Additive Manufactured Copper Conductors: Impedance Characteristics of Samples with Varying Density and Cross-section profile

Christian Wachter
Institute for Vehicle Concepts
German Aerospace Center
Stuttgart, Germany
christian.wachter@dlr.de

Fenja Haller
Institute for Vehicle Concepts
German Aerospace Center
Stuttgart, Germany
fenja.haller@dlr.de

Florian Liebetrau
Institute for Vehicle Concepts
German Aerospace Center
Stuttgart, Germany
florian.liebetrau@dlr.de

Abstract— **With additive manufacturing, copper windings and even whole coils can be manufactured in a new, totally different approach than with common manufacturing methods. The coil design is no longer bound to the limitations given by the wires bend radius or the geometric capabilities of winding machines. Therefore, additive manufacturing offers new degrees of freedom for the design of copper windings and thus the design of electric machines. However, the electric properties of printed copper material must be known exactly and should be comparable to solid copper wire. This paper examines the impedance characteristics of additive manufactured copper conductors of two different copper alloys with varying print density and two different cross-section areas. Additionally, copper conductors consisting of multiple twisted subprofiles are examined, emulating stranded conductors. The measurement results are set in relation to an extruded copper profile to ensure comparability. The influence of the skin effect is examined by performing the investigations over a wide frequency range. Furthermore, the effect of different print densities on the effective resistance can be shown clearly. Besides the measurement results, an evaluation of the possible field of application and the limitations is given.**

Keywords— Additive Manufacturing, Copper Conductors, Coil, Impedance, Electric Machine

I. Introduction

Additive manufacturing has become state of the art and a widely used method of manufacturing in the recent years. Also known as rapid prototyping, the thought is obvious to use this method to fabricate copper windings/coils for electric machines. Compared to other winding methods, the advantages are clear: a rather fast printing process, geometric freedom and a possibly smaller winding head by avoiding bend radius. Moreover, competitive methods show clear disadvantages: hand wiring is rather slow and costly and only reasonable for small quantities. Insertion windings demand tools and machines, while the hairpin technique offers a good fill factor but comes along with widely protruding winding heads.

However, additive manufacturing comes along with clear limitations. Very fine self-supporting structures, below 1mm size, are likely to come out in bad quality. Therefore, additive manufactured copper conductors are limited to a certain minimal cross-section area. Depending on the additive manufacturing technique, a remaining porosity can not be avoided having a negative effect on thermal and electrical conductivity.

Especially in applications with alternating current of high frequency, the skin effect needs to be considered, since it represents an additional source of losses. To omit these losses, high frequency conductors consist of multiple twisted litz wires. With additive manufacturing, a litz wire can be emulated by dividing the full profile into several sub-profiles separated by a small gap.

With additive manufacturing offering great freedom regarding the geometric design possibilities of conductors, it seems possible that the limitations can be compensated, depending, of course, on the application. Therefore, the study at hand examines the impedance characteristics of additive manufactured copper conductors, since knowing the basic electric properties is the starting point for all ongoing investigations.

II. State of the Art

In previous works the main focus was laid upon maximizing the print density since it has a strong negative effect on both electric and thermal conductivity. Tran et al. [1] investigated different manufacturing methods, finding, that the highest density and conductivity compared to pure copper can be achieved by electron beam melting. Similar results have been achieved by Lodes et al. [2] who used electron beam melting as well and could achieve a maximum density of 99.94%.

Silbernagel et. al. experimented with probes printed by laser powder bed fusion [3] and found interesting dependencies on printing direction as well as post-printing heat-treatment, but could only achieve 50.3% of the conductivity of pure copper.

Silbernagel et. al. also examined SLM-processed AlSi10Mg for use in electric motors [4], where they found similar dependencies as in [3]. Those could be explained by differences in the grain structure which form out differently, depending on the printing direction. The print density was at least at 99.72%, but a comparison regarding conductivity to extruded aluminum profiles has not been done.

In a completely different approach, a team of TU Chemnitz hast printed a whole electric machine with a multi-material printing technology using highly viscous compounds. Though the conductivity of the printed copper structures is stated of only 80% compared to pure copper [5], the approach seems promising due to the high thermal conductivity of the printed ceramic isolation, since good heat dissipation can compensate for higher losses in the coils.

978-1-6654-5404-9/22/$31.00 ©2022 IEEE

An overview about various application possibilities of additive manufacturing in electric machines is given in [6] and [7]. Different additive manufacturing techniques and their application possibilities are discussed, as are coils/windings, magnetic core packs, electrical insulation parts, as well as housing parts and thermal management components.

An example of how the advantages of additive manufacturing can be put to account is given in [8]. A shaped profile winding is optimized by an algorithm presented in the paper with the goal to minimize AC losses. Compared with a conventional winding, the output torque of a test machine could be increased by 20%.

A comprehensive study of the possibilities offered by additive manufacturing is given in [9]. Different manufacturing techniques for stator core, rotor core, winding, insulation and magnets are presented and rated. Some examples for printed copper windings with special regard to customized form winding and hollow conductors are given as well, but again, a comparison to conventional copper windings regarding conductivity is not given.

Wrobel and Chiodetto [10] show in a theoretical study how different winding configurations can benefit of additive manufacturing. Thereby they aim for compensating the lower conductivity of printed copper, which they cite from as being between 75% and 90% of that given by the International Annealed copper Standard (IACS).

Lorenz et al. [11] give a conductivity of 71% caused by the remaining porosity in the printed material. They show an interesting comparison regarding losses between coils with wire, strip and printed conductors.

Though additive manufacturing of electric conductors has been examined under various aspects, an investigation of the impedance characteristics has apparently not been carried out yet. Therefore, the study at hand examines additive manufactured copper conductors under AC-current in a wide frequency range.

III. Material and Sample Design

The SLM process (Selective Laser Melting) is used to manufacture the samples. Based on the information found in previous papers, this is the most suitable method for the application at hand, as fine structures can be reproduced well and a good component quality can generally be achieved.

A. Material

Two different copper materials, which are available on the market as printing powder, were used for the printed test samples. The solid conductors, which serve as a reference, are made of Cu-ETP.

<u>CuNi2SiCr</u>: A widely used copper alloy for additive manufacturing. Usual applications are heat sinks, heat pipes, etc. Good printing properties and high component quality. However, poorer electrical conductivity than pure copper due to the alloying elements. Despite this limitation, the material was chosen because only with the CuNi2SiCr printing machine it was possible to vary the path width and thus the print density.

<u>CuCp</u>: This is almost pure copper (99.95% purity). The porosity of the print with standard parameters is less than 0.5% (manufacturer information). The material was developed for use in electric motors and thus shows a higher conductivity than CuNi2SiCr.

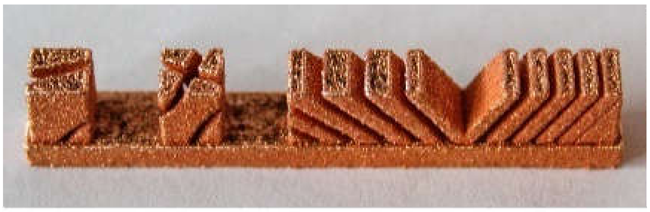

Fig. 1. Print of a preliminary test sample for investigation of the geometric limits of the printing process

<u>Cu-ETP</u>: Copper alloy for use as an electrical conductor. Purity greater than 99.9%. Since the conductors are produced by extrusion, it can be assumed that there is virtually no porosity.

B. Preliminary investigations

In order to determine the limits of the printing process, preliminary tests were carried out with the sample supplier. Parameters such as minimum gap dimension, overhang ("oblique pressure build-up") and the possibility of twisting several profiles were tested (Fig. 1).

C. Sample Design

All samples have been printed in the way, that their cross-section area (2x2mm or 4x4mm) was lying in the printing layer plane and their length-direction was build up along the z-axis. Following the results of Silbernagel et al. [3], [4] it was assumed that the best possible conductivity could be achieved that way.

Fig. 2. Conductors of 100% (sample 2.5), 80% (sample 2.3) and 60% (sample 2.1) printing density.

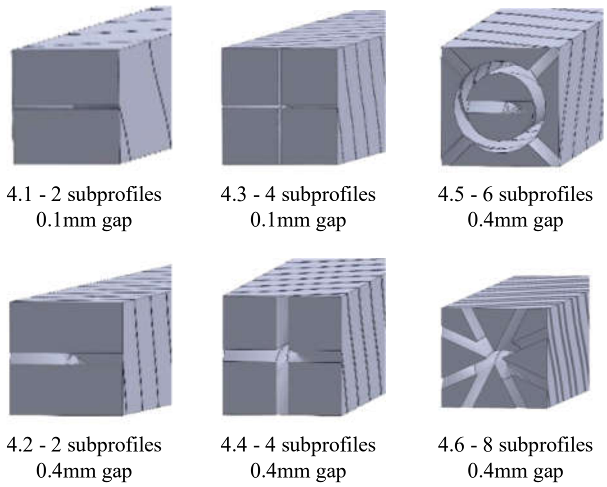

Fig. 3. Conductor samples (4.1 to 4.6) consisting of twisted sub-profiles

TABLE I. OVERVIEW OF MANUFACTURED SAMPLES

SAMPLE	MATERIAL	DIMENSION	COMMENT
1 - extruded	Cu-ETP	4x4mm	extruded profile
2.1 - printed	CuNi2CiCr	4x4mm	60% density
2.2 - printed		2x2mm	
2.3 - printed	CuNi2CiCr	4x4mm	80% density
2.4 - printed		2x2mm	
2.5 - printed	CuNi2CiCr	4x4mm	100% density
2.6 - printed		2x2mm	
3 - printed	CuCp	4x4mm	100% density
4.1 - printed	CuCp	4x4mm	2 twisted sub-profiles 0.1mm gap
4.2 - printed	CuCp	4x4mm	2 twisted sub-profiles 0.4mm gap
4.3 - printed	CuCp	4x4mm	4 twisted sub-profiles 0.1mm gap
4.4 - printed	CuCp	4x4mm	4 twisted sub-profiles 0.4mm gap
4.5 - printed	CuCp	4x4mm	6 twisted sub-profiles 0.4mm gap
4.6 - printed	CuCp	4x4mm	8 twisted sub-profiles 0.4mm gap

Two different approaches were investigated. One is the variation of the path width during printing (= print density) in order to vary the copper grid (Fig. 2). This assumes that the contact resistance to non-fused copper particles is high enough that the current only flows along fused paths. This approach was only possible with the CuNi2SiCr material, as only the printing machine used for this material allowed a corresponding parameter modification.

Furthermore, conductors were printed consisting of 2 to 8 twisted sub-profiles, similar to a stranded conductor (Fig. 3). Since it became apparent during the course of the project that the CuCp material behaves much better in terms of its electrical conductivity, the stranded wire profiles were only realized with the CuCp material. The possible number of strokes was determined in the preliminary tests (Fig. 1). For some samples, the gap dimension between the sub-profiles was also varied. Again, it is assumed that the contact resistance between the non-fused copper particles is significantly higher than the resistance of the fused material and thus the current only flows in fused areas. In order to be able to introduce the current into all sub-profiles via the Kelvin terminals, a short section is printed as a solid profile at the ends of the conductors.

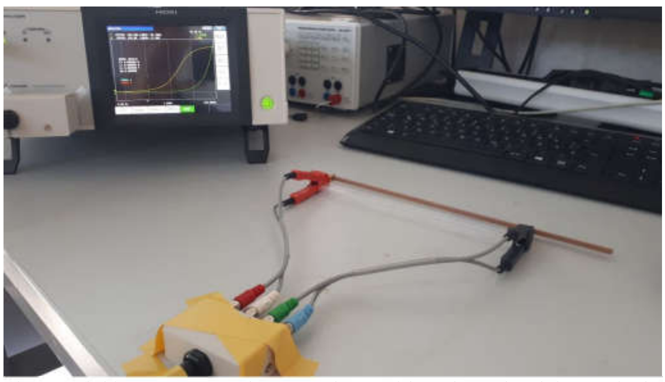

Fig. 4. Hioki IM3570 Impedance Analyzer with probe and Kelvin terminals

IV. RESULTS

A. *Measuring instrument and experimental setup*

A Hioki IM3570 Impedance Analyzer is used to measure the samples. The measuring instrument can independently pass through a predefined frequency range by means of an analysis function. The probe is equipped with two Kelvin clamps so that a four-wire measurement can be carried out. The samples were measured at constant terminal spacing, adjusted by a gauge (Fig. 4). The instrument measures impedance and phase angle. The results were converted to effective resistance.

Five copies of each sample geometry were printed, measured and the results averaged. In this way, scattering due to fluctuations in the manufacturing process should be averaged out. However, since the measuring points were very close to each other, an error bar is not shown.

All measurements show a characteristic buckle in the measurement curves, which occurs between 35 and 40 kHz. As the manufacturer of the measuring device stated, the internal measuring circuit is switched over in this range. The buckle is therefore due to the measuring method and cannot be avoided. However, this is insignificant for the qualitative comparison of the samples.

B. *Comparison of extruded conductors with printed conductors*

An extruded copper profile made of Cu-ETP with a length of 200mm and a cross-section of 4x4mm is compared with printed samples made of the two different printing materials.

It turns out that the effective resistance of the samples made of CuNi2SiCr material is significantly higher than that of the other samples (Fig. 5). Thus, it can already be determined that this material is only suitable for use as an electrical conductor with clear limitations.

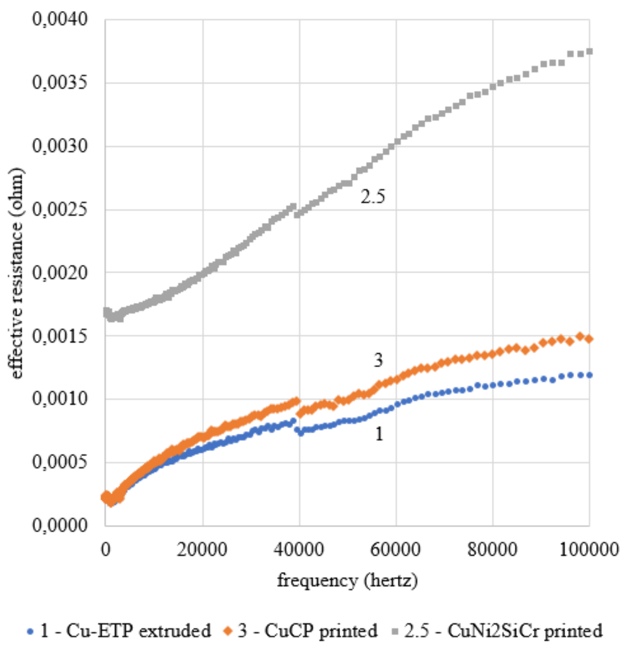

Fig. 5. Comparison of extruded with printed conductors of different print material. Probe length 200mm.

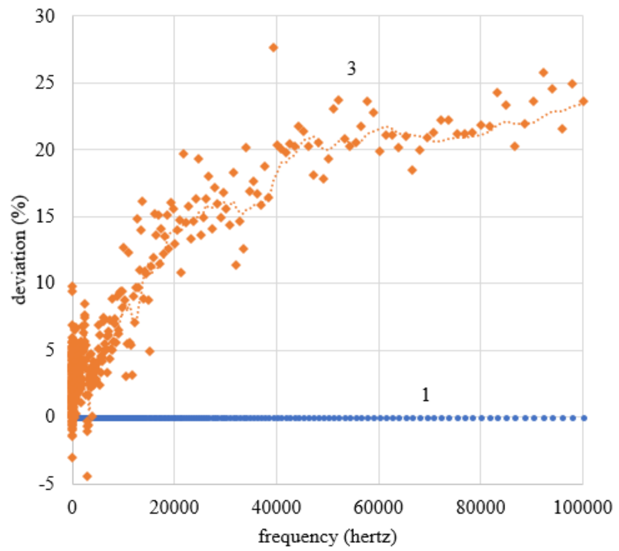

Fig. 6. Percentage deviation of printed CuCP to extruded Cu-ETP material. Probe length 200mm.

The printed CuCp, on the other hand, has only a slightly higher resistance below 20 kHz than the extruded material. Towards higher frequencies, the curves diverge increasingly (Fig. 5). This becomes particularly clear when looking at the percentage deviation of the effective resistance of printed CuCp to extruded Cu-ETP (Fig. 6).

Depending on the application, the increased electrical resistance of up to 10% up to frequencies of about 10 kHz can possibly be accepted, especially considering the advantages of the additive manufacturing process. However, the application as a high-frequency conductor seems not reasonable, as an imaginable positive impact on the skin effect (due to the structure of the printed material) does not occur and on the contrary the lower density and thus conductivity of the printed material is dominant.

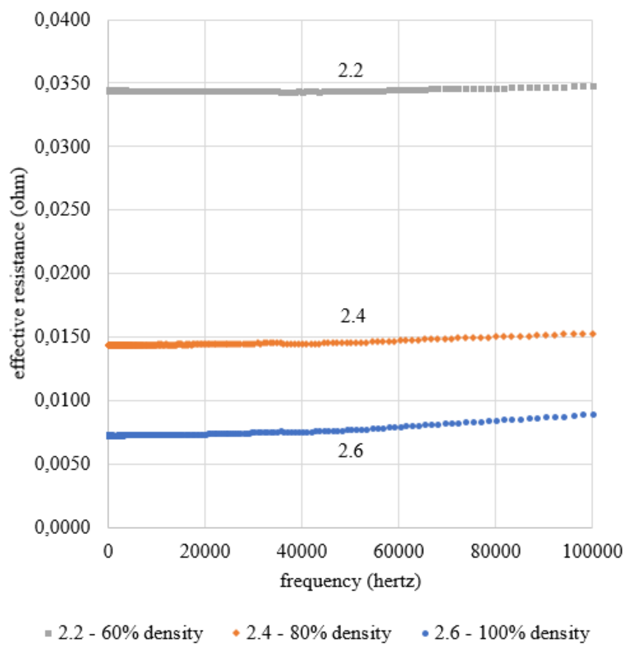

Fig. 7. Variation of print density. CuNi2CiCr, 2x2mm. Probe length 250mm.

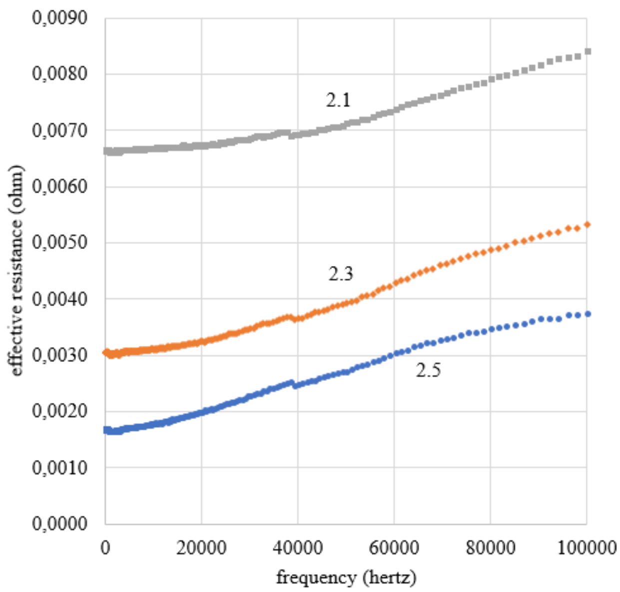

Fig. 8. Variation of print density. CuNi2CiCr, 4x4mm. Probe length 250mm.

C. Variation of the print density

The print density was varied in such a way that the width of the print paths was changed. This was only possible on the machine that processes CuNi2SiCr. Although the non-melted copper cannot be removed from the melted areas at the end of the printing process, the contact resistance is considered to be significantly greater than the electrical resistance, which means that current conduction can only be expected in the melted areas.

As can be seen in Fig. 7 and 8, the effective resistance increases as the print density decreases. This is reflected in an offset between the curves. It seems that the offset of the curve of the 60% sample decreases slightly towards higher frequencies, both for the 2x2mm cross-section (Fig. 7) and for 4x4mm (Fig. 8), which could indicate a slightly positive influence on the skin effect. However, the negative effect due to the density reduction, which can also be derived from theory, far outweighs this

$$R = \rho \frac{l}{A}$$

Width the specific resistance ρ being only temperature dependent, it becomes clear, that the reduced cross section area has a strong negative impact on the resistance. For the samples with 2x2mm cross-section, a significantly lower frequency dependence of the effective resistance can be observed. This is to be expected, as the penetration depth is significantly greater in relation to the conductor cross-section due to the skin effect.

D. Investigation of conductors consisting of sub-profiles

As listed in Table 1, several conductors consisting of twisted sub-profiles have been examined. Compared to the printed full profile, most profiles behave significantly worse, with the exception of the 2- and 4-part geometry with a gap of 0.1mm (Fig. 9). These initially show a slightly increased resistance below approx. 37 kHz, but above this frequency the resistance becomes increasingly lower than that of the solid cross-section. Apparently, despite the small gap size, the

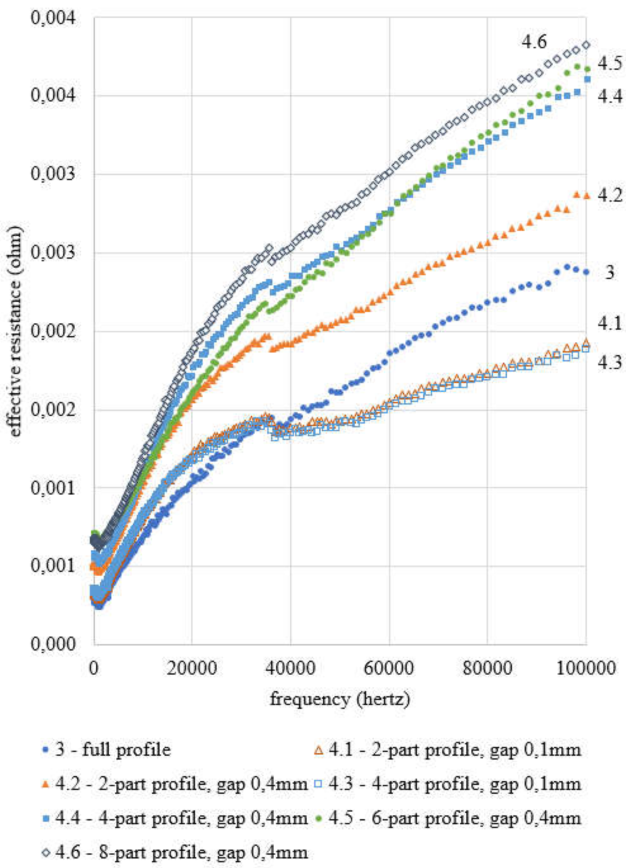

Fig. 9. Comparison of the sub-profile conductors, CuCP, 4x4mm. Probe length 250mm.

contact resistance is large enough that the sub-profiles behave like separate strands, while the reduction in cross-sectional area due to the small gap size does not have an overly negative effect on the resistance. For printed high-frequency conductors, the printing of a "litz wire geometry" consisting of several twisted sub-profiles thus appears to be a possibility worth to be further investigated.

V. APPLICATION POSSIBILITIES

As it turns out, the imaginable positive effect on the skin effect due to the partly melted lattice structure of the printed material does not appear for additively manufactured electrical conductors. The increase of the electrical resistance due to the lower density of the printed material outweighs by far. Up to about 10 kHz, however, the deviation is less than 10%. Since the geometry of the conductors can be designed more freely through the additive manufacturing process (avoidance of bending radius, compare in particular with hairpin winding technology), it is possible to compensate for the slightly increased resistance. The company "Additive Drives" [12], for example, states that the winding head discharge can be halved. If the length of the conductor can thus be shortened by more than 10%, the poorer electrical conductivity would be overcompensated. However, it is hardly possible to make general statements on this, as it depends on machine design, winding concept, ratio of winding head to iron length, etc.

Because the costs are difficult to quantify, it is not possible to make a general assessment of possible cost advantages. For single pieces or small series, an advantage is certainly conceivable, as there is no need for additional tools or devices. For demonstrator/prototype construction, additive manufacturing could be used profitably. The winding could be produced with significantly less effort and since the "offset" in conductivity to a conventional winding is known, the results can be extrapolated accordingly.

In addition, the properties of additive manufacturing open up possibilities in the manufacturing process that are otherwise only known from large electric machines. For example, roebel bars can be manufactured on a small scale in order to minimize the properties of the grooved staircase field. A significantly higher copper fill factor could be achieved than with twisted stranded conductors, which could more than compensate for the disadvantages of the printed material.

Finally, as shown in [3], post-printing heat-treatment can lower the resistivity significantly and can be considered when additive manufactured parts are applied as electric conductors.

VI. REFERENCES

[1] T. Q. Tran, A. Chinnappan, J. K. Y. Lee, N. H. Loc, L. T. Tran, G. Wang, V. V. Kumar, W. A. D. M. Jayathilaka, D. Ji, M. Doddamani, and S. Ramakrishna. "3D Printing of Highly Pure Copper", Metals, vol. 9(7), 756, July 2019.

[2] M. A. Lodes; R. Guschlbauer; C. Körner, "Process development for the manufacturing of 99.94% pure copper via selective electron beam melting", Materials Letter, vol. 143, pp. 298–301, Elsevier Science, 2015.

[3] C. Silbernagel, L Gargalis, I. Ashcroft, R. Hague, M. Galea, P. Dickens, "Electrical resistivity of pure copper processed by medium-powered laser powder bed fusion additive manufacturing for use in electromagnetic applications", Additive Manufacturing, vol. 29, October 2019.

[4] C. Silbernagel, I. Ashcroft, P. Dickens, M. Galea, „Electrical resistivity of additively manufactured AlSi10Mg for use in electric motors", Additive Manufacturing, vol. 21, pp. 395-403, May 2018.

[5] J. Rudolph, F. Lorenz, R. Werner, „3D-Multimaterialdruck für die Fertigung von Komponenten elektromagnetischer Energiewandler", *Freiberger Kolloquium Elektrische Antriebstechnik. Freiberg,* 2017, pp. 46-56.

[6] R. Wrobel and B. Mecrow, "Additive Manufacturing in Construction of Electrical Machines – A Review," *2019 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, 2019, pp. 15-22, doi: 10.1109/WEMDCD.2019.8887765

[7] R. Wrobel and B. Mecrow, "A Comprehensive Review of Additive Manufacturing in Construction of Electrical Machines," in *IEEE Transactions on Energy Conversion*, vol. 35, no. 2, pp. 1054-1064, June 2020, doi: 10.1109/TEC.2020.2964942

[8] N. Simpson and P. H. Mellor, "Additive Manufacturing of Shaped Profile Windings for Minimal AC Loss in Electrical Machines," *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018, pp. 5765-5772, doi: 10.1109/ECCE.2018.8557999

[9] F. Wu and A. M. El-Refaie, "Towards Fully Additively-Manufactured Permanent Magnet Synchronous Machines: Opportunities and Challenges," *2019 IEEE International Electric Machines & Drives Conference (IEMDC)*, 2019, pp. 2225-2232, doi: 10.1109/IEMDC.2019.8785210

[10] R. Wrobel and N. Chiodetto, "A Comparative Study of Additively Manufactured Low-Power-Loss Windings for PM Machines," *The 10th International Conference on Power Electronics, Machines and Drives (PEMD 2020)*, 2020, pp. 700-705, doi: 10.1049/icp.2021.1048

[11] F. Lorenz, J. Rudolph, R. Werner, "Design of 3D printed High Performance Windings for Switched Reluctance Machines", *International Conference on Electrical Machines (ICEM)*, 2451 – 2457, 2018

[12] Additive Drives GmbH, *Additive Drives*. Accessed: 2022-04-22. [Online]. Available: https://www.additive-drives.de/