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Additive Manufacturing of Next Generation Electrical Machine Windings - Opportunities in Fusion Engineering?

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***Abstract*—More electric propulsion across automotive and aerospace has lead to a demand for significant improvement in the power density of electrical machines. This has, in turn, triggered research into advanced manufacturing methods for higher performance magnet systems in machines. The application of Laser Powder Bed Fusion (LPBF), a form of Additive Manufacture (AM), to the current carrying coils of the electromagnetic circuit of a machine has allowed several significant improvements to the design of these parts. One benefit which can be realised in this way is the tailoring of conductor form to the operating field and the alteration of conductor topolgy to reduce AC loss. Another advantage of these manufacturing techniques is the ability to introduce methods of direct cooling to the coil, including highly efficient heat exchangers derived from generative design techniques. It is significant that the electrical conductivity achieved is now equivalent to that of conventional drawn Cu wire. This paper hypothesises that the lessons learned in developing production methods for next generation, high performance components for electric machines might also find utility in the very demanding electromagnetic circuits found in magnetic confinement fusion. Potential benefits for the production of Cable-in-Conduit Conductor (CICC) superconducting (SC) bus-bar joints, or even larger elements of conductors are discussed. This is used to motivate future experimental studies of the mechanical and electrical performance of AM Cu at cryogenic temperatures as well as the further development of the manufacturing state of the art.**

***Index Terms*—Additive manufacturing, Electromagnetic coils, Magnet systems, Powder metallurgy, Direct cooling**

I. INTRODUCTION

THE move towards carbon net zero, prompted by the 2015 Paris agreement has resulted in a demand for a technological step change in many parts of the energy and mobility sectors. The Aerospace Technology Institute [1] and Advanced Propulsion Centre [2] roadmaps call for electric machine power density to reach 9-25kW/kg by 2035 depending on application, with efficiency reaching greater than 96% and ideally reducing dependence on rare-earth minerals. This represents a 4-5 fold increase in power density over current state of the art machines. The solution to this, for electric machine designers, requires a reduction in coil losses, coupled with improvements in cooling and heat extraction from coils carrying high currents. Both of these aspects independently increase the current-carrying efficiency of a coil, but are difficult to achieve using conventional manufacturing technologies. Additive and Advanced Manufacturing (AAM) gives engineers the freedom work with complex geometries and the possibility to functionally vary material properties through a part, which in turn facilitates design of parts combining multiple functions such as integral cooling, terminals and sensors.

Increasingly, attention is being paid by researchers and engineers on developing techniques and know-how for applying and exploiting metal AM and other advanced manufacturing techniques in the active electro-magnetic (EM) components of machines. This includes developing multi-physics design tools, design for AM, material property studies, post-processing, insulation and coatings, to provide a cross-discipline academic underpinning to this emerging field. The techniques currently being developed are focused on the use of LPBF techniques and studies relevant to electrical conductors have been carried out using Cu, Cu-Cr-Zr and AlSiMg. LPBF for AM of metals is a broad field in its own right [3]–[5]. Much of the effort is focused on the manufacture of complex highly optimised structural topologies resulting from generative design tools or very specific requirements for a part. Some metals such as Ti lend themselves more readily to AM processes than others, and Cu is particularly challenging because of its thermal conductivity and reflectivity.

There is an obvious parallel between the advanced manufacturing techniques being developed in the field of electrical propulsion and the requirements for commercialising magnetic confinement fusion power-plants as they involve the construction of large systems of conductors and solenoids operating in an extreme environment. Magnet and conductor systems for Tokamak reactors present challenges for accuracy and repeatability of manufacture and their performance is highly sensitive to the manufacturing techniques employed. Tokamaks such as ASDEX Upgrade [6], JET [7] use substantial directly cooled copper coils in their magnet systems [8]–[10], whilst ITER [11] uses superconducting magnet systems [12]–[14] for the Toroidal Field (TF) coils, Poloidal Field (PF) coils, Central Solenoid (CS) and field Correction Coils (CC).

For the ITER project, these magnets are constructed from SC filaments (e.g. Nb_3Sn or $NbTi$) bundled alongside a significant bulk of Cu conductors to form a Cable-In-Conduit Conductor (CICC) [15]–[17], the purpose of which is to act as a stabiliser, providing a path for the excess current if

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the superconductor quenches. Typical Cu to SC ratios are between 1 and 2, and some conductors may include other materials separating filament bundles and providing diffusion barriers [15]. Maintaining conductivity in these Cu bundles is very important, and the process of winding a magnet and its subsequent deployment within the reactor cryostat, introduces strains to the material that have a negative impact on conductivity. Some parts of the magnet system operate under Direct Current (DC), while others are 'pulsed' with Alternating Current (AC) for plasma control [18]. Although the frequency of these pulses is not high when compared to electrical machine applications, the rate of change of current is hundreds of amperes per second during pulsed operation. The transverse magnetic loads experienced by the conductors of the ITER magnet system may be as much as 800kN/m. Furthermore, the geometrical constraints are very stringent; the TF magnets for ITER have a major diameter of 17.5m, but a positional tolerance of ± 1.5mm. In conventional winding, the lay of conductor and filament in the casing is critical to correct field production but very difficult to ensure. For this reason, smaller field correction magnets are also employed and tuned based on metrology of the larger magnets, as well as being used to correct fluctuations introduced by the winding and bundling of the conductors.

Future application of AAM Cu to advanced magnets and conductor components for fusion could have significant benefits. For example, the geometric freedom to construct coils with tight radii whilst eliminating the need for bending the conductor to its final multi stranded form. Furthermore, features such as direct cooling or conductor form optimised for loss reduction are possible. These ideas are further developed in section III. However, considerable advancements from the current state of the art would be required, including work on the performance of AAM components at cryogenic temperatures and scaling of manufacturing techniques; further work relating to these challenges is motivated in section IV.

This paper seeks to illustrate and explain some of the benefits achieved for electrical machine electromagnet systems using AAM components. Most of the examples are based on the optimisation of coil design for high fundamental frequency electric machines. We begin with a summary of material property state of the art and an overview of post processing and insulation techniques in section II-A. This is followed by several approaches to integrated direct cooling in current-carrying components in section II-B and the optimisation of conductor form for AC loss reduction in machines in sections II-C and II-D.

II. Examples of AAM in Electromagnet Design for Electric Machines

A. Improving Conductivity and surface finish

Given its applications to both electrical components and thermal management, considerable effort has been given to improving the electrical properties and reducing the porosity of AM Cu. This is a field that is advancing rapidly, in 2019, Jadhav *et al.* [19] reported conductivity at 88.8% of the International Annealed Copper Standard (IACS) for a best performing print. By 2022, Simpson *et al.* [20] were reporting experimental results shoWing that AM Cu has achieved conductivity that matches conventional pure Cu, up to 100% IACS, with minimal dependency on build orientation. Aluminium based AM conductors have now reached 55% IACS, with some dependence on build orientation. It is possible to control conductivity in a part by changing the porosity of the print via laser intensity, in the future this may allow current carrying to be tailored within a part.

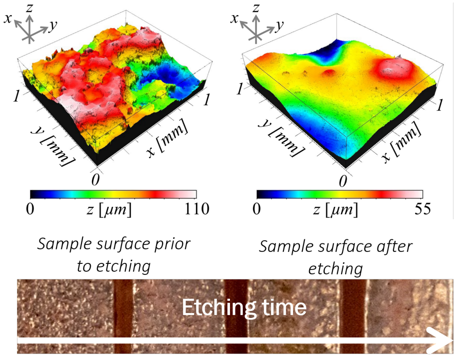


Fig. 1: The effect of carrying out a chemical etching process on the surface roughness of a Cu AM part.

Application of insulation to AM parts requires a good surface finish, free of asperities and pits which will weaken the insulation or create localised electrical effects. Successful chemical etching and electro-polishing techniques have been developed [20]. The impact of etching time on surface asperities is illustrated in figure 1. These have allowed experimental treatments to be carried out with conventional varnish as well as high performance ceramic nanocomposite insulations.

B. Enhanced thermal management

AM via LPBF gives the freedom to produce extremely complex geometry within a part. As techniques have developed for applying these manufacturing techniques to metals with favourable heat transfer properties, such as aluminium, Cu and Cu-Cr-Zr, interest in the use of AM for thermal management parts has increased. Applications range from intricate heatsinks with air as a working fluid [21] to complex internal geometries for liquid cooled heat exchangers [22], [23].

This allows realisation of geometry that is generated in CAD from a functional representation rather than a conventional boundary representation, such as Triply Periodic Minimal Surfaces (TPMS) [24]–[28]. Figure 2 shows an example 'cut-away' print with a programatically generated gyroid heat exchanger infill, whilst also showcasing the potential to switch materials through the thickness of a print.

Geometric freedom allows compact or complex thermal management solutions to be deployed in windings. Direct cooling is highly beneficial compared to more convoluted thermal paths involving multiple material and component interfaces. The inclusion of heat exchanger topologies in prototype electrical machine windings has been shown to be an effective thermal management strategy. Two experimental topologies have been considered, one using a compact heat exchanger incorporated in the end turn, shown sectioned in figure 2 and the other with through-turn cooling channels in a shaped winding, figure 3. The latter was shown to be effective at reducing the temperature of the coil during a direct current heating calorimetry experiment [29]. Neither geometry would be possible by conventional manufacturing.

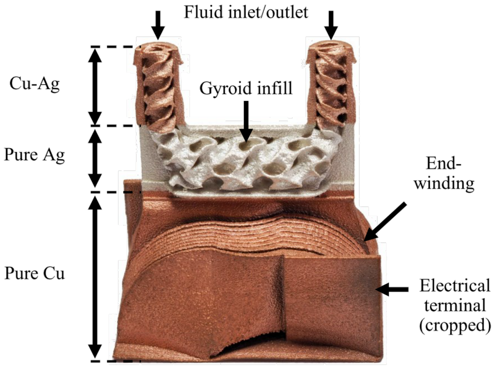


Fig. 2: A gyroid heat-exchanger end winding build as a 'cut-away' in multiple materials to illustrate the internal geometry and demonstrate capability.

C. Loss minimisation via field driven design

Consider a conductor subject to an external time varying magnetic flux. It is well known that thin, broad, conductors shaped to remain perpendicular to the external magnetic field will exhibit minimal loss, an example of the field in the slot of an electric machine is shown in figure 5a. Edge-wound conductors are a preferred solution for this, which result in the winding being effectively laminated in the direction of magnetic flux. Manipulation of conventionally produced conductors into these types of geometries limits both the form of the conductor and the nature of insulation coatings which can be used. AM windings allow for optimisation of conductor profiles [30], [31], whilst novel coating solutions allow the additively produced winding to be insulated post-manufacture. The optimisation of conductor shapes iterates over a Time-Harmonic Finite Element (THFE) model that accounts for the change in flux distribution due to the movement of the rotor. An example iteration of conductor shape is shown in figures 5 a, b, c. The manufactured final geometry is shown in figure 4.

D. Loss minimisation via "Litzpin" Conductors

Losses due to eddy currents within the conductors are worse in regions where the magnetic flux gradient is greater. One solution for this is the use of multi-stranded conductors which reduce the impact of skin effects in the conductor. Further mitigation for eddy-currents is introducing transposition in the conductor, as in Litz-wire.

Two studies are presented here based on the requirements of electric machines, both of which take advantage of the geometric freedom offered by AAM techniques. One is a hybrid-strand winding with multiple strands in the region of high AC flux and wide flat conductors in the region of low AC flux. This design incorporates a twist in the multi-strand layers, causing imbalanced strand currents to cancel out within the winding, illustrated in figure 6. A full development of this concept is presented by Simpson *et al.* [32]. The other design is an AM drop-in replacement for a solid hairpin winding, of the type currently favoured in high performance automotive applications. In this proof-of-concept it incorporates a twisted, multi-strand design like Litz-wire, illustrated in figure 7. This conductor topology has been shown to dramatically reduce AC loss at high frequency (figure 8).

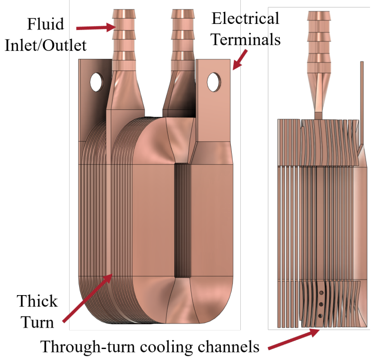


Fig. 3: An AM Cu winding with cooling channels in the thickness of a turn.

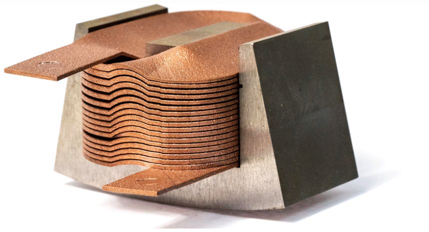
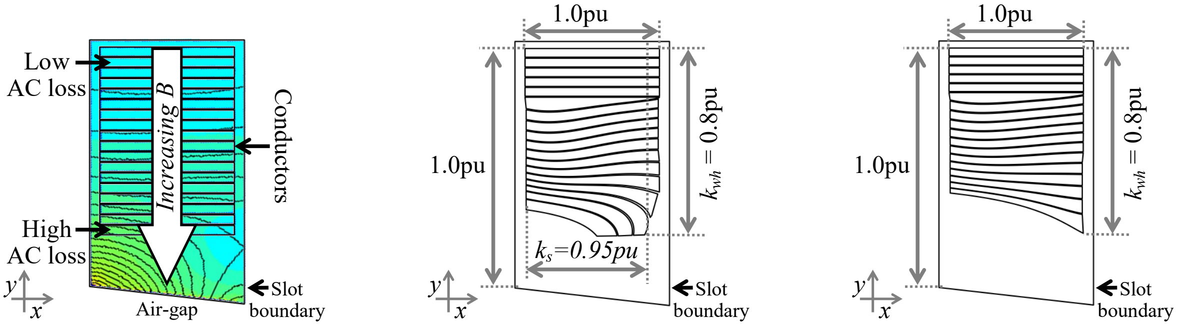


Fig. 4: A geometry optimised coil produced using LPBF in Cu.

III. OPPORTUNITIES FOR AAM CONDUCTORS IN FUSION

The electrical parts of the confinement system in magnetic confinement fusion offer numerous opportunities for AAM. Many of the SC components use Cu substrates and would benefit from both direct cooling and geometry control. For example, the SC bus-bar joints described by Rong *et al.* [33] and Ilyin *et al.* [34] use Cu 'soles' to connect the SC busbars. The joints require maximal conductivity and operate in a strong magnetic field at liquid-He temperatures, as they form the connection between the magnetic coils and their power supply. The EM and thermal properties of the ITER joint design, for example, were the subject of a study by Rolando,[35] who offers a detailed models of their performance. According to Ilyin *et al.* there are 288 such joints in ITER, for example, and they require repeatable performance of below $2n\Omega$ at $70kA$ or $5n\Omega$ at $10kA$ depending on the location. The joints require coolant feedthrough from one Busbar to the next. In such an arrangement, there are opportunities for thermal performance improvement and design freedom via the greater geometric freedom offered by AM.



(a) (b) (c)

Fig. 5: Stages of the optimisation process.

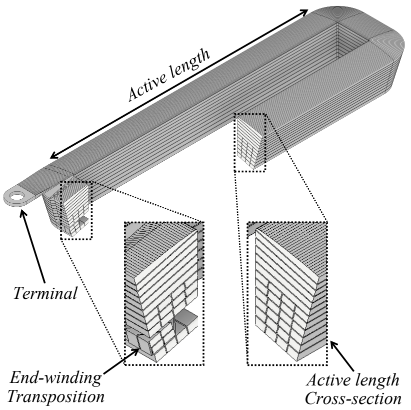


Fig. 6: An example coil topology with stranded conductors in high loss regions and an end winding transpose.

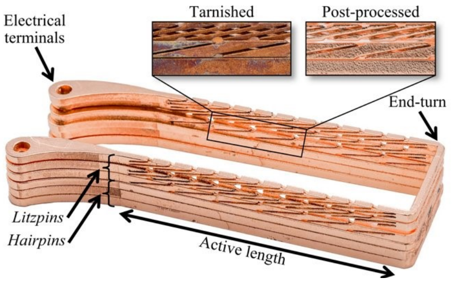


Fig. 7: A selection of “Litzpins” of different strand thicknesses showing the results of chemical post processing.

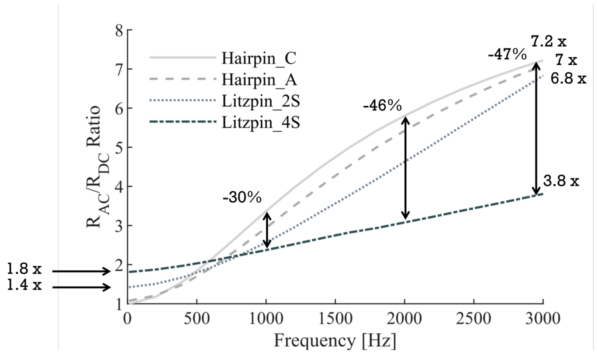


Fig. 8: The reduction in high frequency AC loss achieved with a “Litzpin” stranded conductor in AM Cu.

A more ambitious application of AAM techniques in the design and production of superconductors is in the production of conductors themselves. The critical current for a superconductor can be defined by the power factor n in the voltage-current relationship. De Marzi *et al.* [36] and Schild *et al.* [37] noted a critical drop in the value of the n-factor when CICC conductors were cyclically loaded and subject to self-field; the reduction in n increases the likelihood of the superconductor reaching a ’quenched’ state due to the reduction in critical current. Mitchel [38] explained this as an effect of the variation in bending strain during cycling resulting in plastic deformation of the Cu stabiliser strands, which are already at their plastic limit due to ‘cooldown’ strain, i.e. the thermal strain induced by bringing a reactor to operating temperature. The construction of CICC and the twisting of filaments around each other was demonstrated to play a part in the variation in n over the length of a conductor, and that the presence of cable supports also had an impact on the cyclical variation in strain throughout the CICC. It may be possible, via future AAM techniques to tailor properties such as mechanical stiffness and conduction paths, or build in strain relief in certain stabiliser components to relieve the build up of undesirable strains due to current cycling and thereby increase the resiliance of a conductor to reduction in n and consequent susceptibility to quench.

IV. CHALLENGES FOR AAM CONDUCTORS IN FUSION

A. Characterisation of AM Cu performance at Cryogenic Temperatures

The operating temperature of the SC magnet systems in tokamak devices may be as low as 4K. The change in temperature from ambient down to operating also induces thermal stress throughout the magnet and cooling systems. In addition to this, the forces generated by the field and its interaction with the plasma are very large.

It is therefore beneficial to the potential utility of AM Cu in SC applications to experimentally determine any changes in material properties with temperature change. Ambient temperature tensile testing has been conducted as part of many studies into AM Cu build parameters[39], material testing has been used to examine the effect of deliberately tailored porosity within a print [20]. Specialist cryogenic material testing of this kind is carried out for other applications at a number of research institutions [40], [41].

The electrical performance of a material at cryogenic temperatures is also different than at room temperature. The value typically used to describe this is the Residual Resistivity Ratio (RRR), which is the ratio of resistivity of the material at either 273K or 'room temperature' and at a low cryogenic temperature [42]–[44]. Investigations of this type should be carried out on AAM parts to confirm their usefulness in superconductor stabilisers.

B. Scaling up Build Volume

The current upper limit on build volume on most commercial LPBF systems is less than $0.5 \times 0.5 \times 0.5$m. Many of the largest machines are also not equipped to build Cu, which requires different laser frequencies due to the heat absorbtion and reflectivity of Cu [45]. The largest LPBF machines available are GE's 2-laser X-line 2000R with a build volume of $0.8 \times 0.4 \times 0.5$m and SLM's innovative 12-Laser NXG XII 600, which can build $0.6 \times 0.6 \times 0.6$m . Although these volumes are large in the context of coils for automotive or aerospace propulsion, they is small in comparison to most of the magnet hardware used in fusion at a commercial scale. There is currently a gap in research for techniques to scale up the production of AM Cu parts. Combining the current state-of-the art in different branches of powder-based metallurgy with that from other AM disciplines such as blue laser directed energy deposition [46] or in-situ composite repair [47], [48] may further increase the usefulness of AAM for large, complex structures.

V. CONCLUSION

This paper seeks to present a body of work from the domain of electric machine development that may be of use or interest to the fusion engineering sector. The work presented describes the use of AAM of Cu in the production of windings for machines, principally via LPBF techniques. The use of AAM for Cu and other conductor materials allows the designer greater freedom to tailor the geometry of the conductors in an electromagnet and thereby increase efficiency and reduce AC loss. It is also possible to include direct cooling in the solenoid components, either by through-turn conduits or by cooling the end turns, both methods have been shown to be effective for improving the current-carrying performance of a coil. A suite of methods has been developed for post processing of coils to allow insulation to be applied to them in their final state, as opposed to manufacturing coils from conventionally coated conductor wire. These techniques include chemical methods for the improvement of surface finish.

AM Cu has now reached 100% IACS, and therefore has the same room-temperature performance as conventional Cu conductor wire. However, an experimental study to determine the RRR value and structural properties of AM Cu at cryogenic temperatures would be of value. Furthermore, some applications within magnetic confinement fusion reactors involve huge components that far exceed the build volumes currently achieved with LPBF.

In this paper, the authors seek to motivate possible fields of application of AAM Cu in fusion magnetics and superconductivity. These are suggestions made by engineers from a different field, and as such are presented as high level concepts. The most promising avenue might be the the manufacture of novel SC bus-bar joint topologies, which could benefit from ease-of manufacture of complex topologies and integrated cooling. Another, more ambitious application could be in some sections of the conductors themselves, where design freedom could allow the mitigation of problems caused by cyclical straining of the Cu stabiliser and increased quench risk.

There are, of course, many other potential applications for AAM of Cu, CuCrZr and even Al-based components in the huge technological challenge that is bringing viable fusion energy on grid. The use of advanced methods may not be suitable for the first generation of commercial reactors, where well understood methods are preferred. However, as the focus shifts to improving performance of these machines yet further, the lessons learned from the existing demands on electromagnetics may become valuable in this new field.

ACKNOWLEDGMENT

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