Munagala, S. P., Pang, Y., Dalton, C., & Simpson, N. (2024). Investigation of Post Processing and Robust Insulation of High-Performance Additively Manufactured Al-Fe-Zr Electrical Machine Windings. In *2024 IEEE Electrical Insulation Conference (EIC)* (pp. 361-365). (Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/EIC58847.2024.10579332

Investigation of Post Processing and Robust Insulation of High-Performance Additively Manufactured Al-Fe-Zr Electrical Machine Windings

Priya Munagala
Electrical Energy Management Group
University of Bristol
Bristol, UK
priya.munagala@bristol.ac.uk

Yongxin Pang
School of Computing, Engineering and Digital Technologies
Teesside University
Middlesborough, UK
y.pang@tees.ac.uk

Chris Dalton
The Manufacturing Technology Centre
Coventry, UK
Chris.Dalton@the-mtc.org

Nick Simpson
Electrical Energy Management Group
University of Bristol
Bristol, UK
nick.simpson@bristol.ac.uk

Abstract—**Metal Additive Manufacturing (AM), in which feedstock is selectively bonded in a succession of 2D layers to incrementally form a 3D part, offers unparalleled design freedom in realising high-performance windings for electrical machines. AM allows unconventional combinations of conductor profiles and topology, intended to minimise frequency dependent losses, and enables embedding of thermal management features such as fluid cooling channels. The resulting conductors are inherently produced in the *wound* state allowing use of novel electrical insulation formulations that can exhibit superior thermal performance (> 200 ºC) and dielectric strength at the cost of reduced mechanical properties. The resulting *as-built* windings are often heat treated to improve both electrical conductivity and mechanical properties and typically exhibit a level of surface roughness that requires post-processing to facilitate insulation coating. This study focuses on a commercial aluminium alloy (Al-Fe-Zr), for mass-critical applications such as aerospace, paired with a commercially available dielectric resin. The type and extent of surface post-processing in terms of heat treatment and surface polishing required to achieve robust high-voltage insulation coating of AM windings is explored. Firstly, batches of AM windings are produced, subject to varying heat treatment and then characterised in terms of electrical conductivity, surface roughness, and light microscopy. Results obtained elucidate the evolution of the microstructure with heat treatment and its influence on the electrical conductivity. The second part of the study involves applying an insulation coating on the windings. Preliminary studies have identified surface roughness as a parameter that impacts the homogeneity of the insulation coating thickness. The samples are subject to varying levels of electrochemical polishing to reduce the surface roughness. The prepared samples are coated with resin in a controlled process and the resulting layer inspected for thickness and homogeneity. Finally, breakdown voltages of the coatings are established. The dataset is used to establish the post-processing requirements for robust electrical insulation coatings on AM parts and underpins future steps in applying novel, high-performance coatings that are ideally suited to the pre-formed winding geometry arising from AM.**

Keywords— *Electrical insulation, heat treatment post processing, additive manufacturing, windings, dielectrics, electrical machines, surface polishing*

I. INTRODUCTION

Transportation has been identified as one of the major factors contributing to carbon emissions (24% of the total emissions) after agriculture [1]. With the increase in the urgency to reduce these carbon emissions, research effort is directed to improving the current state of electrical machines for transport electrification, with a major focus on power density. A number of studies have demonstrated the potential of metal AM in reducing AC loss and improving thermal management of electrical windings [2-4], which directly contributes to enhanced power density. However, a significant challenge, and barrier to adoption, is the application of robust electrical insulation coatings to meet ever increasing voltage and temperature ratings.

This study focuses on aluminium alloy (Al-Fe-Zr) windings intended for future lightweight electrical machines; owing to its comparatively low mass density and AM processability, achieving more than 98% density via Laser based Powder Bed Fusion (LPBF) [2]. Electrical conductivity measurements show 55 International Annealed Copper Standard (IACS)% post heat treatment for rectangular concentrated windings, Fig. 1. Prior to use, the windings must be subjected to electrical insulation Lack of repeatability, particularly surface morphology, and the present need for build supports are limitations of the AM process, which ultimately results in the need for post processing to make the part suitable for the end application. Post processing includes various operations such as heat treatment (HT), surface finish, among others. Heat treatment of the parts has been proven to increase the electrical conductivity. However, the surface finish remains a challenge for applying a coating of electrical insulation for AM components, [3]. Therefore, this paper explores the extent of the post processing required to apply a robust electrical insulation coating on concentrated aluminium alloy AM windings intended to improve the power density of electric machines. Two main operations have been selected for this study, namely, heat treatment and surface finishing via electrochemical means. The main emphasis of this study is on the effect of heat treatment on the electrical conductivity and the surface profile of the components which in turn affect the application of robust electrical insulation coatings. Practical aspects of the coating process are also discussed to improve the process and to suggest modifications in the geometric design of the component for a better coating performance.

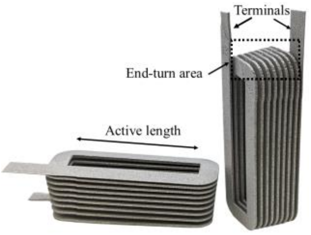

Fig. 1 Rectangular concentrated Al alloy windings used in this study

II. EXPERIMENTAL

A. Materials and Equipment

The Al-Fe-Zr rectangular windings were produced on an EOS M 290, Fig. 1. The raw powder was procured from Constellium, France under the trade name of Aheadd® CP1 alloy. Loctite 7840 from Henkel was used as a degreaser. The contents for the electropolishing were procured from Sigma Aldrich/Merck, UK. A phenolic based polyester resin under the trade name of Hi Therm® BC 325 was procured from PAR insulation, UK. The surface profilometry was conducted using Alicona from Bruker, Germany. The equipment HVC 360 SA from DSE Test Solutions, Germany was used to test the quality of the coatings for weak spots and pin hole detection. The breakdown voltage of the insulation was measured using Megger MIT2500 (DC supply) from Megger Ltd., UK. The Euromex bScope® was used for the optical analysis. Scanning electron microscopic images were taken on TM3030Plus tabletop microscope. Insulation coating measurements were made using an Isoscope® DMP 30 with probe, FTA 2.4 MC, from Helmut Fisher, Germany. A low-ohmmeter, RM 805 from RS Components, UK was used to measure the resistance of the windings.

B. Experimental Methodology

Two different batches of AM Al windings were received which differed in the post heat treatment cycles. One set of windings were heat treated at 500 ^{o}C for 4h (referred to as HT1 from hereon) and the other set was subjected to an additional 4h at 400 ^{o}C (referred to as HT2 from hereon). Both the HT cycles were based on the recommendations of the powder manufacturer. Preliminary characterisation was conducted via microscopic analysis, electrical resistance, and surface roughness measurement on these samples.

Besides HT, both sets of windings were subjected to two different levels of Electrochemical Polishing (EP). The windings were carefully cleaned using a degreaser, followed by non-etchant cleaning and subsequent EP. The levels of EP were determined based on the duration with a continuous monitoring of the surfaces using an optical microscope for surface changes. Care was taken not to pit the sample, hence durations of 15 and 45 min. were considered as the two levels of roughness reduction, as informed by preliminary testing. Surface profilometry was undertaken on the end windings before and after the electropolishing and the results were quantified in terms of S_a (average height of an area, µm). The process then concluded with manual dip coating of the windings. The windings were initially preheated to 110 ^{o}C and cooled to 60 ^{o}C before the first dip and then were subjected to a further fourteen coats and cured in the oven at 165 ^{o}C. Subsequently, the insulation coating was tested for overall and localised high voltage breakdown testing to assess the quality of the insulation. The coating thickness was assessed at different points of the windings using a film thickness gauge.

III. RESULTS

A. Effect of the heat treatment

The final components manufactured via LPBF AM route often lack homogeneity in the microstructure [4]. This happens since the individual metal particles experience different heating and cooling profiles. Thus, HT has become an indispensable post processing operation to achieve uniform microstructure along with improved electrical and mechanical properties. Here, the effect of HT was evident as an improved electrical conductivity was measured when compared to the *as built* windings. The HT1 and HT2 windings recorded a resistance of 6.8 mΩ and 6.7 mΩ across the path length, whereas a resistance of 10.4 mΩ was recorded for the *as built* winding.

Besides its electrical conductivity, one of the major reasons for selecting Al-Fe-Zr alloy for this application is due to its precipitation strengthening due to Zr – a quality that is lacking in conventional Al alloys. Zr is known to increase the tensile strength of the alloy as it ages during the HT cycles [2]. These precipitates can be seen in the microstructures of the HT1 samples (Fig 2a). Some of the precipitates can also be Fe rich areas that indicate the presence of dislocations. Although not much of a change was measured in the HT2 sample in terms of electrical resistance, the microstructures revealed enlarged precipitates indicating aging of the alloy, Fig. 2b. These are especially responsible for the heterogenous nucleation of Al aiding to denser and homogenous alloys [5]. Studies are being conducted to confirm the exact compositions of these precipitates. The microstructures also reveal the presence of internal porosity and the layering of the alloy, as expected from an AM process.

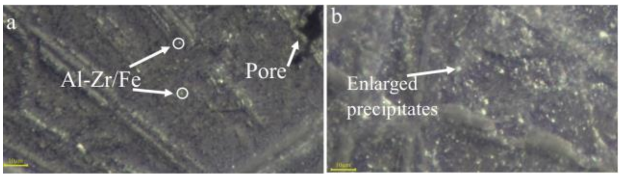

Fig. 2 Microstructure of a. HT1 windings exhibiting the Zr/Fe rich areas responsible for strengthening, b. enlarged precipitates due to aging in HT2

B. Surface profilometry before and after EP

The AM process being a bottom-up approach of manufacturing - meaning the entire component is fabricated building up on powder layers, makes the presence of surface pores and roughness evident. Post HT processing improves these unwanted defects to a certain extent; however, it fails to make the surface relatively flat for the application of electrical insulation coatings. Hence, EP was selected to reduce the overall surface roughness of the windings by reducing the peaks on the surfaces. The HT1 windings exhibited a S_a of 25 µm whereas the HT2 windings exhibited a slightly reduced value of 18 µm. The positive effect of HT becomes evident compared to the baseline *as-built* winding which showed S_a of 33 µm and a higher electrical resistance. The initial cycle of cleaning and EP for 15 min. was performed on both sets of windings. Although the HT2 sample showed a marginal reduction in S_a 17 µm, (-1 µm), a significant decrease was measured in the HT1 sample, S_a 16 µm, (-9 µm). This change in S_a was evident in the 3D image of the surface (Figs. 3 and 4). An additional EP cycle was conducted for 30 min. (total of 45 min.) which resulted in S_a of 14 µm in both samples. From the surface profiles in Figs. 3 and 4, the layers of the powder and the successive layers beneath can be seen. Although the peaks can be smoothened out to a large extent, getting an absolute flat surface can be challenging in the case of AM components as subsequent layers are revealed. The decrease of the average roughness values of an area can be seen clearly in Fig. 3 and 4.

C. Insulation coating

Liquid dip coating is a common and simple dipping process [6]. Manual dip coating was applied to the windings in this study. The process consisted of initial preheating of the substrate followed by dipping it for a set time in the resin and the withdrawing the winding at a relatively constant speed. This process is considered as a versatile and robust processes for complex geometries. Previous research studies have established that the main factors dictating a good coating are the drag force among the molecules along with gravitational and viscous forces, [7]. The dielectric resin chosen for this study is a phenolic based polyester resin included in Underwriters Laboratory Inc. Electrical Insulation Systems up to 180°C, [8]. This resin has a solids content of 52% with the reminder of it as a mixture of solvents, facilitating excellent dip coating conditions with a short cure time. Fig. 5 shows the resulting dip coated windings.

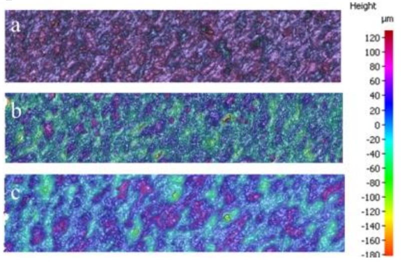

Fig. 3 Avg. surface roughness contours of a) HT1 sample as received, b) HT1 winding after 15 min. EP, c) HT1 winding after 45 min. EP

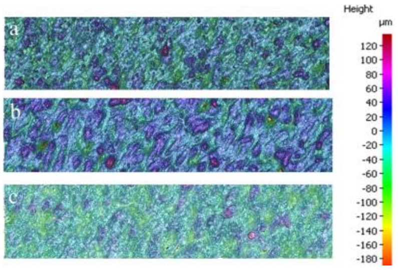

Fig. 4 Avg. surface roughness contours of a) Extra. HT sample as received, b) Extra. HT winding after 15 min. EP, c) HT2 winding after 45 min. EP

TABLE I SUMMARY OF THE RESULTS OF THE FILM THICKNESS MEASUREMENTS

Sample	**Avg. thickness, µm**	**Min. thickness, µm**
HT1, 15 min. EP	120	5
HT1 45 min. EP	162	100
HT2, 15 min. EP	120	17
HT2, 45 min. EP	74	11

Past studies have identified sharpness geometry along the edges/ thin sections of the winding to pose a challenge for dip coating leading to inhomogeneous or inadequate coverage [3]. Hence, with the complexity of the geometry of the windings in the present study and the presence of thin sections (edges of the windings), an attempt was made to mitigate this challenge by securing one of the windings (HT1, 45 min. EP) on a fixture clamp in a splayed condition; whereas the other windings were coated and suspended in a vertical direction during the entire coating operation. The fixture clamp was a rectangular block whose orientation could be changed to help distribute the resin evenly instead of dripping in one single suspended direction during the drying and curing processes. This fact was evident from the thickness measurements performed at different points on the external faces of the windings. A minimum of ten points along a gradual path from the top (terminals) to the bottom of the windings were considered. Table 1 summarises the average and the minimum thicknesses obtained from the measurements. Although the process requires improvisation in the dipping technique, the sample (HT1, 45 min.) secured on the clamp displayed a mean thickness of 162 µm with a min. reading of 100 µm. Although the sample of HT2, 45 min. exhibited the same roughness levels as HT1, 45 min. sample, the average thickness was 74 µm (reduction of 54%) with a mere 11 µm min. thickness. This comparison and the further breakdown voltage results emphasise the role of the multi-orientation clamp in achieving a consistent coating thickness and minimising drips. Although the samples of 15 min. EP jointly had an average coating thickness of 120 µm, the minimal thicknesses were far from desired levels. A general trend of increase in the thickness values was observed from the top to the bottom in the windings that were dried and cured in the suspended vertical direction, consistent with effects of gravity on the coating. These windings consistently recorded minimal coating thickness values at the top – sometimes leading to exposed regions resulting in low breakdown voltage. As expected, the thickness values were the highest at the bottom of the samples – leading to accumulated drips as shown in Fig. 5a. This not only resulted in the inconsistency of the coating, but also compromised the dimensional tolerances of the entire windings. Additionally, the edges of these samples were observed as almost bare in some areas since there was a lack of surface tension among the molecules of the resin to rest on. These results were further complemented by the results of the overall and localised breakdown voltage measurements of the insulation.

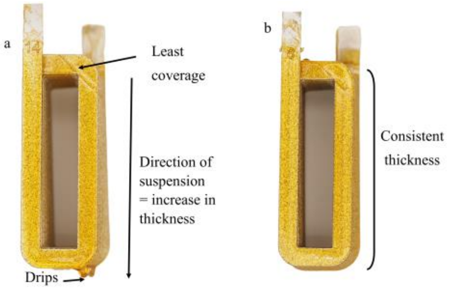

Fig. 5 End product of the dip coated windings a. vertically suspended (HT2, 45 min..), b.- using the clamp fixture (HT1, 45 min. EP)

Voltage breakdown testing for weak spots on the resin was conducted at 9µA threshold current for all the measurements (DC). The initial voltage setting began at 750 V and was slowly incremented to 1 kV, 1.5 kV, 2 kV and finally 3 kV. The machine detected the weak spots in the insulations by detecting the flow of current. On closer inspection of those areas, thin layers of coating/ bare metal/sharp protruding edges were observed which confirmed the inadequate coverage of the insulation resin. These observations were in line with the thickness measurements. Both the tests were conducted at various points and in areas (both internal and external) to have a thorough analyses of the distribution and quality of the insulation. A summary of the results of the overall and localized breakdown voltages are presented in Table II. The experimental set up is shown in fig. 6.

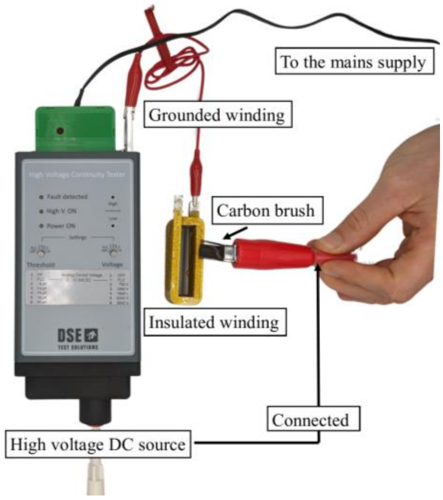

Fig. 6 The experimental testing set up for the insulated windings for the continuity testing

TABLE II SUMMARY OF THE RESULTS OF THE CONTINUITY TESTING AND THE BREAKDOWN VOLTAGE TESTING

Sample	**Continuity testing flaw detection, V/Breakdown voltage, V**	
	Face of the windings	*Edge of the windings*
HT1, 15 min. EP	1000/ <1000	750/50
HT1 45 min. EP	3000/<2500	750/500
HT2, 15 min. EP	1000/<1000	750/50
HT2, 45 min. EP	1000/<1000	750/50

From the results summarised in Table 2, it is evident that fourteen coats of resin insulation coating exhibited better coverage on the wider surfaces of the windings when compared to the edges. However, looking at the windings of lower duration of EP, these exhibited weak spots at <1 kV. This can be seen in both the sets of windings with the flaws being optically visible. Additionally, the edges of the windings exhibited significantly lower breakdown voltages (50 V). In this case, the bare metallic edges were visible which indicates the absence of the coating. In the case of the windings of longer durations of EP, weak spots were detected at much higher voltages (3 kV) on the surfaces of the windings and at 500 V (10x improvement) along the edges indicating better coating and the efficacy of the dip coating fixture clamp.

IV. CONCLUSIONS

In this paper, an attempt has been made to explore the extent of the post processing required to apply robust functioning electrical insulation coatings to AM windings. The main post processing operations were heat treatment and surface finishing via electrochemical polishing. Firstly, concentrated rectangular windings were manufactured via LPBF AM using Al-Fe-Zr alloy. These windings were heat treated in two different cycles resulting in the improvement of electrical conductivity and different surface finishes. The HT1 (500 °C, 4h) reduced the electrical resistance to 6.8 mΩ from 10.4 mΩ and the S_a to 25 µm from 33 µm when compared to an *as-built* winding. An additional HT cycle – HT2 (400 °C, 4h) further reduced the S_a to 18 µm and the electrical resistance to 6.7 mΩ. Although these results prove the positive effects of HT, the surfaces needed further post processing for the application of insulation coating. Electropolishing was deemed effective in reducing the overall surface roughness of the windings even further with time. S_a values of 16 and 17 µm were recorded on the HT1 and HT2 windings when the EP was conducted for 15 min. These values were further decreased to 14 µm in both the cases when the EP was done for 45 min. This demonstrated the limitation of EP for preparing an absolute flat surface given the working principle of EP and the layers in AM.

These windings were then manually dip coated using a phenolic based polyester resin and tested for their insulation quality via voltage breakdown measurement. Multiple coating cycles helped to reduce the flow of the resin during the process. The use of a custom fixture clamp proved to be beneficial in improving the mass flow of resin along the edges and the coating homogeneity in general. This fact was proven during the high voltage breakdown testing where the edges exhibited 10 times more voltage withstand compared to other windings that were suspended in a single orientation throughout the operation.

Insulation coating thickness measurements were made, with the most promising result recorded on the HT1 sample, 45 min. among the others. This sample exhibited an average coating thickness of 162 µm with a minimal thickness of 100 µm. This can be attributed to the reduction in the surface roughness along with the use of the multi-orientation fixture clamp used during the dipping process. The windings that were vertically suspended during the dipping process had higher inconsistency and lower coating thickness values. The windings subjected to shorter EP duration exhibited slightly less voltage bearing capacities, both on the face of the windings and along the edges compared to the longer EP samples. This can be attributed to the fact that the reduction in the surface roughness was not sufficient for a good performance of the insulation coating. The HT2 process did not significantly contribute to the increase in electrical conductivity nor to the coating process. Therefore, from the current study, it can be concluded that a HT1 cycle along with a 45min. EP is appropriate for robust coating applications. Further research is being carried out to improve the coating set up to ensure the homogeneity of the film across complex geometries. Additionally, the insulation coating is expected to have better performance in the absence of sharp edges/thin sections – something that can be incorporated as design rules during the design stage of the AM component geometry.

ACKNOWLEDGMENT

This work was supported by a UKRI Future Leaders Fellowship [grant number: MR/V024906/1]. The authors are grateful to the team at Manufacturing Technology Centre, Coventry, UK for manufacturing and supplying the samples, facilitating this research to be conducted.

REFERENCES

[1] H. Ritchie, “Cars, planes, trains: where do CO2 emissions from transport come from?,” *Our World Data*, 2020, [Online]. Available: https://ourworldindata.org/co2-emissions-from-transport#article-

citation.

[2] C. Pauzon, M. Buttard, A. Després, B. Chehab, J. J. Blandin, and G. Martin, "A novel laser powder bed fusion Al-Fe-Zr alloy for superior strength-conductivity trade-off," *Scr. Mater.*, vol. 219, 2022, doi: 10.1016/j.scriptamat.2022.114878.

[3] S. P. Munagala, Y. Pang, S. Hodgson, and N. Simpson, "A Study on the Parameters Influencing Insulation Coating on Copper Based Electrical Windings Fabricated via Additive Manufacturing," *INSUCON 2023 - Proc. 14th INSUCON Int. Electr. Insul. Conf.*, pp. 134–139, 2023.

[4] Y. Kok *et al.*, "Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review," *Mater. Des.*, vol. 139, pp. 565–586, 2018, doi: 10.1016/j.matdes.2017.11.021.

[5] P. H. L. Souza, J. M. Do Vale Quaresma, and C. A. Silva De Oliveira, "Precipitation evolution and modeling of growth kinetics of L12-structured Al3Zr particles in Al-0.22Zr and Al-0.32Zr (wt.%) alloys isothermally aged," *Mater. Res.*, vol. 20, no. 6, pp. 1600–1613, 2017, doi: 10.1590/1980-5373-MR-2017-0481.

[6] L. E. Scriven, "Physics and Applications of DIP Coating and Spin Coating," *MRS Proc.*, vol. 121, p. 717, 1988, doi: 10.1557/PROC-121-717.

[7] S. Munagala, Y. Pang, S. Hodgson, and N. Simpson, "Fabrication of insulation coatings on additively manufactured CuCrZr electrical windings," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 31, no. 1, pp. 505–512, 2023, doi: 10.1109/TDEI.2023.3324285.

[8] P.A.R Insulations, "Hi Therm BC 325." https://www.par.uk.com/files/1401 Hi-Therm BC-325.pdf.