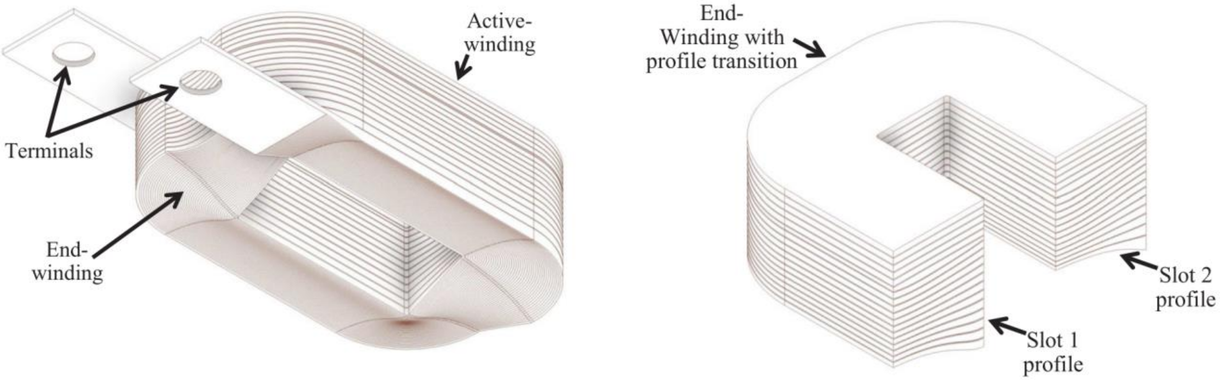


Loss Minimisation – Shaped Profile Windings



Conductor shaping algorithm

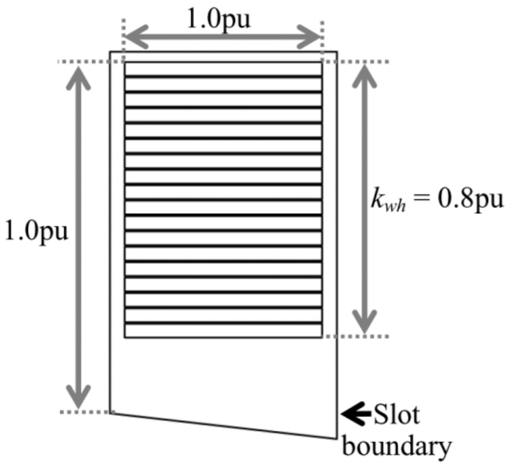
- Convert conductor cross-sections into a helical winding structure



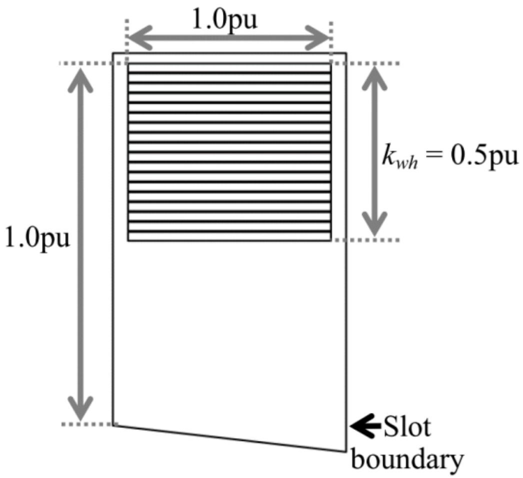
- Shaped profile winding with asymmetric cross-section
  - Operating quadrant dependent loss characteristics
  - Well suited to generators, propulsors and electric vehicles

Loss Minimisation – Shaped Profile Windings

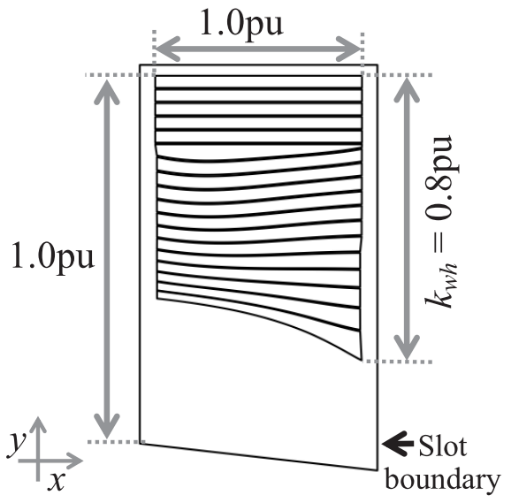
- Three winding variants compared – 80% high fill, 50% low fill, and shaped profile



80% Winding Height



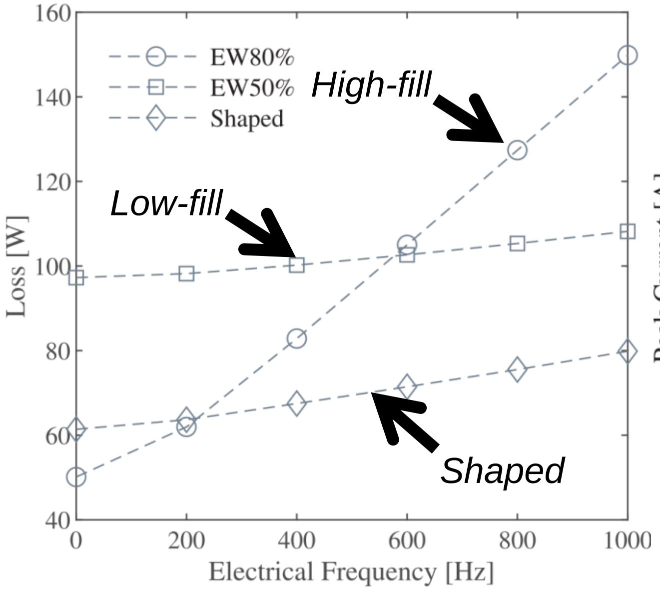
50% Winding Height



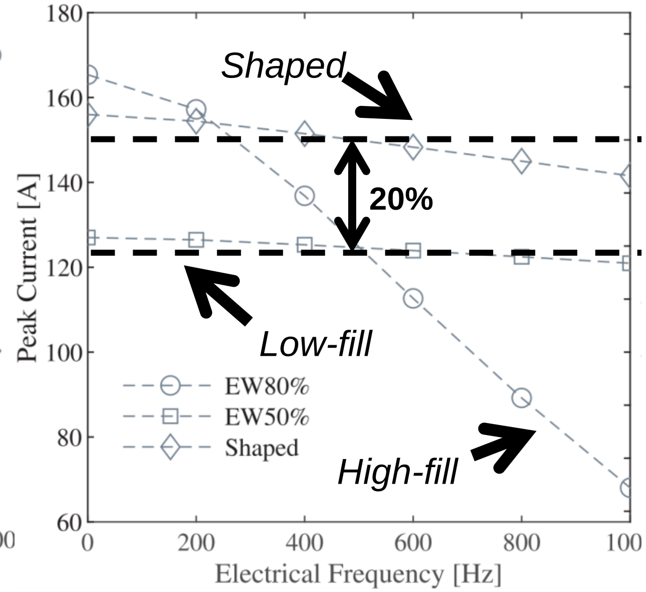
Shaped profile

Loss Minimisation – Shaped Profile Windings

- Winding loss prediction for I = 100A
- Continuous operating envelope for 180°C average winding temperature



Winding Loss



Continuous current at 180°C average

Copper AM Winding

Aluminium AM Winding

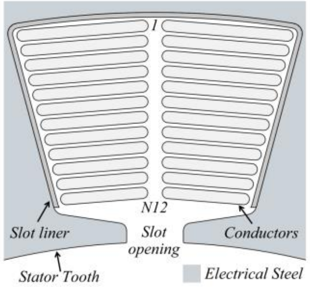
- **Low AC loss winding while maximising slot fill → increasing electric loading capability by ~20%**

Field Driven Design → Automatically Apply a Design Rule

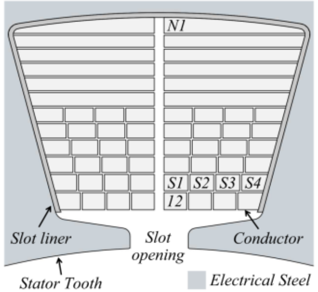
N. Simpson, D. J. North, S. M. Collins and P. H. Mellor, "Additive Manufacturing of Shaped Profile Windings for Minimal AC Loss in Electrical Machines," in IEEE Transactions on Industry Applications, May-June 2020

Loss Minimisation – Hybrid Strand Windings

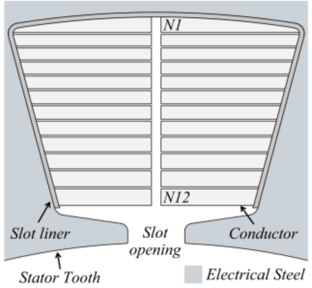
- Conformal windings with balanced strand currents through end-winding transposition



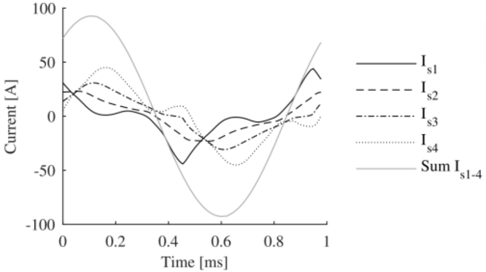
Original AM winding



Hybrid-strand winding

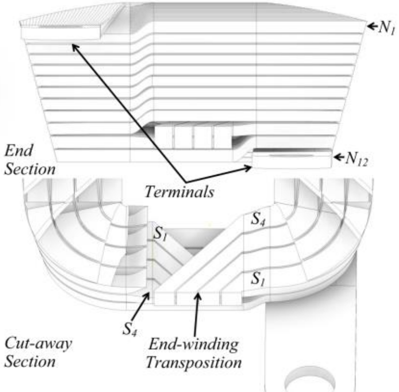


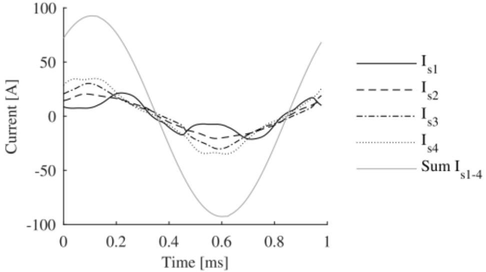
Conformal AM winding



Unbalanced strand currents

Litz



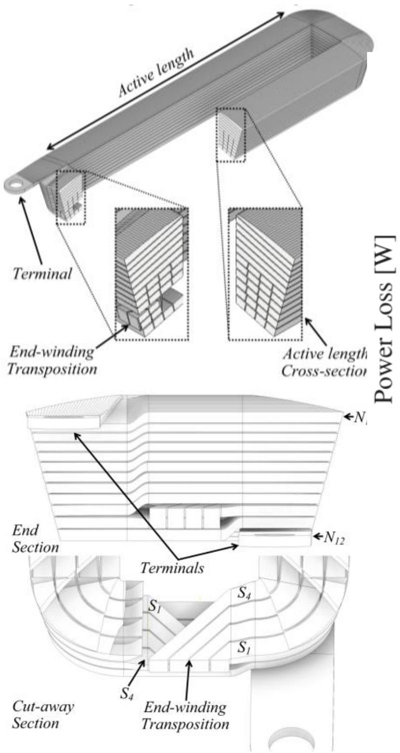


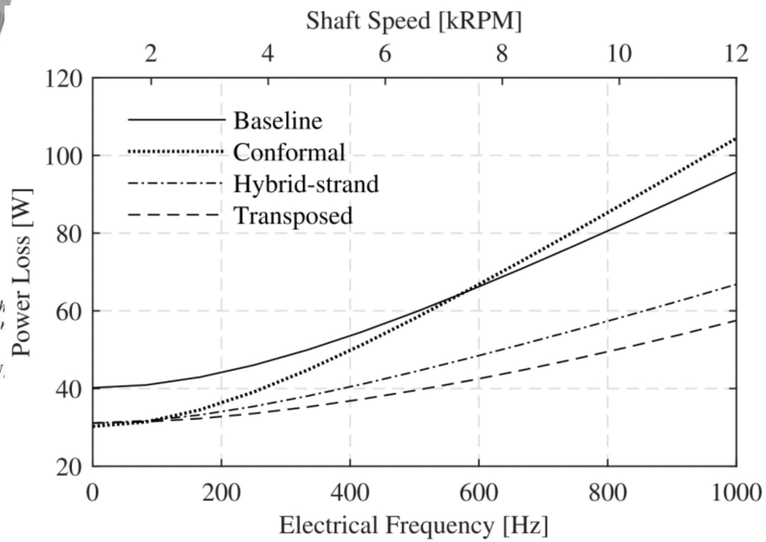
More balanced strand currents

- ***Improved thermal and AC loss performance***

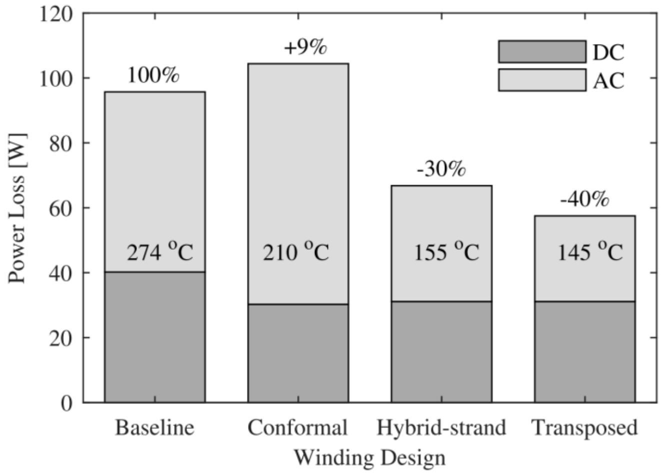
Loss Minimisation – Hybrid Strand Windings

- Comparison of loss minimisation techniques





Power loss as a function of frequency



Power loss comparison at 1 kHz

- **Targeted loss minimisation strategies → 40 % reduction in loss**

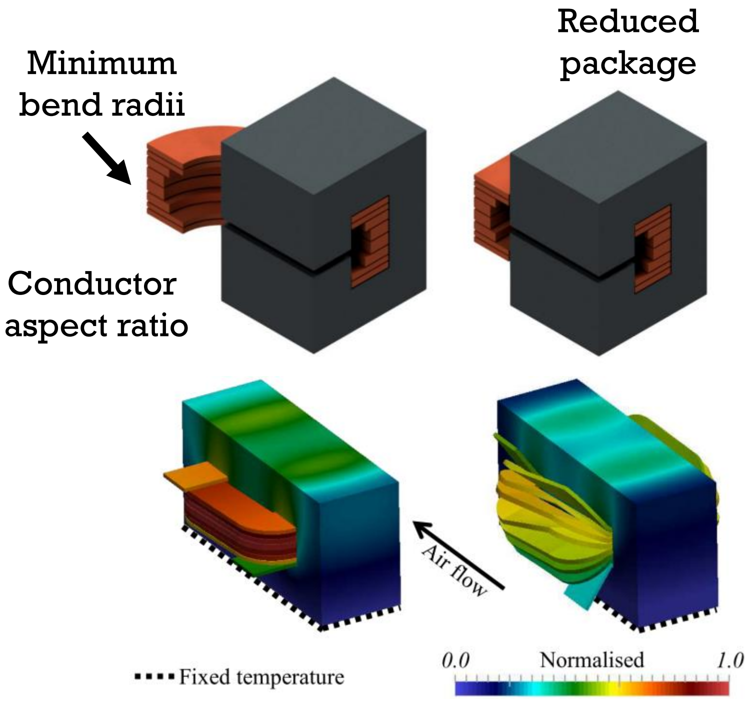
Field Driven Design → Automatically Apply a Design Rule

Heat, Fluid Flow, Parasitics?

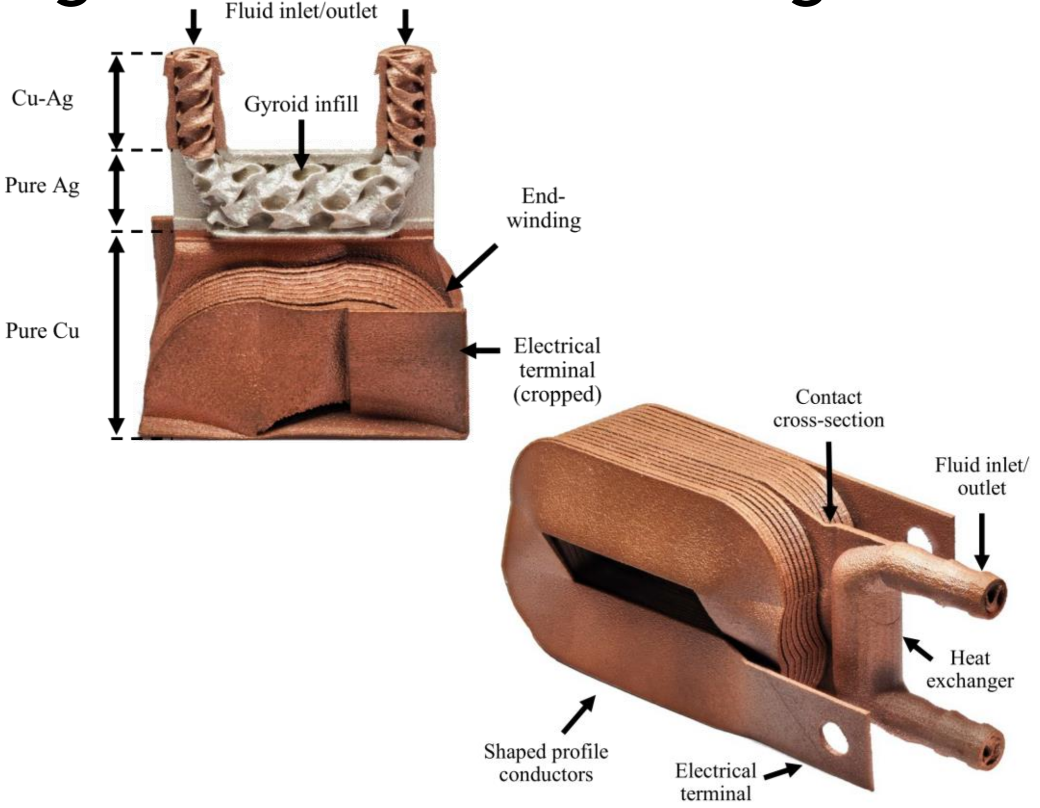
Simpson, N. and Mellor, P., 2021, October. Additive Manufacturing of a Conformal Hybrid-Strand Concentrated Winding Topology for Minimal AC Loss in Electrical Machines. In 2021 IEEE Energy Conversion Congress and Exposition (ECCE) IEEE.

Enhanced Thermal Management – End Winding

- Direct cooling of coils



Splayed end-winding heat sinking



Compact end-winding heat exchanger 4-terminal device

N. Simpson, C. Tighe and P. Mellor, "Design of High Performance Shaped Profile Windings for Additive Manufacture," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 761-768, doi: 10.1109/ECCE.2019.8912923.

Enhanced Thermal Management – Infill

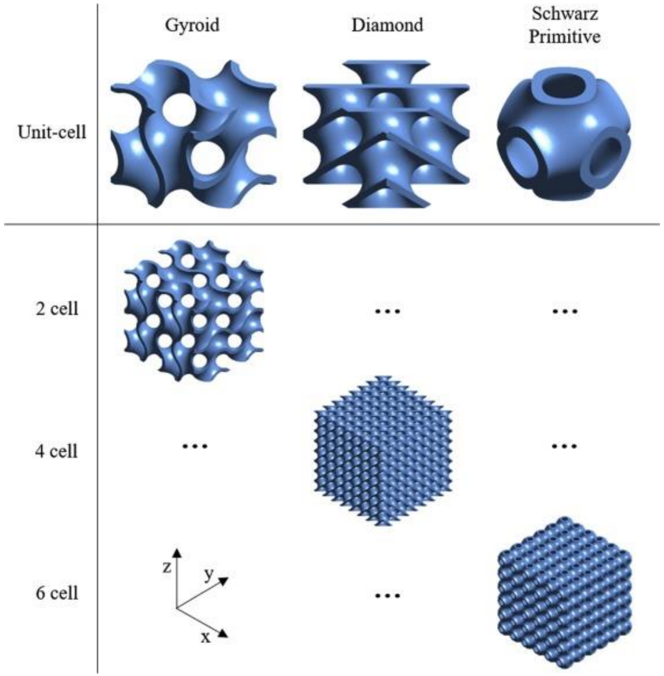
A few KB

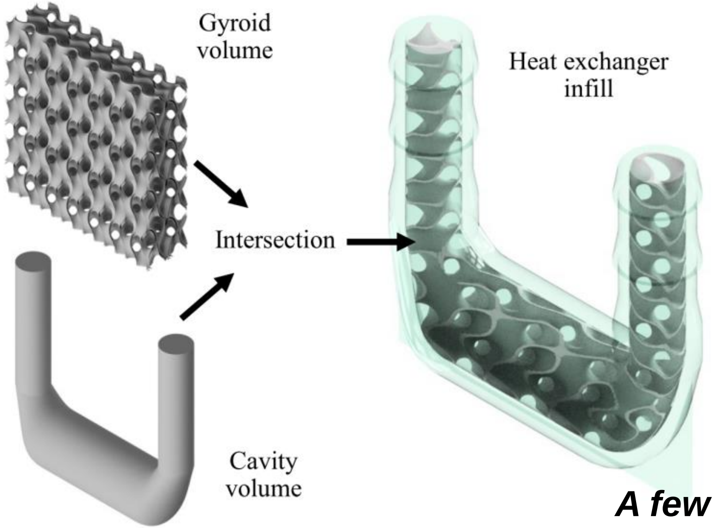
- Boundary Representation – Functional Representation

Vertex → Edge → Face → Solid

$$f(x,y,z)=\begin{cases} sin(k_g x)cos(k_g y)+sin(k_g y)cos(k_g z)+\\ sin(k_g z)cos(k_g x)+\frac{W_t}{2},\\ -sin(k_g x)cos(k_g y)-sin(k_g y)cos(k_g z)-\\ sin(k_g z)cos(k_g x)-\frac{W_t}{2}\end{cases}$$

Signed Distance or Level Set





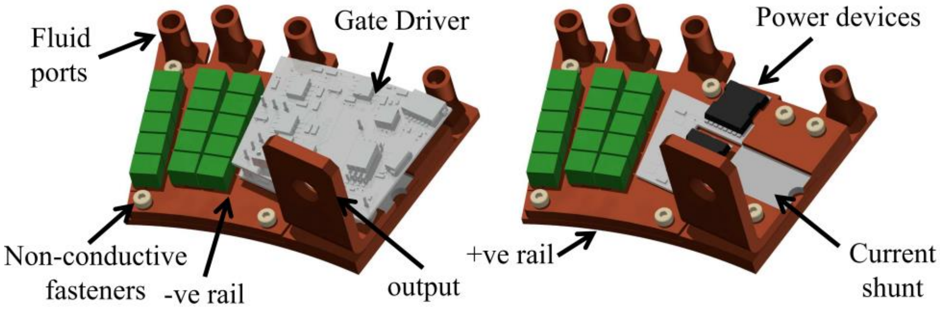
A few hundred MB

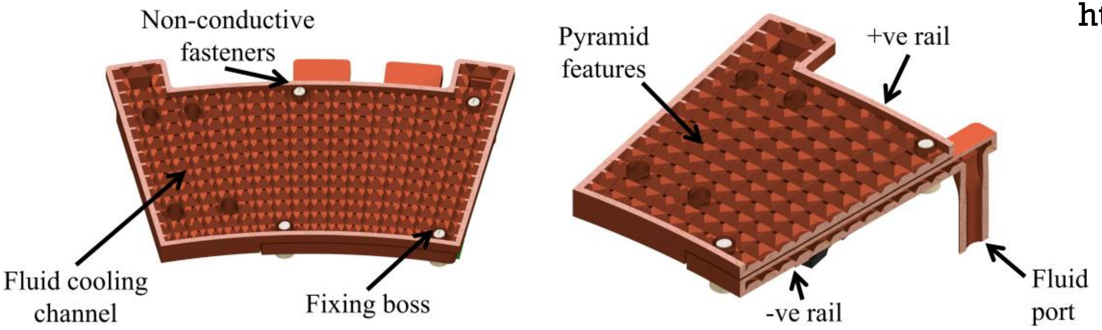
S. Catchpole-Smith, R.R.J. Sélo, A.W. Davis, I.A. Ashcroft, C.J. Tuck, A. Clare,
Thermal conductivity of TPMS lattice structures manufactured via laser powder bed fusion,
Additive Manufacturing,Volume 30,2019,

F-Rep → Requires Meshing Methods

Power Electronics Integration

- Integration of Inverter and Electrical Machine





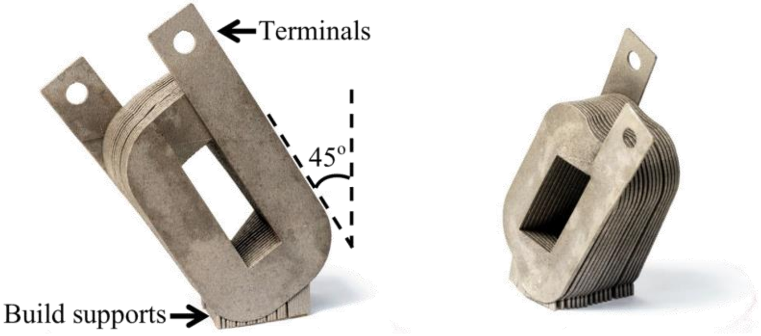
- Extension of previous phase module to AM
  - Integrated cooling
  - Design for AM (DfAM) rules
  - Design for Assembly
  - Naïve in terms of layout

- Feasibility study funded by EPSRC *Future Electrical Machines Manufacturing Hub* https://electricalmachineshub.ac.uk/

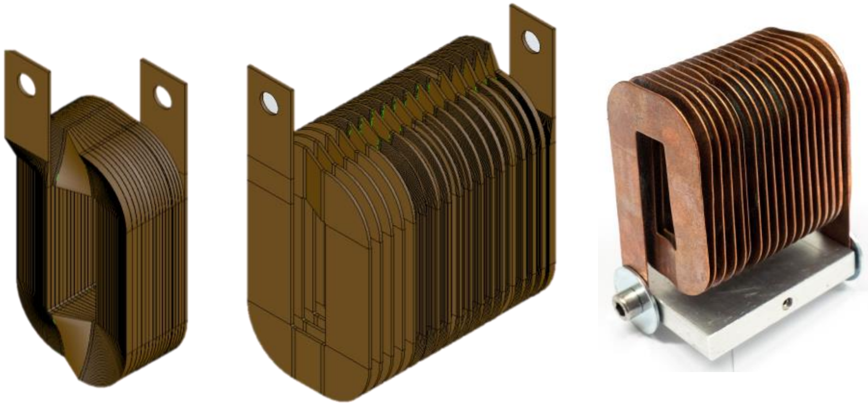
Manufacturing Challenges – Orientation/Supports

- Safe build angle for most materials ~45° to build plate
- Unsupported overhang ~1 mm
  - Supports needed thereafter
- Minimum feature size ~0.5 mm
- Minimum separation ~1 mm
- Surface finish/build speed trade-off
  - Over-size if post-processing
- Build supports
  - Minimise post-processing
  - Manage residual stress

- **DfAM rules are process driven – e.g. powder bed, binder jetting**
- **Design tools must account for DfAM**



Example AM windings built 45° to build plate



Manufactured in an expanded state

Manufacturing Challenges – Electrical Conductivity

Casting
(not covered here)

Copper Based

Aluminium Based

Standardised serpentine samples – time/cost efficient, sized according to ASTM B193-02

Up to 99% IACS

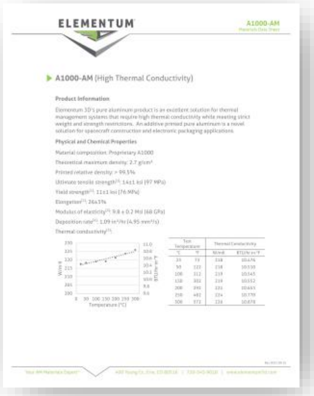
Negligible build orientation dependence

Note: surface finish

Up to 45% IACS

2-10% Build orientation dependence

Improvement possible



ELEMENTUM

A1000-AM

A1000-AM (High Thermal Conductivity)

Product Information

Elementum 3D's pure aluminum product is an excellent solution for thermal management systems that require high thermal conductivity while meeting strict weight and strength restrictions. An additive printed pure aluminum is a novel solution for spacecraft construction and electronic packaging applications.

Physical and Chemical Properties

Material composition: Proprietary A1000

Theoretical maximum density: 2.7 g/cm³

Printed relative density: > 99.5%

Ultimate tensile strength: 14±1 ksi (97 MPa)

Yield strength: 11±1 ksi (76 MPa)

Modulus of elasticity: 9.8 ± 0.2 Msi (68 GPa)

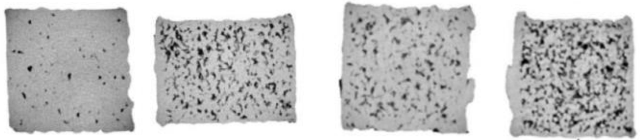
Deposition rate: 1.09 in³/hr (4.95 mm³/s)

Thermal conductivity:

Pure aluminium under investigation

Manufacturing Challenges – Porosity

- Controlled porosity → controlled effective conductivity



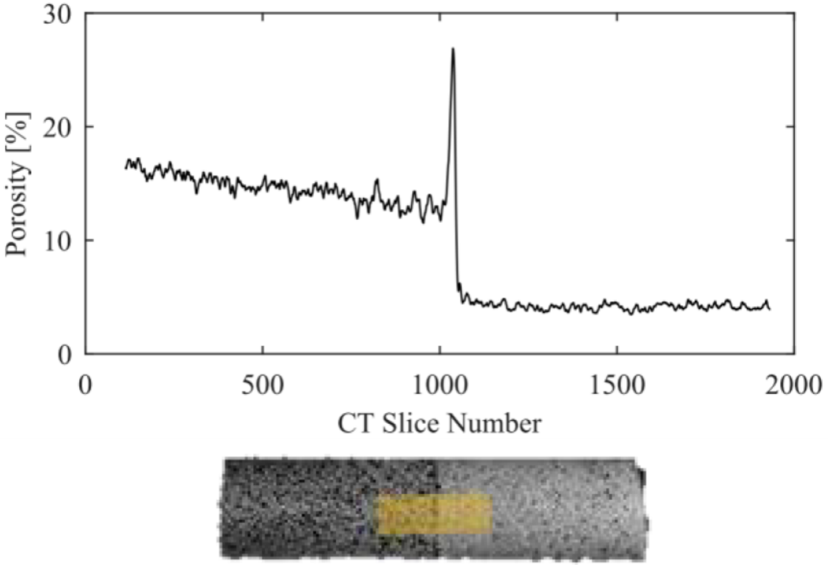


Fig. 10. Porosity calculated from CT cylindrical ROI (highlighted) across the interface between prescribed conductivities.

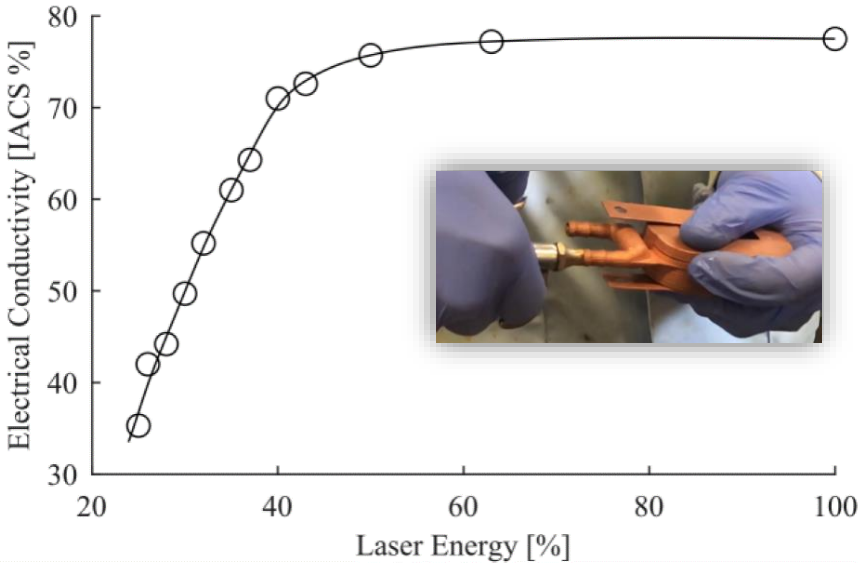
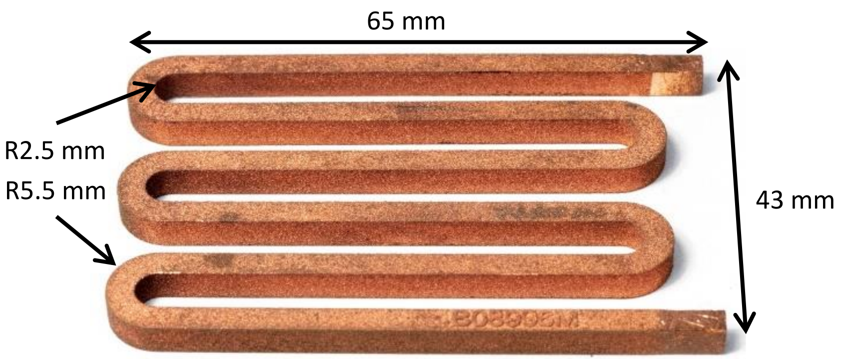


Fig. 7. Electrical conductivity (IAC) as a function of applied laser energy during the LPBF manufacturing process.

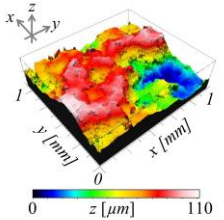
Manufacturing Challenges – Surface Roughness



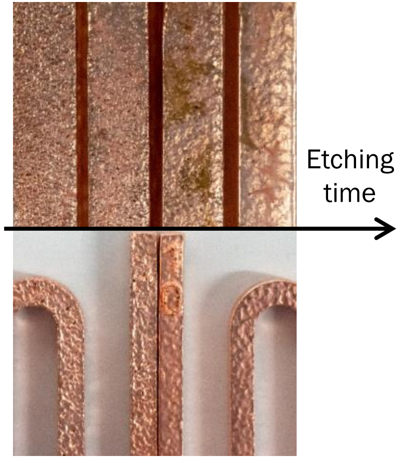
Standard serpentine sample – time/cost efficient, sized according to ASTM B193-02

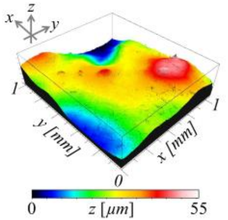
- Surface roughness depends on build parameters
  - Layer height/build speed/applied energy
- Surface roughness post-processing
  - Chemical etching
  - Electropolishing
  - Mechanical abrasive

Chemical Etching Example



Sample surface prior to etching





Sample surface after etching

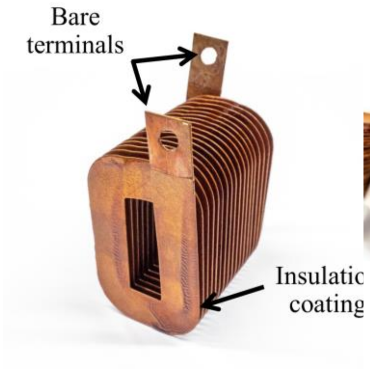
Advantages

- Smooth surfaces – no high-spots
- Edge radii
- Removes build support artefacts

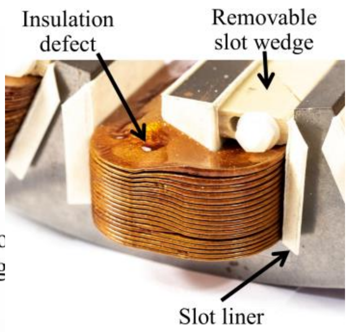
Manufacturing Challenges – Electrical Insulation

Post-manufacture application of electrical insulation

- Conventional
  - Dolph Synthite AC-43 Class H Polyester Varnish
  - Dip coated on 2-axis rotary tool
  - Air dried – oven cured
- High-performance Composite Coatings
  - Ceramic based nanocomposite up to 500°C
  - Electro-deposition/dip coated
  - Hot air dried – oven cured

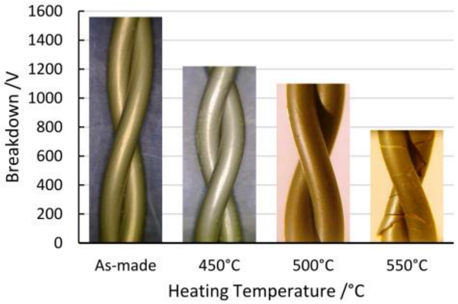


Dip varnished AM coil



AM coil installed in stator

Composite coated AM sample



Breakdown vs. Temperature

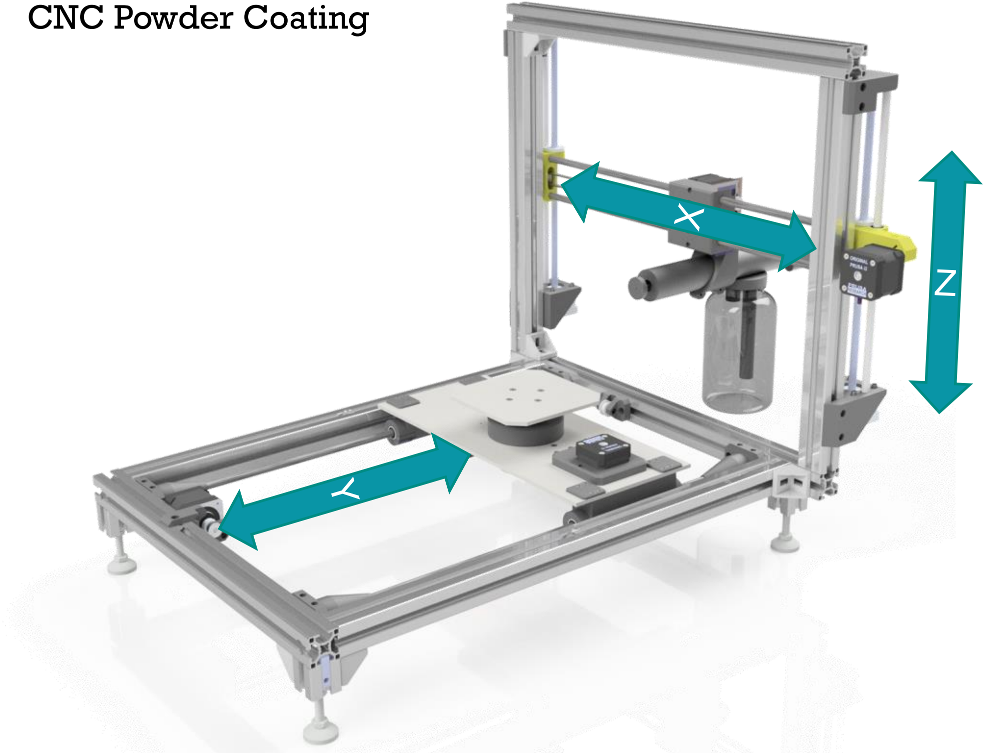
University of BRISTOL

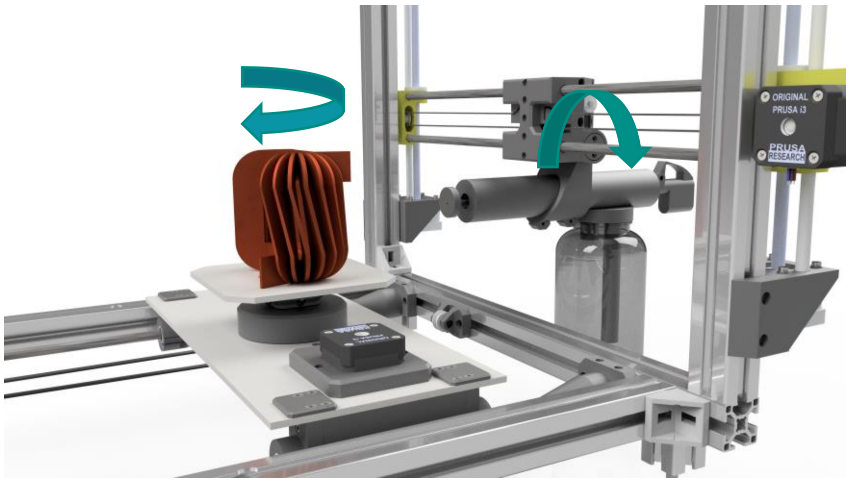
Teesside University

Pang, Y.X. and Hodgson, S.N., 2020. Ceramic/inorganic-organic nano-hybrid composites for thermally stable insulation of electrical wires. Part I: Composition and synthetic parameters. *IEEE Transactions on Dielectrics and Electrical Insulation*, *27*(2), pp.395-402.

Manufacturing Challenges – Electrical Insulation

CNC Powder Coating

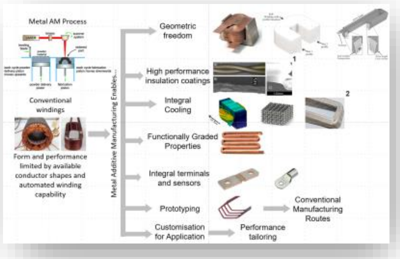




Conclusion

- AM significantly increases available design space
  - Shape, topology, material properties, integral cooling & other functions

Enabled by AM ✓
- minimise loss (conduction, wound passives)
- enhance heat extraction (to dissipate loss)
- raise temperature ratings



Copper (CuCrZr) AM winding

Aluminium (AlSiMg) AM winding

- Multiphysics design methodologies/tools are required
  - DfAM must be considered as early as possible
  - Design tools must account for 3D design space
  - Combine analytical and numerical methods to constrain computational cost?

Additive Manufacturing has the potential to overcome power-density limitations of conventional manufacturing methods.

University Research Groups → Bristol, Bath, Nottingham, Leeds etc
Compound Semiconductor Applications Catapult (CSA)
Manufacturing Technology Centre (MTC)

Thank you.

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Be part of the
Electric Revolution

Electrical Energy Management Group