

Additive manufacturing of ferromagnetic parts for electrical machines

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Acknowledgments

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May, 2024

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Lukas Lammens

May, 2024

Preface

This paper is the last step of obtaining my engineering degree. The education was a long process where I was able to meet passionate people that would share their knowledge. Lectures full information explained fundamental principles and tried to shine light upon new concepts that will shape the future. I hope to keep meeting passionate people, and never stop learning.

I want to thank my friends and family who supported me during this time, especially my parents that made it possible for me to obtain this degree.

The past few years have been a long adventure full challenges, sometimes stumbling from course to course without thinking beyond the end of the academic year. Completing this thesis feels like the next milestone. Looking back on al the hidden stray paths that kept me from reaching the end, knowing that it is only the start of a new adventure.

Lukas Lammens

May, 2024

Abstract

This paper investigates the possibility of crystallographic alignment during additive manufacturing. Electrical machines make use of grain-oriented or non-grain oriented electrical steels depending on the application. The crystallographic orientation of the steel is important to reduce the energy losses, and thus consumption of the machine. Additive manufacturing has the potential to create new designs with high geometric complexity, but there is no possibility to control the crystal alignment of the deposited materials during the additive manufacturing process. This paper explores the use of Fe6.5Si particles, which are put under magnetic saturation, by pre-magnetizing them in a custom made magnetic circuit. The remanence of the particles will create a magnetic moment, which will try to align the particles when under the influence of a magnetic field during extrusion. This enables additive manufacturing of high-density Fe6.5Si components for electrical machines with preferred crystal orientations. Tested samples show alignment with low intensity. This suggests that crystal rotation is possible during the 3D micro-extrusion process, but partially prevented by the high viscosity of the paste material.

Keywords

Additive manufacturing, 3D micro-extrusion, Fe6.5Si, magnetic circuit, highly-filled polymer, grain-oriented material, magnetic field-influenced extrusion.

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Keywords: Additive manufacturing, 3D micro-extrusion, Fe6.5Si, magnetic circuit, highly filled polymer, grain-oriented material, magnetic field-influenced extrusion.

I. INTRODUCTION

Electrical motors- driven systems (EMDS) consume between 43% to 46% of the global electricity production today, which was estimated to be around 25 500 TWh in 2022 [1]. For decades, the design of electro motors has been optimized to have the best possible efficiency. The importance of increasing the efficiency of the EMDS enable a significant reduction of CO₂ emissions.

A. Problem statement

To increase electric machine efficiency, iron losses must be minimized by reducing laminate thickness or electrical conductivity of the electrical steel. Adding 6.5% Si to steel reduces eddy current losses, but conventional processes cannot handle the brittleness of the alloy. Using grain-oriented (GO) materials can reduce the hysteresis loss of the electrical machine. During the micro-extrusion process there is no control over the crystallographic orientation of the material.

Additive manufacturing can create Fe6.5Si parts and can potentially be combined with a system to control the crystallographic orientations to increase the efficiency.

B. Basic principles magnetism

The relation of magnetic field strength H and flux density B is dependent on the crystallographic orientation of the material. The single crystal unit cell for iron is body centered cubic (BCC) and has an easy direction of magnetization in

the [100] direction. The difference between the other directions is presented in Figure I-1.

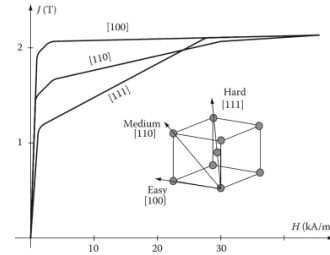


Figure I-1: Magnetization curves of single crystal of iron [2]

The importance of the crystal orientation is linked to the required field strength needed to magnetize the material. For electrical machines this results in energy losses when the material undergoes rotational magnetization. Figure I-2 shows the energy losses for each cycle when the crystallographic orientation is anisotropic in the rolling direction (RD) and the transverse direction (TD).

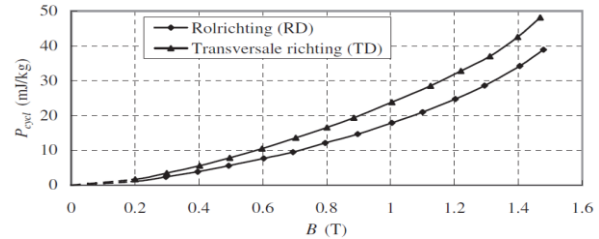


Figure I-2: Hysteresis loss per cycle for unidirectional magnetization [3].

C. State-of-the-art advancements in materials and fabrication techniques

1) Crystal alignment for soft robotics fabrication

Kim et al. investigated the possibility of particle alignment during Direct Ink Writing (DIW) for the creation of soft robotics [4]. By utilizing neodymium-iron-boron (NdFeB) particles within an elastomer matrix, a complex structure is 3D printed. The external magnetic field gives control over the particles by rotating them to align the polarity with the field.

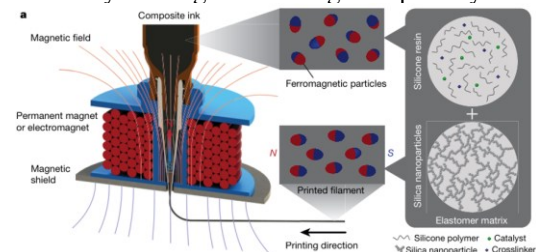


Figure I-3: Schematic of the printing process with alignment of the ferromagnetic particles in the composite ink [4].

The 3D printed structures are programmed with distinct ferromagnetic domains where the polarity of the particles is the same. When the structure is in the presence of a magnetic field, a torque is induced upon the domains. This results in macroscale movement of the structure as a response. Figure I-4. shows an example of a two-dimensional soft robotic structure that is simulated and tested.

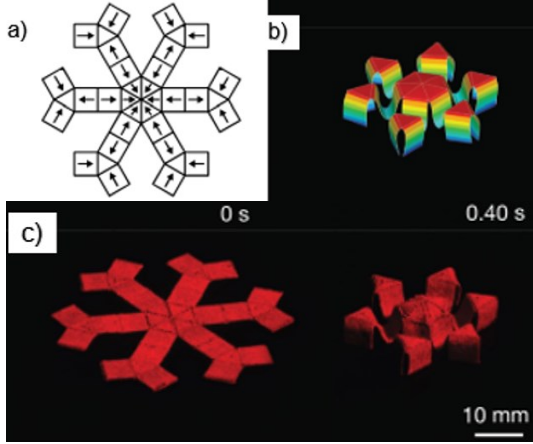


Figure I-4: Example of a 2D soft robotic structure: a) Schematic design of the domains; b) Simulation; c) Experimental results [4].

2) High-density copper components by paste-based 3D micro-extrusion

Koli et al. investigated the possibility of manufacturing high-density copper parts by using 3D micro-extrusion in combination with a composite paste material [5].

The powder loaded feedstock consists of copper particles and a hydroxypropyl cellulose (HPC) in 1-propanol and additives to form the binder solution. The composition is 95 wt% Cu particles and 5 wt% HPC binder. The paste is mixed in a speed mixer (Hauschild DAC1100) that is able to perform a degassing step in vacuum to lower entrapped air bubbles in the paste.

Post-processing is needed to debind the polymer matrix and to achieve a density of 98.8% of the theoretical density after sintering.

D. Problem approach

This paper will investigate the possibility of achieving crystal alignment during additive manufacturing of high-density ferromagnetic parts for electrical machines.

The problem is split into two sections: pre-magnetization of the single crystal Fe6.5Si powder and magnetic field-influenced 3D extrusion. The powder will be mixed in a HPC paste for extrusion and sintered to a dense part.

II. PRE-MAGNETIZATION OF FESI POWDER

A. Introduction and design requirements

The single crystal powder will be magnetized to above saturation of 1.5 T with a custom made magnetic circuit. By putting small amounts of powder in a capsule and in the circuit recess, the flux density is forced through the powder. The electromagnetic force of the circuit can be generated via either permanent magnets or via an electromagnet by applying a DC-current through a copper winding. The design is validated with Finite Element Method Magnetics (FEMM) before physically creating it.

B. Toroidal design

A first design is made by bending a low carbon steel rod into a toroidal shape. The first flux density measurements in the air gap of this design showed significant differences with the simulated FEMM model. The main reason for not reaching the expected values is saturation of the core material. The small cross-section of the rod in combination with poor magnetic material properties limit the achievable flux density in the air gap.

C. Rectangular design

The next rectangular design will incorporate the insights gained from the first design. The biggest changes are the increase in cross-sectional area and the addition of flux concentration. Fiorillo found that a tapered angle of the pole tips $\beta = 54.74^\circ$ is the best to obtain the best flux concentration [6]. Additionally, the core material will now consist out of non-grain oriented electrical steel laminates that have better magnetic properties than low carbon steels. The core has a uniform stack thickness of 20 mm. The final dimensions of the design are presented in Figure II-1.

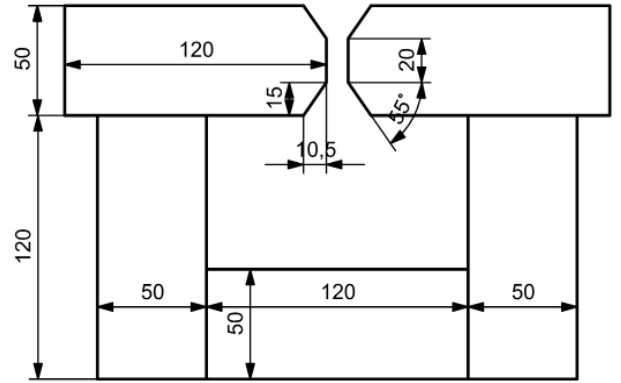


Figure II-1: Technical drawing of the rectangular core design with a thickness of 20 mm.

By using the formulas of Ampère's circuit law (1) and the magnetic reluctance (2), the needed current can be determined:

$$\oint_l \vec{H} \cdot d\vec{l} = N \cdot I \quad (1)$$

$$R = \frac{l}{\mu_0 \mu_r A} \quad (2)$$

$$R_{tot} = R_{core} + R_{gap} + R_{powder} + R_{sensor} = \frac{l_{core}}{\mu_0 \mu_{r,core} A_{core}} + \frac{l_{gap}}{\mu_0 A} + \frac{l_{powder}}{\mu_0 \mu_{r,powder} A} + \frac{l_{sensor}}{\mu_0 A_{gap}} \quad (3)$$

Because the permeability of the powder $\mu_{r,powder}$ is unknown, it is difficult to include in the calculation. The calculation is executed in the worst possible scenario, where the powder has no positive effect on the reluctance, and thus has a permeability equal to air, which is one. Modifying equation (3) becomes the following for an air gap of 6 mm:

$$R_{tot} = \frac{0.580m}{\mu_0 7493 \cdot 0.001m^2} + \frac{0.006m}{\mu_0 \cdot 4 \cdot 10^{-4}m^2} = 12 \cdot 10^6 H^{-1} \quad (4)$$

$$I = \frac{\Phi \cdot R_{tot}}{N} = \frac{B \cdot A_{gap} \cdot R_{tot}}{N} = \frac{1.5T \cdot 4 \cdot 10^{-4} m^2 \cdot 12 \cdot 10^6 H^{-1}}{200} = 35.99 A \quad (5)$$

From (5) the estimated current is found that is needed to provide the magnetomotive force to reach a flux density of 1.5T in the air gap, which is around 36 A in 200 windings.

The design is modeled in FEMM to get an estimation of the results. For a current of 36A the simulated flux density in the gap is 1.436T, which is an acceptable difference with wanted 1.5 T that was used in the calculations.

First measurements on the rectangular core do not reach the wanted flux densities of 1.5 T. This discrepancy is attributed to leakage flux in the circuit due to parasitic air gaps and the cutting edge effect. The FEMM simulation is not capable of calculating 3D effects of the air gap, so this could also add to the difference. To improve the flux density, additional coils are added to a total of 282 windings in the circuit. The physical end result of the rectangular core is presented in Figure II-2.

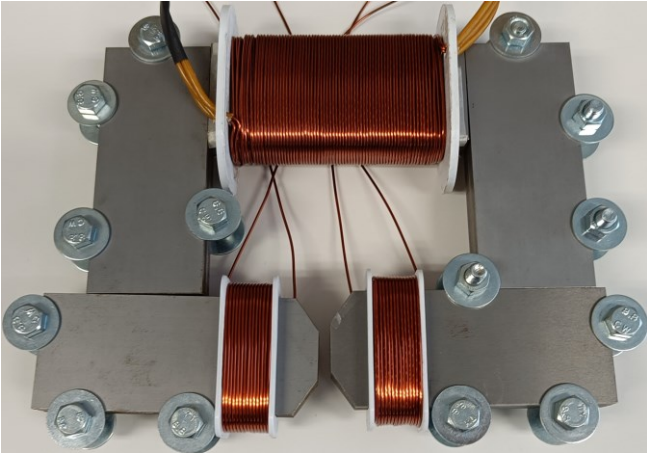


Figure II-2: Rectangular core design with additional windings at the bottom of the circuit.

The setup is tested for different currents and for different configurations. To make it possible to compare the results, the setup has an air gap of 6 mm thickness in all configurations, and when powder is added, this results in a 4 mm powder thickness. The configurations will be referred to as the following:

- Setting 1:** only air, main coil
- Setting 2:** powder-filled capsule, main coil
- Setting 3:** only air, additional coils
- Setting 4:** powder-filled capsule, additional coils

Figure II-3 shows the measured results for the different settings. The additional coils give a significant boost on the flux density. The saturation effect with additional coils is also reduced. For high currents, the measurements show deviations and inaccuracies. This is because the excitation of the coils can only be maintained for short periods of time, otherwise the coils would overheat and be destroyed. This is why the peak-function is used to measure the highest flux density peak, which results in a small inaccuracy.

For setting 4 it is possible to reach the wanted level of flux density of 1.566 T for a current of 55 A.

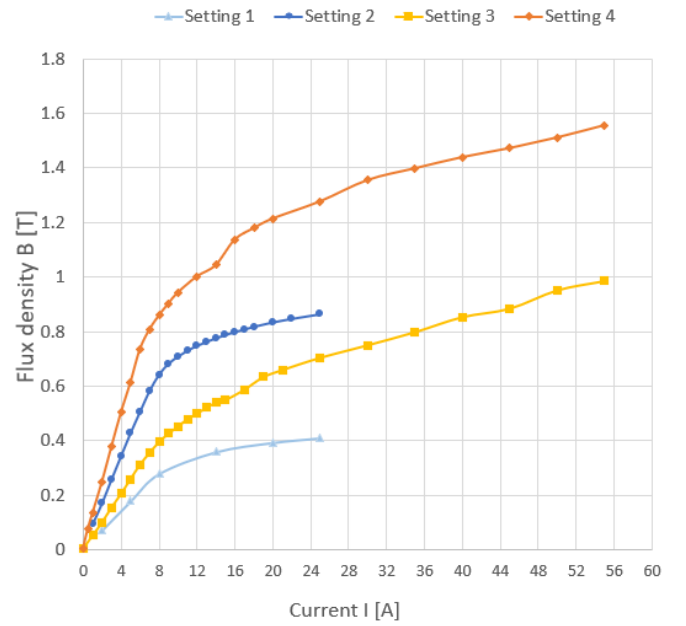


Figure II-3: Flux density measurements in the air gap of the rectangular core for different settings.

III. MAGNETIC FIELD-INFLUENCED 3D EXTRUSION

A. Introduction

This paper will use indirect extrusion-based additive manufacturing. The Fe6.5Si particles are combined with the HPC binder material to form a paste that can be extruded with a plunger-based system. This section will discuss different approaches of extruding the paste when under the influence of a magnetic field.

B. Manual extrusion

The first test uses the syringe nozzle to extrude 2 mm diameter fibres that have sufficient strength for later post-processing. The advantage is the simplified setup that can be operated by hand, without the need of controlled movement of a 3D printer. The powder for this paste is magnetized to 1.2 T.

A permanent magnet is used to provide the magnetic field around the nozzle. It was observed that the apparent viscosity of the paste material increased significantly and became impossible to extrude. This is due to the magneto-rheological behaviour of the highly loaded paste. More investigation is needed into this behaviour. As an alternative, a small electromagnet with 80 windings is designed to provide the magnetic field by a DC current. Figure III-1 shows the design.

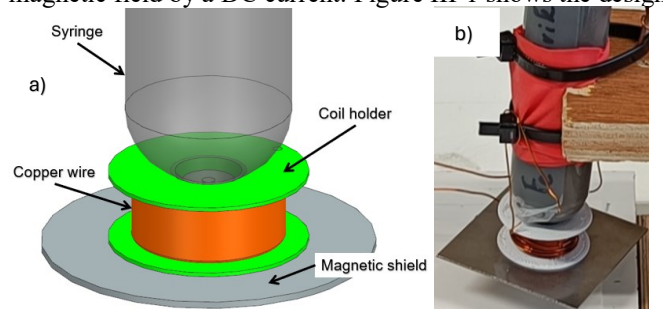


Figure III-1: a) CAD rendering of the electromagnet; b) Physical setup of the electromagnet.

The electromagnet allows dynamic control over the field strength that is simulated in FEMM.

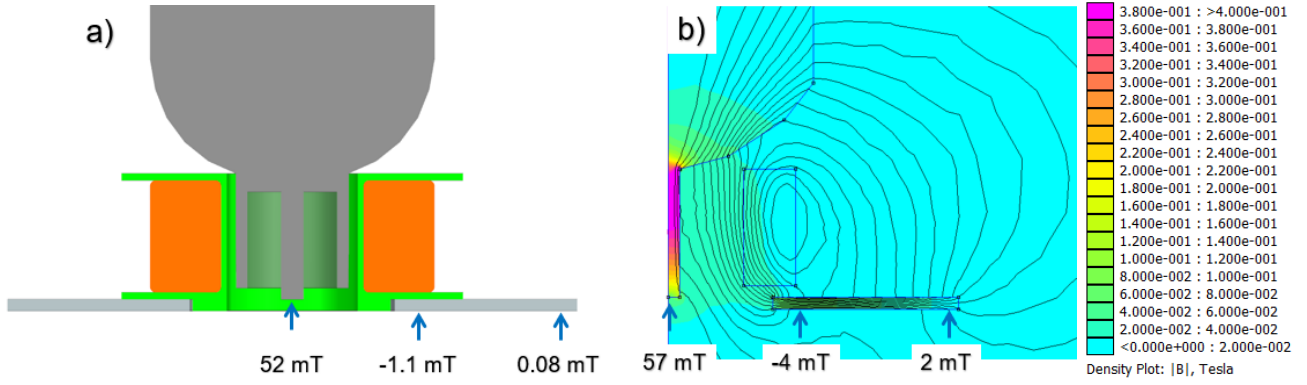


Figure III-2: Flux density points indicated by the arrows at the nozzle and at the magnetic shield for 5 A inside the coil: a) Physical measurements of the setup presented on the cross-section of the system; b) Axisymmetric simulation of the electromagnet with 5A for manual extrusion.

By using an axisymmetric simulation, it is possible to find an estimation for the flux density inside the nozzle tube. This is presented in Figure III-2 (b).

Figure III-2 compares the physical measurements to the simulation flux densities. Different currents are used to extrude the fibre samples, which sample 1 and sample 4V are extruded with 86mT and 354mT, respectively based on the simulation. The permeability of the paste is matched to $\mu_{\text{paste}}=15$ inside the simulation to match the physical measurements.

C. State-of-the-art extrusion at VITO

Manual extrusion has no control over the flow rate and accuracy of the deposited paste material. To accommodate for some of the limitations, a test is done at VITO on a high end 3D printer. For this test, a conical nozzle is used with an opening of 580 μm to increase the shear rate in the paste and achieve shear thinning effect. This will reduce the viscosity of the paste and lower the resistance for rotating the particle during extrusion. This paste is pre-magnetized to 1.6T.

To match the conditions of the magnetic field strength so the results can be compared, a similar electromagnet is designed to fit the new longer nozzle. The end result is presented in Figure III-3.

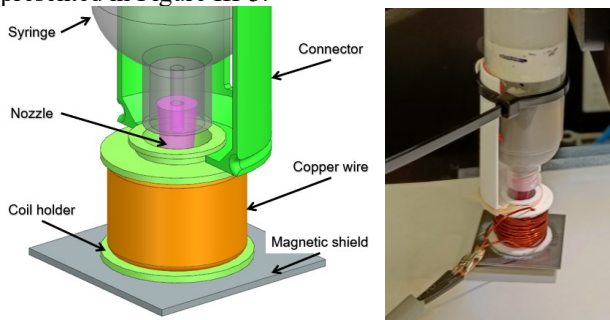


Figure III-3: CAD model and complete setup of the electromagnet for the extrusion at VITO.

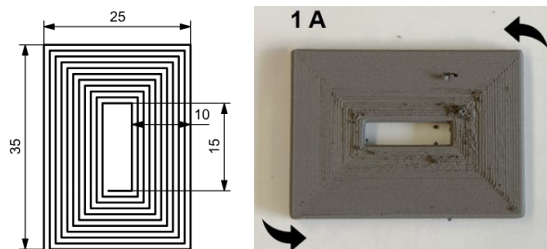


Figure III-4: Spiralled sample dimensions and end result for 1A.

Figure III-4 shows the spiralled printing strategy and dimensions 15x10x2.4 mm of the part. This is done so that continues flow is maintained during the extrusion process. The field strengths for 1A and 3A are extruded, and result in a flux density of 77 mT and 230 mT, respectively.

D. Post-processing of the green samples

After extrusion of the green samples, the polymer binder has to be removed. This is done by debinding the polymer during a heat treatment in an argon gas atmosphere, followed by a sintering step to achieve a high-density sample. The temperature progression of the heat treatment is presented in Figure III-5.

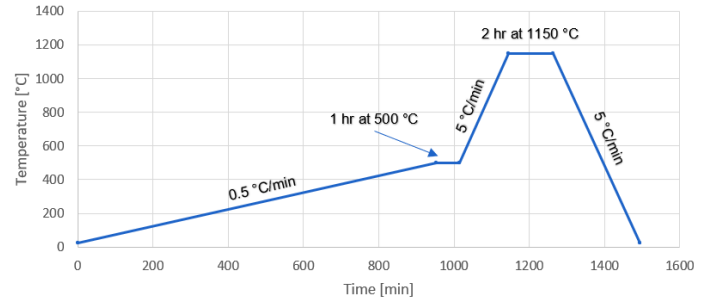


Figure III-5: Temperature progression of the post-processing step.

The fibre and spiralled samples are sintered and presented in Figure III-6.

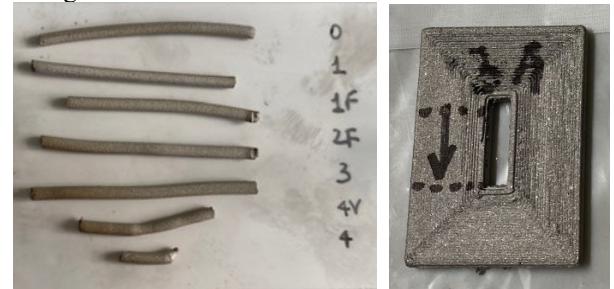


Figure III-6: Fibre and spiralled samples after sintering.

IV. RESULTS

The scanning electron microscope used for electron backscatter diffraction (EBSD) measurements is a Philips XL 30 FEG with a 1.4 megapixel resolution (1392 (H) x 1040 (L)), a data collection rate of up to 200 indexed patterns per second, and an EDAX-TSL Digiview V, with a 25 kV beam. The program TEAM: Texture & Elemental Analytical Microscopy is used for the data computation.

Analysing the samples with EBSD is a time consuming and labour intensive process because the samples require a high surface quality. This is the reason why not all sintered samples are analysed. The EBSD measurements is done for fibre sample 1 and 4V, and spiralled sample 3A.

A. Manual extruded fibre samples

The results of the fibres show no significant texture. The crystallographic orientation of the extrusion direction (ED) of the inverse pole figure is presented in Figure IV-1. If crystal alignment is achieved the results would show more colours close to the [001] direction.

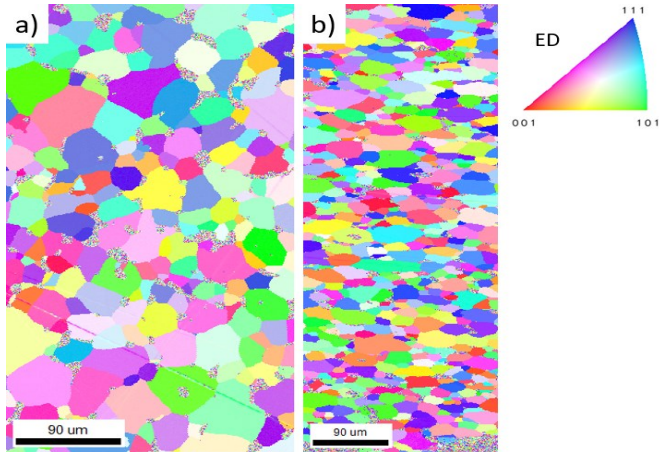


Figure IV-1: EBSD measurement of the fibres: a) sample 1; b) sample 4V.

The first EBSD measurements of the extruded material confirms the single crystal condition of the Fe_{6.5}Si powder.

B. Micro-extruded spiralled samples

The cross-section of the micro-extruded spiralled sample 3A is examined. Because the large surface area, multiple sections are measured by EBSD. This is to increase the data points to increase the statistical value of the measurement. The covered areas are represented on the polished sample surface in Figure IV-2.

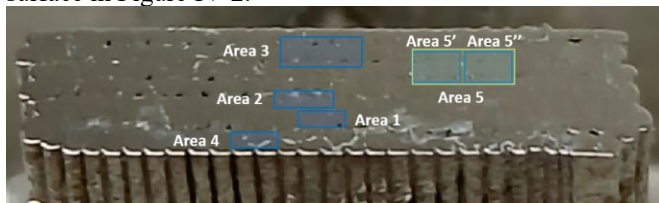


Figure IV-2: Cross-section of sample 3A with indicated locations of the examined areas.

Area 5' and 5'' are combined to a large area to increase the statistical significance of the measurements. Figure IV-3 gives the colour legend for the inverse pole figure that shows the crystal orientation of the grains inside the material.

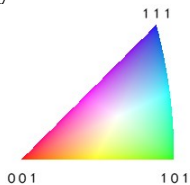


Figure IV-3: colour coded legend for the inverse pole figure for the extrusion direction.

Figure IV-4 presents the inverse pole figure for the ND, extrusion direction of the sample.

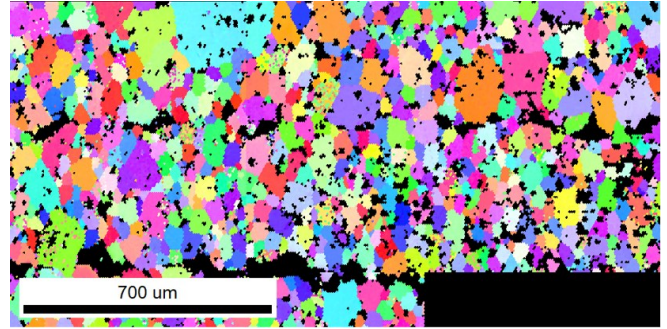


Figure IV-4: Inverse pole figure of ND, sample 3A, area 5, magnification 100x, step size 6 μm.

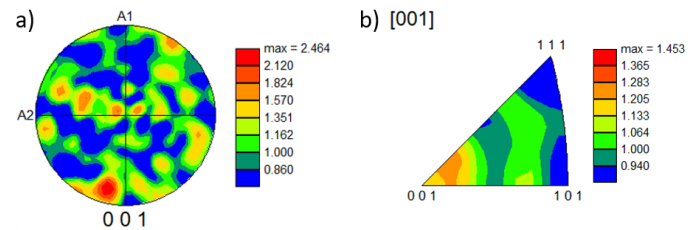


Figure IV-5: Sample 3A, area 5: a) pole figure; b) inverse pole figure.

The results of Figure IV-4 do not show a large amount of red [001] orientation, what is the wanted result. Figure IV-5 shows the intensity of the alignment of the extrusion direction of the sample. A small intensity is visible around the [001] direction, but it is insufficient to classify the material as textured.

What is interesting is the difference between the [001] and the [111] direction. The low intensity around the [111] direction could be the result of a depletion zone where the crystals were rotated away from in the direction of the [001] direction.

A conclusion is that the angle of application between the crystal and the magnetic field is maximum for the [111] direction and reduces in strength the closer the orientation comes to the [001] direction when the particle would be fully aligned with the magnetic field during extrusion.

V. CONCLUSION

The creation of a magnetic circuit is achieved by using a large cross-sectional area and additional coils that are positioned close to the air gap to reduce the leakage flux. Flux concentration with a taper angle of $\beta = 55^\circ$ helps to boost the flux density inside the air gap and powder capsule. For a total of 282 windings, a current of 55A and a gap thickness of 6 mm, it is possible to magnetize the Fe_{6.5}Si powder to 1.6 T.

For the magnetic field-influenced extrusion of the paste, two different extrusion tests are conducted, one manual extrusion and one using a state-of-the-art 3D printer setup. Manual extrusion is done to see if fundamental crystal alignment is possible. The test with the 3D printer at VITO enables for better control of the flow rate of the material. The tests used an electromagnet with low magnetic field strengths to limit the increase in apparent viscosity of the paste material, so extrusion remains possible. After extrusion of the samples, a debinding and sintering step creates a high-density solid sample that is possible to analyse via EBSD.

The EBSD measurements of the fibre samples showed no significant crystal alignment to the preferred direction. The

results for sample 3A are showing possible signs of crystal alignment. A small intensity is visible around the preferred [001] direction, but it is insufficient to classify the material as textured.

The results of the areas uniformly show a depletion zone for the intensity of the [111] direction. This is the direction with the largest angle of application of the magnetic moment. It could be possible that this is the result of crystal rotation in this zone. Perfect alignment of the [001] crystal direction with the magnetic field direction remains difficult because of the small angle of application. This suggests that crystal rotation is possible during the 3D micro-extrusion process, which would confirm the prove of concept. The rotation is possibly partially prevented by the high viscosity of the paste material.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Prof. Peter Sergeant and Prof. Leo Kestens for giving me the opportunity to investigate this topic and for guiding me with suggestions and feedback during the development of this paper. I also extend my thanks to Mohamed Ibrahim for providing weekly feedback and suggestions. My appreciation goes to Margherita Beretta for her incredible contribution in providing the Fe_{6.5}Si powder and for sintering, preparing, and performing EBSD measurements of the samples. I am grateful to Marleen Rombouts and Jo Verwimp for sharing their knowledge and insights in micro-extrusion. I also thank Ahmed Selema for measuring the anhysteretic magnetization curve, and Mahdi Mahmoudiniya for assisting with and analysing the EBSD measurements.

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Additief vervaardigen van ferromagnetische onderdelen voor elektrische machines

Lukas Lammens

Promotoren: Prof. dr. ir. Peter Sergeant, Prof. dr. ir. Leo Kestens
Counsellors: Dr. ir. Marleen Rombouts (VITO), Dr. ir. Mohamed Ibrahim

Abstract: Deze paper onderzoekt de mogelijkheid van kristallografische oriëntatie tijdens additieve vervaardiging. Elektrische machines maken gebruik van korrel georiënteerd of niet-korrel georiënteerd elektrisch staal, afhankelijk van de toepassing. De kristallografische oriëntatie van het staal is belangrijk om de energieverliezen, en daarmee het energiegebruik van de machine, te verminderen. Additieve vervaardiging biedt de mogelijkheid om nieuwe ontwerpen met hoge geometrische complexiteit te creëren, maar er is geen mogelijkheid om de kristaloriëntatie van de afgezette materialen te controleren tijdens het additief vervaardigingsproces. Deze paper onderzoekt het gebruik van Fe6.5Si deeltjes, die onder magnetische verzadiging worden gebracht door ze vooraf te magnetiseren in een op maat gemaakt magnetisch circuit. De remanentie van de deeltjes zal een magnetisch moment creëren, dat zal proberen de deeltjes te oriënteren tijdens de extrusie onder invloed van een magnetisch veld. Dit maakt additieve productie mogelijk van componenten met hoge dichtheid van Fe6.5Si voor elektrische machines met geprefereerde kristaloriëntaties. Geteste proefstukken tonen oriëntatie met lage intensiteit. Dit suggereert dat kristalrotatie mogelijk is tijdens het 3D-micro-extrusieproces. De rotatie wordt mogelijk gedeeltelijk voorkomen door de hoge viscositeit van het pastamateriaal.

Keywords: Additive vervaardiging, 3D micro-extrusie, Fe6.5Si, magnetisch circuit, *highly filled polymer*, korrel georiënteerd materiaal, magnetisch veld-geïnculteerd extrusie.

I. INTRODUCTIE

Systemen aangedreven door elektromotoren verbruiken vandaag 43% tot 46% van de wereldwijde elektriciteitsproductie, die geschat wordt op ongeveer 25.500 TWh in 2022 [1]. Decennialang is het ontwerp van elektromotoren geoptimaliseerd om de best mogelijke efficiëntie te bereiken. Het belang van het verhogen van de efficiëntie van de elektromotoren maakt een aanzienlijke vermindering van de CO₂-uitstoot mogelijk.

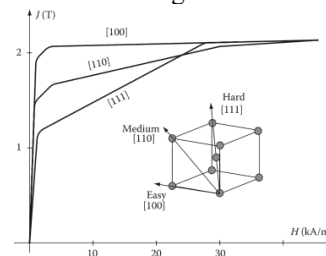
A. Probleemstelling

Om de efficiëntie van elektrische machines te verhogen, moeten ijzerverliezen worden geminimaliseerd. Dit kan door de dikte van het laminaat of de elektrische geleidbaarheid van het elektrische staal te verminderen. Het toevoegen van 6,5% Si aan staal vermindert wervelstroomverliezen, maar conventionele processen kunnen de brosheid van de legering niet aan. Het gebruik van korrelgeoriënteerde materialen kan het hysteresisverlies van de elektrische machine verminderen. Tijdens het micro-extrusieproces is er geen controle over de kristallografische oriëntatie van het materiaal.

Additieve vervaardiging kan Fe6.5Si onderdelen maken en kan mogelijk worden gecombineerd met een systeem om de kristallografische oriëntaties te controleren om de efficiëntie te verhogen.

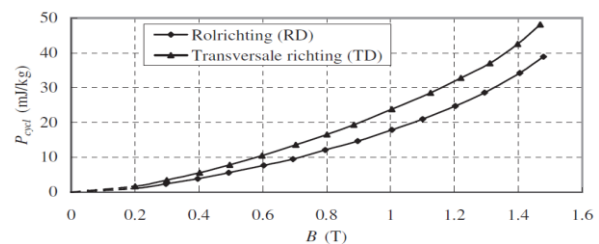
B. Basisprincipes magnetisme

De relatie tussen de magnetische veldsterkte H en de fluxdichtheid B is afhankelijk van de kristallografische oriëntatie van het materiaal. De *single crystal unit cell* voor ijzer is *body centered cubic* (BCC) en heeft een gemakkelijke magnetisatie-richting in de $[100]$ richting. Het verschil tussen de andere richtingen wordt weergegeven in figuur I-1.



Figuur I-1: Magnetisatiecurves van een ijskristal [2].

Het belang van de kristaloriëntatie is gekoppeld aan de vereiste veldsterkte die nodig is om het materiaal te magnetiseren. Voor elektrische machines resulteert dit in energieverliezen wanneer het materiaal roterende magnetisatie ondergaat. Figuur I-2 toont de energieverliezen voor elke cyclus wanneer de kristallografische oriëntatie anisotroop is in de rolrichting (RD) en de dwarsrichting (TD).

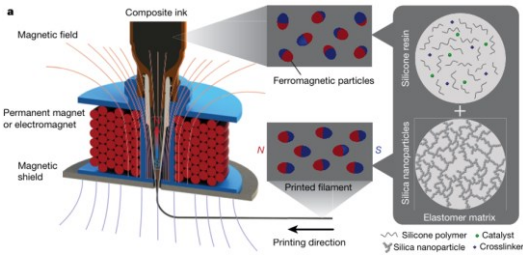


Figuur I-2: Hysteresis verlies per cyclus bij unidirectionele magnetisatie [3].

C. State-of-the-art vooruitgang in materialen en fabricagetechnieken

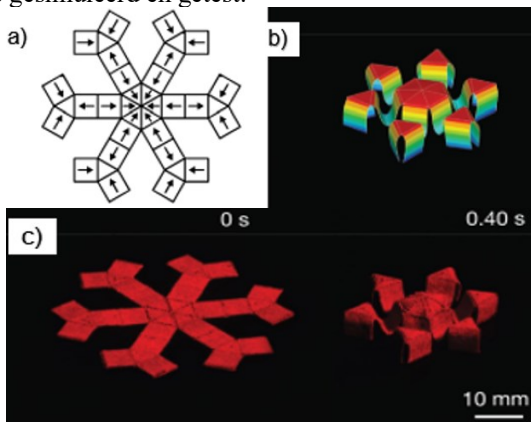
1) Kristaloriëntatie voor de fabricage van zachte robotica

Kim et al. onderzochten de mogelijkheid van oriëntatie van deeltjes tijdens *Direct Ink Writing* (DIW) voor het maken van zachte robotica [4]. Door gebruik te maken van neodymium-ijzer-borium (NdFeB) deeltjes in een elastomeer matrix, wordt een complexe structuur 3D-geprint. Het externe magnetische veld geeft controle over de deeltjes door ze te roteren om de polariteit af te stemmen op het veld.



Figuur I-3: Schematische weergave van het printproces met uitlijning van de ferromagnetische deeltjes in de composietinkt [4].

De 3D-geprinte structuren zijn geprogrammeerd met verschillende ferromagnetische domeinen waarbij de polariteit van de deeltjes hetzelfde is. Wanneer de structuur zich in de aanwezigheid van een magnetisch veld bevindt, wordt er een koppel op de domeinen uitgeoefend. Als reactie hierop beweegt de structuur op macroschaal. Figuur I-4 toont een voorbeeld van een tweedimensionale zachte robotstructuur die is gesimuleerd en getest.



Figuur I-4: Voorbeeld van een 2D zachte robotstructuur: a) Schematisch ontwerp van de domeinen; b) Simulatie; c) Experimentele resultaten [4].

2) Koperen componenten met hoge dichtheid door 3D micro-extrusie op basis van pasta

Koli et al. onderzochten de mogelijkheid om koperen onderdelen met een hoge dichtheid te maken met behulp van 3D micro-extrusie in combinatie met een composiet pastamateriaal [5].

De poedervormige grondstof bestaat uit koperdeeltjes en een hydroxypropylcellulose (HPC) in 1-propanol en additieven om de bindmiddeloplossing te vormen. De samenstelling is 95 wt% koperdeeltjes en 5 wt% HPC bindmiddel. De pasta wordt gemengd in een mixer (Hauschild DAC1100) die een ontgassingsstap onder vacuüm kan uitvoeren om ingesloten luchtbellens in de pasta te verlagen.

Nabewerking is nodig om de polymeermatrix te ontbinden en een dichtheid van 98,8% van de theoretische dichtheid na sinteren te bereiken.

D. Probleembenadering

Deze paper onderzoekt de mogelijkheid om kristaloriëntatie te bereiken tijdens additieve vervaardiging van ferromagnetische onderdelen met hoge dichtheid voor elektrische machines.

Het probleem is opgesplitst in twee delen: voor magnetiseren van het éénkristal Fe₆Si poeder en magnetisch veld-geïnculteerd extrusie. Het poeder wordt gemengd in een HPC-pasta voor extrusie en gesinterd tot een compact onderdeel.

A. Inleiding en ontwerp vereisten

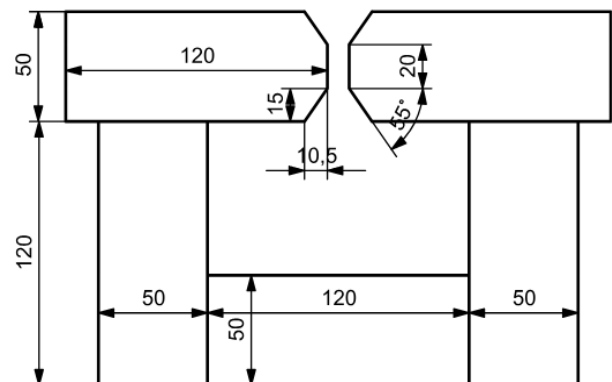
Het éénkristalpoeder wordt gemagnetiseerd tot boven de verzadiging van 1,5 T met een op maat gemaakt magnetisch circuit. Door kleine hoeveelheden poeder in een capsule en in de uitsparing van het circuit te plaatsen, wordt de fluxdichtheid door het poeder geforceerd. De elektromagnetische kracht van het circuit kan worden opgewekt via permanente magneten of via een elektromagneet door een gelijkstroom aan te leggen via een koperen wikkeling. Het ontwerp wordt gevalideerd met de Finite Element Method Magnetics (FEMM) voordat het fysiek wordt gemaakt.

B. Torus ontwerp

Een eerste ontwerp is gemaakt door een laag koolstofstalen staaf in een torusvorm te buigen. De eerste fluxdichtheidsmetingen in de luchtspleet van dit ontwerp vertoonden significante verschillen met het gesimuleerde FEMM-model. De belangrijkste reden voor het niet bereiken van de verwachte waarden is verzadiging van het kernmateriaal. De kleine doorsnede van de staaf in combinatie met slechte magnetische materiaaleigenschappen beperken de haalbare fluxdichtheid in de luchtspleet.

C. Rechthoekig ontwerp

In het volgende rechthoekige ontwerp worden de inzichten uit het eerste ontwerp verwerkt. De grootste veranderingen zijn de vergroting van de dwarsdoorsnede en de toevoeging van fluxconcentratie. Fiorillo ontdekte dat een taps toelopende hoek van de pooluiteinden $\beta = 54,74^\circ$ het beste is om de beste fluxconcentratie te verkrijgen [6]. Bovendien zal het kernmateriaal nu bestaan uit niet-korrelgeoriënteerde elektrostaallaminaten die betere magnetische eigenschappen hebben dan koolstofstaal met een laag koolstofgehalte. De kern heeft een uniforme stapeldikte van 20 mm. De uiteindelijke afmetingen van het ontwerp worden weergegeven in figuur II-1.



Figuur II-1: Technische tekening van het rechthoekige kernontwerp met een dikte van 20 mm

Technische tekening van het rechthoekige kernontwerp met een dikte van 20 mm.

Door gebruik te maken van de formules van de circuitwet van Ampère (1) en de magnetische reluctantie (2) kan de benodigde stroom worden bepaald:

$$\oint_l \vec{H} \cdot d\vec{l} = N \cdot I \quad (1)$$

$$R = \frac{l}{\mu_0 \mu_r A} \quad (2)$$

$$R_{tot} = R_{kern} + R_{gat} + R_{poeder} + R_{sensor} = \frac{l_{kern}}{\mu_0 \mu_{r,kern} A_{kern}} + \frac{l_{gat}}{\mu_0 A} + \frac{l_{poeder}}{\mu_0 \mu_{r,poeder} A} + \frac{l_{sensor}}{\mu_0 A_{gat}} \quad (3)$$

Omdat de permeabiliteit van het poeder $\mu_{r,poeder}$ onbekend is, is deze moeilijk mee te nemen in de berekening. De berekening wordt uitgevoerd in het slechtst mogelijke scenario, waarbij het poeder geen positief effect heeft op de reluctantie en dus een permeabiliteit heeft die gelijk is aan die van lucht, namelijk één. Vergelijking (3) wordt als volgt gewijzigd voor een luchtspleet van 6 mm:

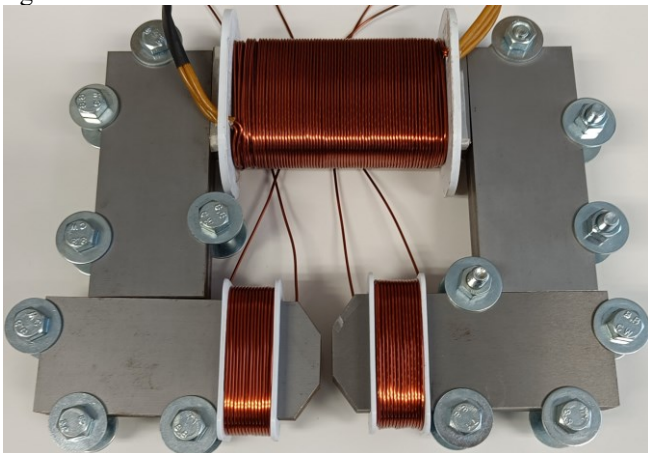
$$R_{tot} = \frac{0.580m}{\mu_0 7493 \cdot 0.001m^2} + \frac{0.006m}{\mu_0 \cdot 4 \cdot 10^{-4}m^2} = 12 \cdot 10^6 H^{-1} \quad (4)$$

$$I = \frac{\Phi \cdot R_{tot}}{N} = \frac{B \cdot A_{gat} \cdot R_{tot}}{N} = \frac{1.5T \cdot 4 \cdot 10^{-4}m^2 \cdot 12 \cdot 10^6 H^{-1}}{200} = 35.99A \quad (5)$$

Uit (5) wordt de geschatte stroom gevonden die nodig is om de magnetomotorische kracht te leveren om een fluxdichtheid van 1,5 T in de luchtspleet te bereiken, wat ongeveer 36 A in 200 wikkelingen is.

Het ontwerp is gemodelleerd in FEMM om een schatting van de resultaten te krijgen. Voor een stroom van 36 A is de gesimuleerde fluxdichtheid in de spleet 1,436 T, wat een acceptabel verschil is met de gewenste 1,5 T die in de berekeningen werd gebruikt.

De eerste metingen aan de rechthoekige kern bereiken niet de gewenste fluxdichtheid van 1,5 T. Dit verschil wordt toegeschreven aan de lekstroom in het circuit als gevolg van parasitaire luchtspleten en het snijrandeffect. De FEMM-simulatie is niet in staat om 3D-effecten van de luchtspleet te berekenen, dus dit kan ook bijdragen aan het verschil. Om de fluxdichtheid te verbeteren zijn extra wikkelingen toegevoegd tot een totaal van 282 wikkelingen in het circuit. Het fysieke eindresultaat van de rechthoekige kern wordt weergegeven in figuur II-2.



Figuur II-2: Ontwerp met rechthoekige kern en extra wikkelingen onderaan het circuit

De opstelling werd getest voor verschillende stromen en verschillende configuraties. Om de resultaten te kunnen vergelijken, heeft de opstelling een luchtspleet van 6 mm

dikte in alle configuraties en wanneer er poeder wordt toegevoegd, resulteert dit in een poederdikte van 4 mm. De configuraties zullen als volgt worden aangeduid:

Opstelling 1: alleen lucht, hoofdspool

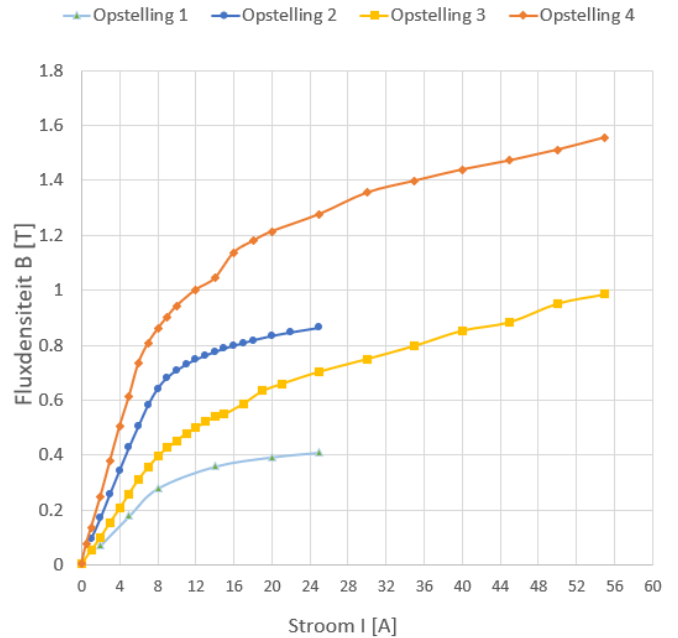
Opstelling 2: met poeder gevulde capsule, hoofdspool

Opstelling 3: alleen lucht, extra spoelen

Opstelling 4: met poeder gevulde capsule, extra spoelen

Figuur II-3 toont de meetresultaten voor de verschillende instellingen. De extra spoelen geven een aanzienlijke verhoging van de fluxdichtheid. Het verzadigingseffect met extra spoelen wordt ook verminderd. Voor hoge stromen vertonen de metingen afwijkingen en onnauwkeurigheden. Dit komt doordat de excitatie van de spoelen slechts gedurende korte tijd kan worden gehandhaafd, anders zouden de spoelen oververhit raken en stuk gaan. Daarom wordt de piekfunctie gebruikt om de hoogste fluxdichtheidspiek te meten, wat resulteert in een kleine onnauwkeurigheid.

Bij opstelling 4 is het mogelijk om het gewenste niveau van fluxdichtheid van 1,566 T te bereiken bij een stroom van 55 A.

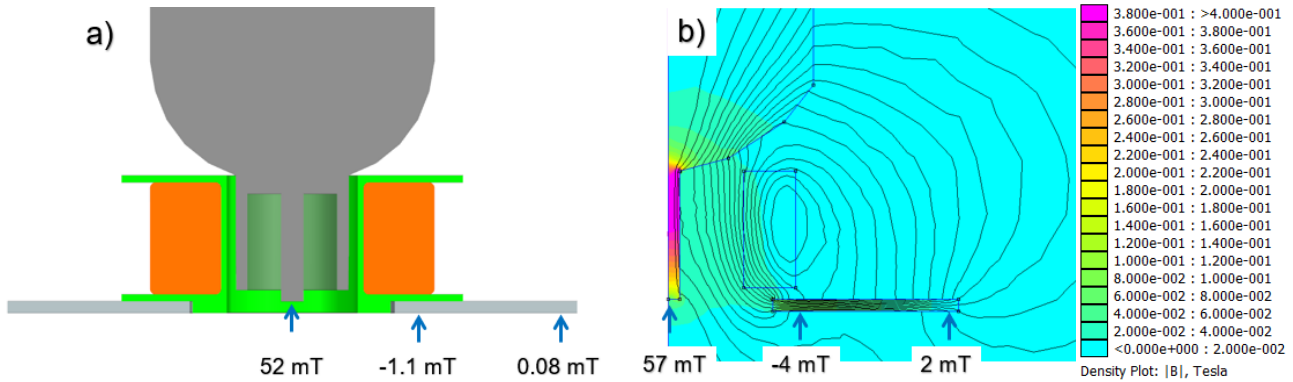


Figuur II-3: Fluxdichtheidsmetingen in de luchtspleet van de rechthoekige kern voor verschillende instellingen

III. MAGNETISCH VELD-GEÏNFLUENCEERDE EXTRUSIE

A. Introductie

Deze paper maakt gebruik van indirecte extrusiegebaseerde additieve vervaardiging. De Fe6,5Si deeltjes worden gecombineerd met het HPC bindmateriaal om een pasta te vormen die geëxtrudeerd kan worden met een plunjer-gebaseerd systeem. Dit hoofdstuk bespreekt verschillende benaderingen van het extruderen van de pasta onder invloed van een magnetisch veld.

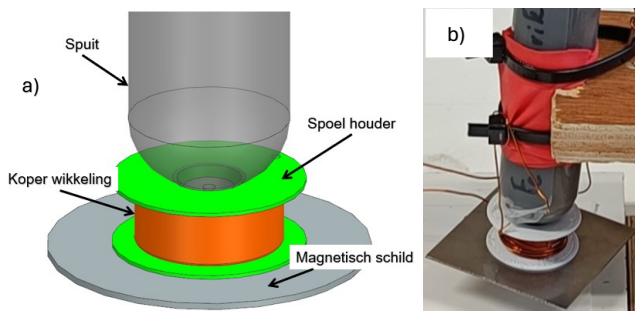


Figuur III-1: Fluxdichtheids punten aangegeven door de pijlen bij de spuitmond en bij het magnetische schild voor 5 A in de spoel: a) Fysische metingen van de opstelling gepresenteerd op de dwarsdoorsnede van het systeem; b) Axisymmetrische simulatie van de elektromagneet met 5 A voor handmatige extrusie.

B. Handmatige extrusie

De eerste test maakt gebruik van de spuitmond om vezels met een diameter van 2 mm te extruderen die voldoende sterkte hebben voor latere nabewerking. Het voordeel is de vereenvoudigde opstelling die met de hand kan worden bediend, zonder dat er een gecontroleerde beweging van een 3D-printer nodig is. Het poeder voor deze pasta is gemagnetiseerd tot 1,2 T.

Een permanente magneet wordt gebruikt om het magnetische veld rond de spuitmond te leveren. Er werd waargenomen dat de schijnbare viscositeit van het pastamateriaal aanzienlijk toenam en extruderen onmogelijk werd. Dit is te wijten aan het magneto-reologische gedrag van de pasta. Dit gedrag moet verder onderzocht worden. Als alternatief is een kleine elektromagneet met 80 windingen ontworpen die het magnetische veld levert door middel van gelijkstroom. Figuur III-1 toont het ontwerp.



Figuur III-2: a) CAD-weergave van de elektromagneet; b) Fysieke opstelling van de elektromagneet.

De elektromagneet maakt dynamische controle mogelijk over de veldsterkte die wordt gesimuleerd in FEMM.

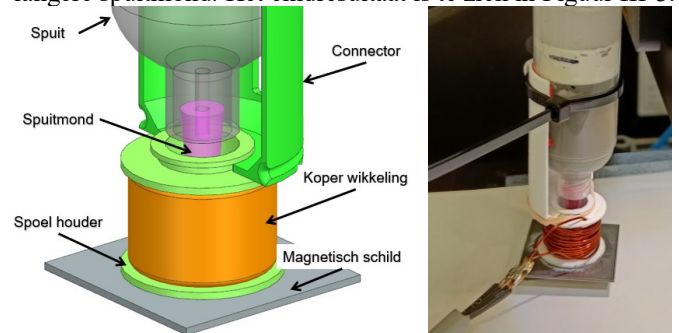
Door gebruik te maken van een axisymmetrische simulatie is het mogelijk om een schatting te maken van de fluxdichtheid in de straalsoopbuis. Deze wordt weergegeven in figuur III-2 (b).

Figuur III-2 vergelijkt de fysische metingen met de fluxdichtheden uit de simulatie. Er worden verschillende stromen gebruikt om de vezelmonsters te extruderen, waarbij monster 1 en monster 4V worden geëxtrudeerd met respectievelijk 86mT en 354mT, gebaseerd op de simulatie. De doorlaatbaarheid van de pasta is in de simulatie afgestemd op $\mu_{paste}=15$ om overeen te komen met de fysische metingen.

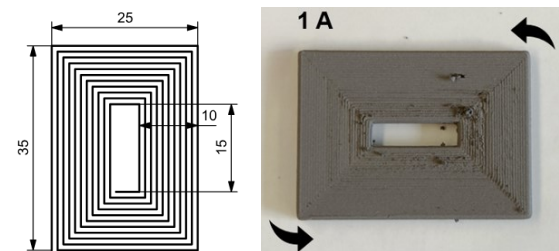
C. Geavanceerde extrusie bij VITO

Handmatige extrusie heeft geen controle over de stroomsnelheid en de nauwkeurigheid van het geëxtrudeerde pastamateriaal. Om enkele van de beperkingen op te vangen, is er bij VITO een test gedaan op een high-end 3D-printer. Voor deze test wordt een conische spuitmond gebruikt met een opening van 580 μm om de *shear rate* in de pasta te verhogen en een *shear thinning* effect te bereiken. Dit verlaagt de viscositeit van de pasta en verlaagt de weerstand voor het roteren van het deeltje tijdens de extrusie. Deze pasta is voor gemagnetiseerd tot 1,6T.

Om de condities van de magnetische veldsterkte te evenaren zodat de resultaten vergeleken kunnen worden, is een vergelijkbare elektromagneet ontworpen voor de nieuwe langere spuitmond. Het eindresultaat is te zien in Figuur III-3.



Figuur III-3: CAD-model en volledige opstelling van de elektromagneet voor de extrusie bij VITO.



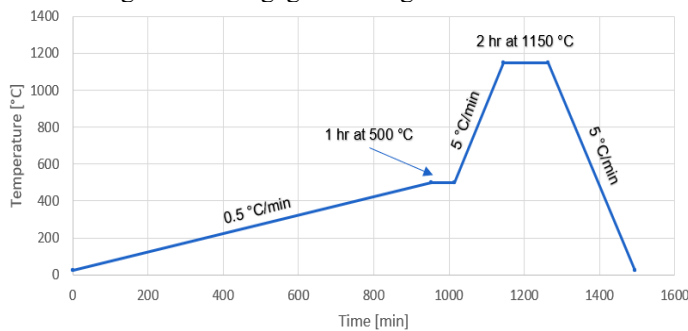
Figuur III-4: Spiraalvormig proefstuk en eindresultaat voor 1A.

Figuur III-4 toont de spiraalvormige printstrategie en de afmetingen 15x10x2,4 mm van het onderdeel. Dit is gedaan zodat de doorstroming tijdens het extrusieproces constant behouden blijft. De veldsterktes voor 1A en 3A worden geëxtrudeerd en resulteren in een fluxdichtheid van respectievelijk 77 mT en 230 mT.

D. Nabewerking van de groene proefstukken

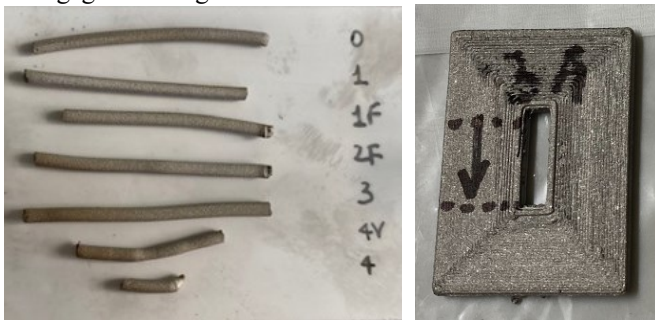
Na extrusie van de groene proefstukken moet het polymeerbindmiddel verwijderd worden. Dit wordt gedaan door het polymeer te ontbinden tijdens een warmte-

behandeling in een argon-gasatmosfeer, gevolgd door een sinterstap om een proefstuk met een hoge dichtheid te verkrijgen. Het temperatuurverloop van de warmtebehandeling wordt weergegeven in figuur III-5.



Figuur III-5: Temperatuurverloop van de warmtebehandeling.

De vezel- en spiraalvormige proefstukken zijn gesinterd en weergegeven in figuur III-6.



Figuur III-6: Vezel- en spiraalvormige proefstukken na sinteren.

IV. RESULTATEN

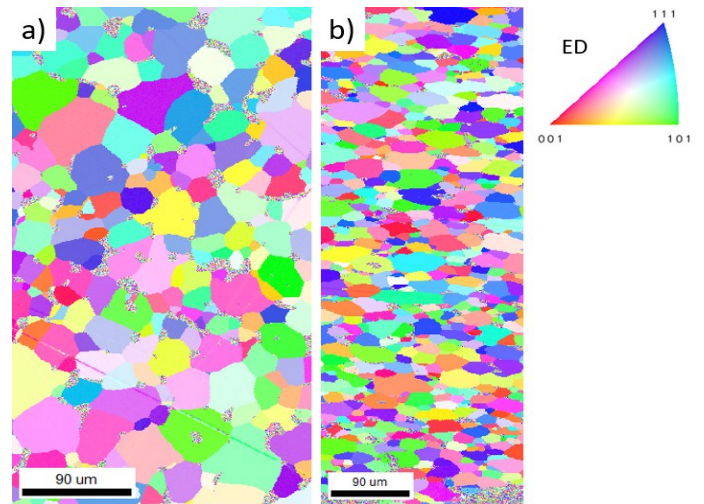
De scanning elektronenmicroscopie die gebruikt wordt voor de *electron backscatter diffraction* (EBSD) metingen is een Philips XL 30 FEG met een 1,4 megapixel resolutie (1392 (H) x 1040 (L)), een gegevensverzamelingsnelheid tot 200 geïndexeerde patronen per seconde en een EDAX-TSL Digiview V, met een 25 kV bundel. Het programma TEAM: Texture & Elemental Analytical Microscopy wordt gebruikt voor de gegevensberekening.

Het analyseren van de proefstukken met EBSD is een tijdrovend en arbeidsintensief proces omdat de proefstukken een hoge oppervlaktekwaliteit vereisen. Daarom worden niet alle gesinterde stukken geanalyseerd. De EBSD-metingen zijn gedaan voor vezel 1 en 4V, en spiraal proefstuk 3A.

A. Handmatig geëxtrudeerde vezelmonsters

De resultaten van de vezels laten geen significante textuur zien. De kristallografische oriëntatie van de extrusierichting (ED) van de *inverse pole figure* wordt weergegeven in figuur IV-1. Als kristaloriëntatie wordt bereikt, zouden de resultaten meer kleuren dicht bij de [001]-richting laten zien.

De eerste EBSD resultaten van het materiaal confirmeren de éénkristal conditie van het Fe₆,5Si poeder materiaal.



Figuur IV-1: EBSD-meting van de vezels: a) proefstuk 1; b) proefstuk 4V.

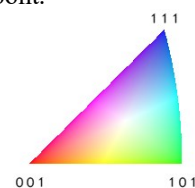
B. Micro-geëxtrudeerde spiraalvormige proefstukken

De dwarsdoorsnede van het microgeëxtrudeerde spiraalvormige proefstukken 3A wordt onderzocht. Vanwege het grote oppervlak zijn meerdere doorsneden gemeten met EBSD. Dit is om de datapunten te vergroten en de statistische waarde van de meting te verhogen. De bedekte gebieden zijn weergegeven op het gepolijste proefstukoppervlak in figuur IV-2.



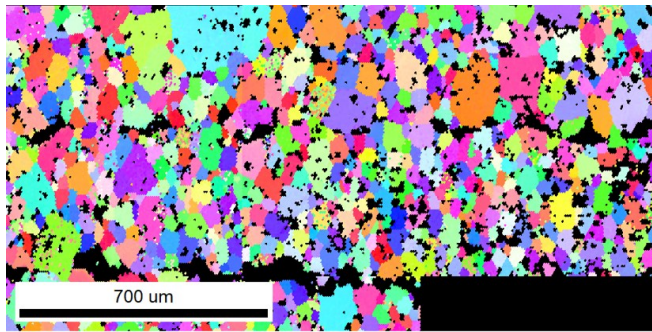
Figuur IV-2: Dwarsdoorsnede van proefstuk 3A met aangegeven locaties van de onderzochte gebieden.

Gebied 5' en 5'' zijn gecombineerd tot een groot gebied om de statistische significantie van de metingen te vergroten. Figuur IV-3 geeft de kleurenlegende voor de *inverse pole figure* die de kristaloriëntatie van de korrels in het materiaal toont.

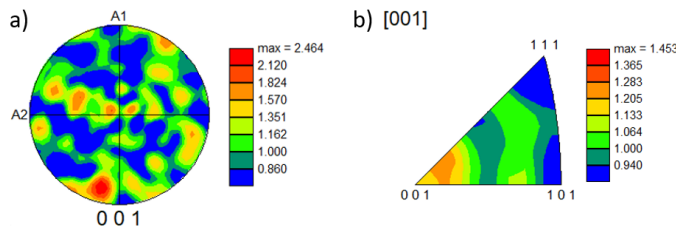


Figuur IV-3: kleurgecodeerde legende voor de *inverse pole figure* voor de extrusierichting.

Figuur IV-4 toont het *inverse pole figure* voor de ND, extrusierichting van het proefstuk.



Figuur IV-4: *inverse pole figure* van ND, proefstuk 3A, gebied 5, vergroting 100x, stapgrootte 6 μm .



Figuur IV-5: Proefstuk 3A, gebied 5: a) poolfiguur; b) *inverse pole figure*.

De resultaten van figuur IV-4 laten geen grote hoeveelheid rode [001]-oriëntatie zien, wat het gewenste resultaat is. Figuur IV-5 toont de intensiteit van de oriëntatie van de extrusierichting van het monster. Er is een kleine intensiteit zichtbaar rond de [001]-richting, maar dat is onvoldoende om het materiaal als getextureerd te classificeren.

Wat interessant is, is het verschil tussen de [001] en de [111]-richting. De lage intensiteit rond de [111]-richting zou het resultaat kunnen zijn van een depletiezone waar de kristallen vanaf gedraaid zijn in de richting van de [001]-richting.

Een mogelijke conclusie is dat de invalshoek tussen het kristal en het magnetische veld maximaal is voor de [111]-richting en in sterkte afneemt naarmate de oriëntatie dichter bij de [001]-richting komt, wanneer het deeltje tijdens de extrusie volledig georiënteerd zou zijn met het magnetische veld.

V. CONCLUSIE

Het creëren van een magnetisch circuit wordt bereikt door gebruik te maken van een grote dwarsdoorsnede en extra spoelen die dicht bij de luchtspleet zijn geplaatst om de lekstroom te verminderen. Fluxconcentratie met een conische hoek van $\beta = 55^\circ$ helpt om de fluxdichtheid binnen de luchtspleet en de poedercapsule te verhogen. Voor een totaal van 282 windingen, een stroom van 55A en een spleetdikte van 6 mm is het mogelijk om het Fe_{6,5}Si poeder te magnetiseren tot 1,6 T.

Voor de extrusie van de pasta onder invloed van het magnetische veld worden twee verschillende extrusietests uitgevoerd: een handmatige extrusie en een extrusie met behulp van een geavanceerde 3D-printer. Handmatige extrusie wordt gedaan om te zien of fundamentele kristaluitlijning mogelijk is. De test met de 3D-printer bij VITO maakt een betere controle van de stroomsnelheid van het materiaal mogelijk. Bij de tests werd een elektromagneet met lage magnetische veldsterktes gebruikt om de toename van de schijnbare viscositeit van het pastamateriaal te beperken, zodat extrusie mogelijk blijft. Na extrusie van de proefstukken

wordt door een ontbindings- en sinterstap een vast proefstuk met een hoge dichtheid gemaakt dat via EBSD kan worden geanalyseerd.

De EBSD-metingen van de vezelstukken toonden geen significante kristaloriëntatie in de voorkeursrichting. De resultaten voor proefstuk 3A vertonen mogelijke tekenen van kristaloriëntatie. Er is een kleine intensiteit zichtbaar rond de voorkeursrichting [001], maar dat is onvoldoende om het materiaal als getextureerd te classificeren.

De resultaten van de gebieden laten gelijkmatig een depletiezone zien voor de intensiteit van de [111] richting. Dit is de richting met de grootste invalshoek van het magnetische moment. Het is mogelijk dat dit het resultaat is van kristalrotatie in deze zone. Perfecte uitlijning van de [001]-kristalrichting met de magnetische veldrichting blijft moeilijk vanwege de kleine invalshoek. Dit suggereert dat kristalrotatie mogelijk is tijdens het 3D micro-extrusieproces. De rotatie wordt mogelijk gedeeltelijk voorkomen door de hoge viscositeit van het pastamateriaal.

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List of abbreviations

EMDS	Electric Motors- Driven Systems
BCC	Body Centered Cubic
TD	Transverse Direction
RD	Rolling Direction
GO	Grain-Oriented
NGO	Non-Grain Oriented
DIW	Direct Ink Writing
LPBF	Laser Powder Bed Fusion
HPC	Hydroxypropyl Cellulose
LT	Layer Thickness
SP	Scan Spacing
SEM	Scanning Electron Microscopy
EBSD	Electron Backscatter Diffraction
FEMM	Finite Element Method Magnetics
AM	Additive Manufacturing
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
PLA	Polylactic Acid
ABS	Acrylonitrile Butadiene Styrene
FFF	Filament Fused Fabrication
MIM	Metal Injection Moulding
CAD	Computer Aided Design
OIM	Orientation Imaging Microscopy
ED	Extrusion Direction
ND	Normal Direction

1 Introduction

1.1 Electrical machines and energy consumption

Electric motors- driven systems (EMDS) convert electrical power into mechanical power. As for 2011, it was estimated that EMDS consume between 43% and 46% of the global electricity consumption, which is for 2022 estimated around 25 500 TWh (Statista, 2023). This results in an energy consumption by EMDS of 11 730 TWh. This energy consumption is expected to rise to 13 360 TWh per year by the year 2030 (Waide & U. Brunner, 2011), but based on data of 2022 this will most likely exceed this expectation. The efficiency of these machines is important to maximise because of the huge energy saving potential. Electrical motors are divided in international efficiency-classification using IE1, IE2, IE3 and IE4 which indicate the efficiency of the motor for a given output, as is presented in Figure 1-1 (International Electrotechnical Commission, 2014). For large IE4 motor outputs an efficiency of 97% is achievable.

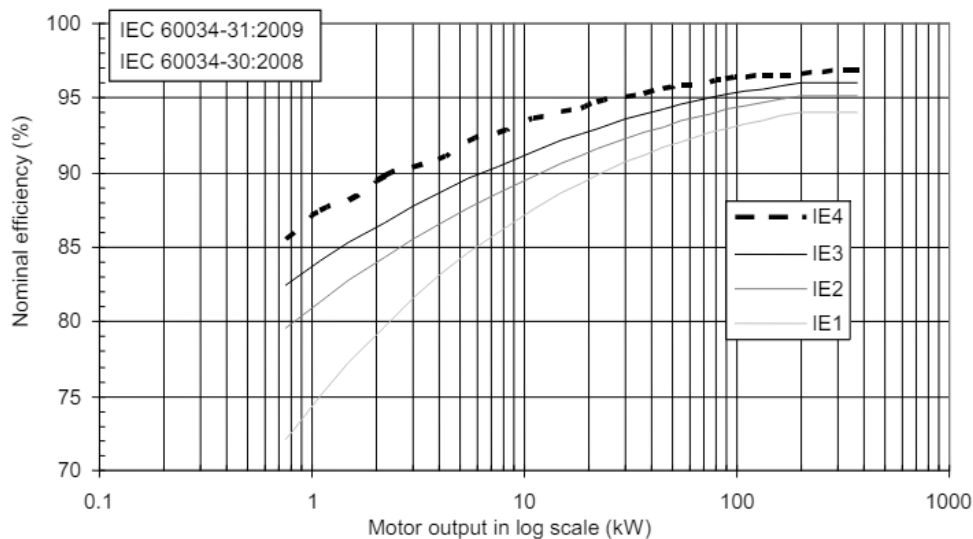


Figure 1-1: Electric motors efficiency classes (4-pole 50 Hz) (IEC 60034-30-1:2014)

The usable mechanical energy is dependent on the efficiency of the motor. For decades, the design of the electro motor is optimised to have the highest possible efficiency. A small breakthrough in increase of efficiency by 1% could mean a large worldwide energy saving and reduction of CO₂ emissions.

1.2 Basic principles of magnetism

This section is a brief introduction into basic concepts and principles needed to understand the problem statement.

1.2.1 Magnetic properties

“Magnetic flux density B represents the magnitude of the internal field strength within a substance that is subjected to a magnetic strength field H ” (Callister, 2010). The relationship in a vacuum between B and H can be written as follows:

$$\bar{B} = \mu_0 \bar{H} \quad (1.1)$$

$$B = \frac{\phi}{A} \quad (1.2)$$

Where $\mu_0 = 4\pi \cdot 10^{-7} \left[\frac{H}{m} \right]$ is the magnetic permeability of vacuum. When mater is present, the field strength $\bar{H}$ magnetizes this mater. This leads to the magnetization vector $\bar{M} \left[\frac{A}{m} \right]$. The new relation between B and H becomes:

$$\bar{B} = \mu_0 (\bar{H} + \bar{M}) = \mu \bar{H} \quad (1.3)$$

This relation shows the contribution of the external source with the component $\mu_0 H$ and also the contribution of the internal material because of magnetization with $\mu_0 M$ (Tumanski, 2016). For low external fields, the contribution of M is very large compared to the H . The previous equation can also be written as follows:

$$\bar{B} = \mu \bar{H} \quad (1.4)$$

With μ the permeability of the medium, which can be written as:

$$\mu = \mu_0 \left(1 + \frac{M}{H} \right) = \mu_0 \mu_r \quad (1.5)$$

The relative permeability μ_r is dependent on the type of material and is a measure of how good the material can be magnetized. In other words, how an B field can be induced in the material when placed in an external H field (Callister, 2010). Ferromagnetic materials have a high relative permeability. Note that for high field strength H the magnetization M is also high and a further increase in H will only result in a slight increase in M . This nonlinear relation between B and H makes the relative permeability, and thus μ , depended on the magnetic field strength (Tumanski, 2016). Figure 1-2 represents the relation between the magnetic field strength and the relative permeability.

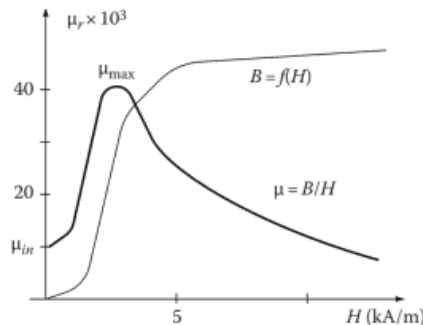


Figure 1-2: Relation between the magnetic field strength and relative permeability for steel (Tumanski, 2016)

1.2.2 Ferromagnetic materials

Magnetic domains are spontaneously magnetized micro-areas, which have a mutual spin alignment of the magnetic dipole moments over a large area (Callister, 2010). The single crystals for iron are body centered cubic (BCC) with three main crystallographic directions: [100], [110] and [111]. The directions have a different rate of magnetization, which means the ease of achieving spin alignment of the magnetic dipoles. This is also called the magnetic anisotropy. The easy direction of magnetization is when saturation is achieved at the lowest H field (Callister, 2010). Figure 1-3 shows that the [100] direction for iron crystals is the easiest to magnetize and [111] is the hardest.

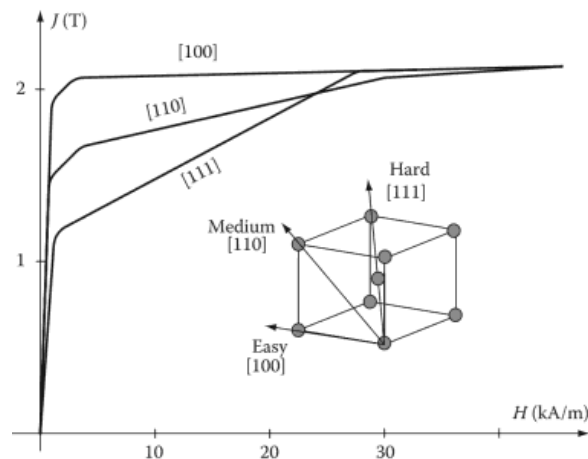


Figure 1-3: Magnetization curves of single crystal of iron (Tumanski, 2016)

When the magnetizing field strength H is small, the domain walls undergo irreversible movement, schematically shown in Figure 1-4. Until the point is reached where all the single crystals are magnetized in the [100] easy direction. This point is called the rotation of magnetization. Note that the arrow of magnetization, and thus the [100] direction of the crystal, are under an angle with the horizontal external H field. A significant increase in H field is needed to complete the saturation of the material. The crystallographic orientation of the crystals is fixed in the bulk of the material. So, to reach complete saturation, a combination of [100], [110], and [111] magnetization direction is needed, which is only reached for very high H fields.

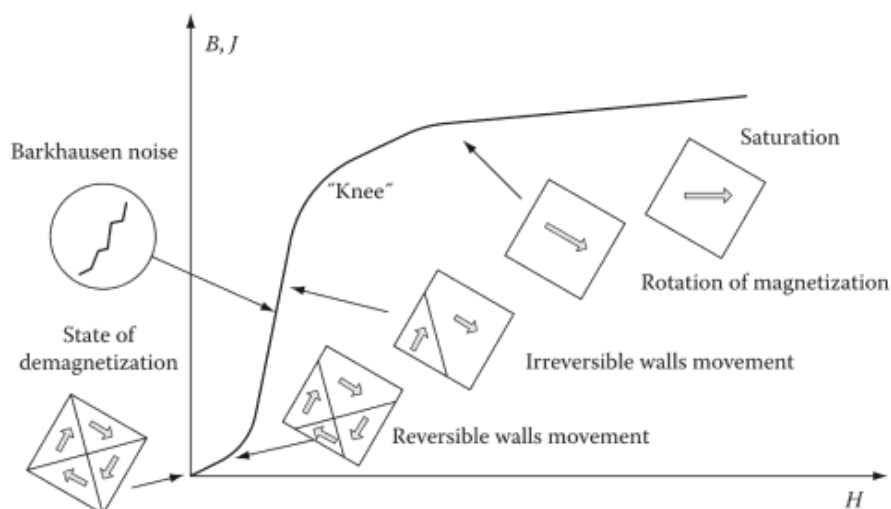


Figure 1-4: Magnetization curve (Tumanski, 2016)

After the material is saturated and the H field is lowered, the magnetic domains rotated back to the preferred easy direction of magnetization. The leftover orientation, when the H field is zero, produces B fields in the material, this is called the remanence B_r . This effect of the B field lagging behind the H field is called hysteresis (Callister, 2010). The complete relation is called the hysteresis loop, as shown in Figure 1-5.

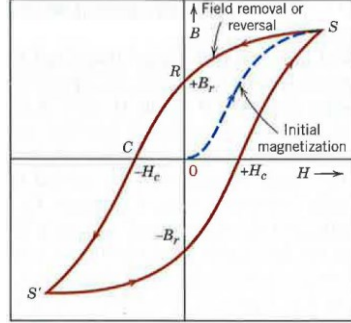


Figure 1-5: Hysteresis loop (Callister, 2010)

The enclosed area of the hysteresis loop is directly proportional to the power loss of the material. For soft magnetic materials it is better to have a small area with a small value for H_c , that is called the coercivity of the material.

1.2.3 Electrical steels

Electrical machines make use of ferromagnetic textured materials to fabricate the core. This material is magnetic and has a high magnetic permeability to conduct magnetic field lines. Minimizing the energy loss in an electrical machine requires to understand the fundamental principles that can be divided in three categories: the copper loss, iron losses and mechanical friction losses in case of a motor.

$$P_{loss} = P_{copper\ loss} + P_{iron\ loss} + P_{friction} \quad (1.6)$$

The iron losses of the material occur during the reversing of the magnetic field inside the material. During each rotation of the machine the ferromagnetic material of the core will cycle and see the reversing of the magnetic field. Iron losses consist of three factors:

$$P_{iron\ loss} = P_{hys} + P_{eddy\ current} + P_{excess} \quad (1.7)$$

To quantify the specific power loss, the following formula is used (Dupré, 2014; Tumanski, 2016):

$$P = \frac{1}{\rho T} \int_0^T H(t) \frac{dB(t)}{dt} dt \quad (1.8)$$

With ρ the density of the material [kg/m^3] and T the inverse of the frequency [s]. This value is often shown as $P_{\frac{1.5}{50}}$ in [W/kg] as a material property which refers to the power loss at 1.5 T and 50 Hz.

This P is equal to the enclosed area of the hysteresis loop and can be linked to the complete iron loss P_{ij} , which can also be rewritten (Sergeant, 2023):

$$P_{ij} = P_{hys} + P_{eddy\ current} + P_{excess} = c_1 f B^{1.6} + c_2 f^2 B^2 + c_3 f^{1.5} B^{1.5} \quad (1.9)$$

Note from equation (1.9) the total iron losses are directly proportional to the frequency of the motor, as is visible in Figure 1-6.

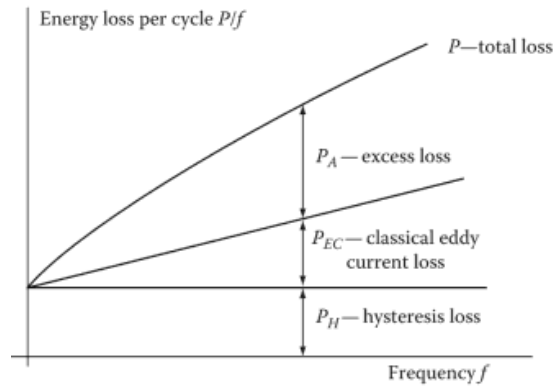


Figure 1-6: Method of loss separation (Tumanski, 2016)

The factors c_2 and c_3 are both dependent on the lamination thickness and the electrical conductivity of the material. Increasing the electrical conductivity will result in lower eddy current losses $P_{eddy\ current}$ and also in lower excess loss P_{excess} . To reduce the iron loss, electrical motors use thin steel laminates.

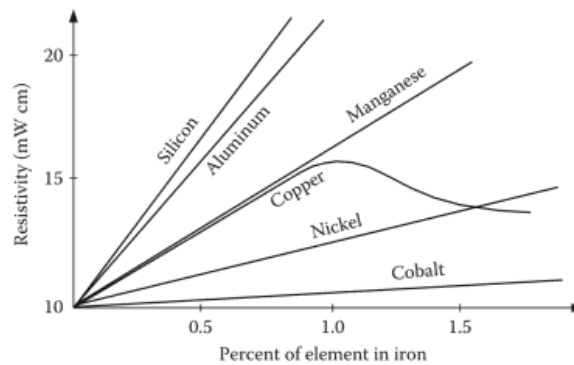


Figure 1-7: electrical resistivity of different iron alloys (Tumanski, 2016)

Figure 1-7 shows the effect of adding Silicon to the steel on the resistivity. This is why electrical steels use around 3% Si in the steel to reduce iron losses. The optimum Si content in the electrical steel would be 6.5% Si, but the manufacturing of this steel is difficult due to the brittle nature of the alloy.

The hysteresis loss is also dependent on the anisotropic behaviour of the material, shown in Figure 1-8. Depending on the magnetization direction this loss can differ. It is possible to separate two types of magnetization: unidirectional and rotational magnetization (Dupré, 2014). Unidirectional magnetization happens when the magnetization vector B always remain under the spatial direction and only changes in magnitude. Rotational magnetization changes in magnitude but also in spatial direction.

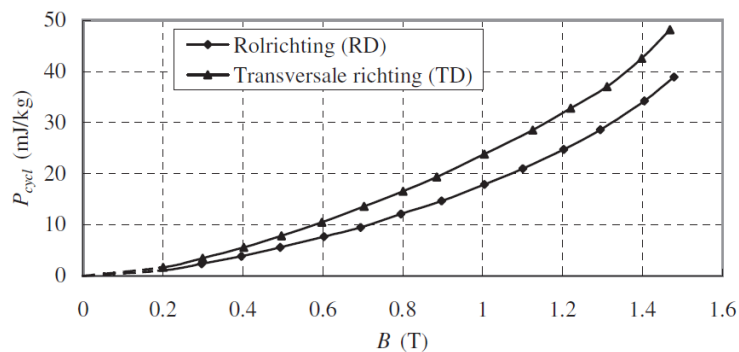


Figure 1-8: Hysteresis loss per cycle for unidirectional magnetization, for the transverse direction (TD) and the roll direction (RD) for non-oriented material (Dupré, 2014)

The anisotropic behaviour is a result of the easy magnetization direction showed in Figure 1-3. Materials can be manufactured with a preferred crystallographic orientation, what is called a textured or grain-oriented (GO) material. Depending on the application of the machine it is wanted to have anisotropic (grain-oriented) or isotropic (non-grain oriented (NGO)) material.

A transformer will be subjected to unidirectional magnetization in the legs and a small amount of rotational in the corners. This is why transformers are primarily made of oriented electrical steels that are anisotropic and have good properties in one axis. Electrical motors have unidirectional and rotational magnetization in the stator and rotor, so it is better to have NGO electrical steel that is isotropic to have the same properties in every direction.

1.3 Problem statement

To increase the efficiency of an electric machine, iron losses must be minimized. Reducing the thickness of the steel laminates, or decreasing the electrical conductivity have large effects. Adding 6.5% Si to the steel optimizes resistivity and reduces the eddy current losses. However, conventional processes are unable to manufacture 6.5% Si steels due to the material's brittleness.

A second solution of increasing the efficiency of an electrical machine is using GO materials. Depending on the application, specific textures can reduce the hysteresis loss of the material. Current processes for creating GO textures typically produce a single common direction across the entire plane of the steel plate due to rolling. This technique does not allow for multiple orientations zones within same plane.

Additive manufacturing is able to create parts out of Fe6.5Si materials. This process can potentially be combined with preferred crystallographic orientations or GO textures to reach the maximum increase in efficiency.

1.4 State-of-the-art advancements in materials and fabrication techniques

The following section will discuss the potential avenues for realizing a solution for the problem statement in section 1.3. A brief review of previous studies is provided, describing different aspects contributing to the objective of this research.

1.4.1 Crystal alignment for soft robotics fabrication

This chapter contains information of the work by Kim et al. that investigated particle alignment in the development of soft robotics (Kim et al., 2018). By using a composite of ferromagnetic microparticles made from neodymium-iron-boron (NdFeB) alloy within an elastomer matrix, a complex structure is 3D printed, allowing control over magnetic domains by selecting the polarity of the extruded filaments. This is achieved by a magnetic field around the nozzle to reorient the particles based on their polarity.

The composite material is in the form of an ink, a viscous liquid, which is extrudable via micro-extrusion. The composite ink is prepared by mixing non-magnetized NdFeB particles and an uncured elastomer matrix. The addition of fumed silica nanoparticles serves as a rheological modifier to improve the properties for direct ink writing (DIW). After the preparation of the ink the particles are magnetized to saturation under an impulse field, which is around 2.7 T. Different compositions for the paste formulation are tested to see the change between the different parameters on the magnetization or magnetic moment density is presented in Figure 1-9.

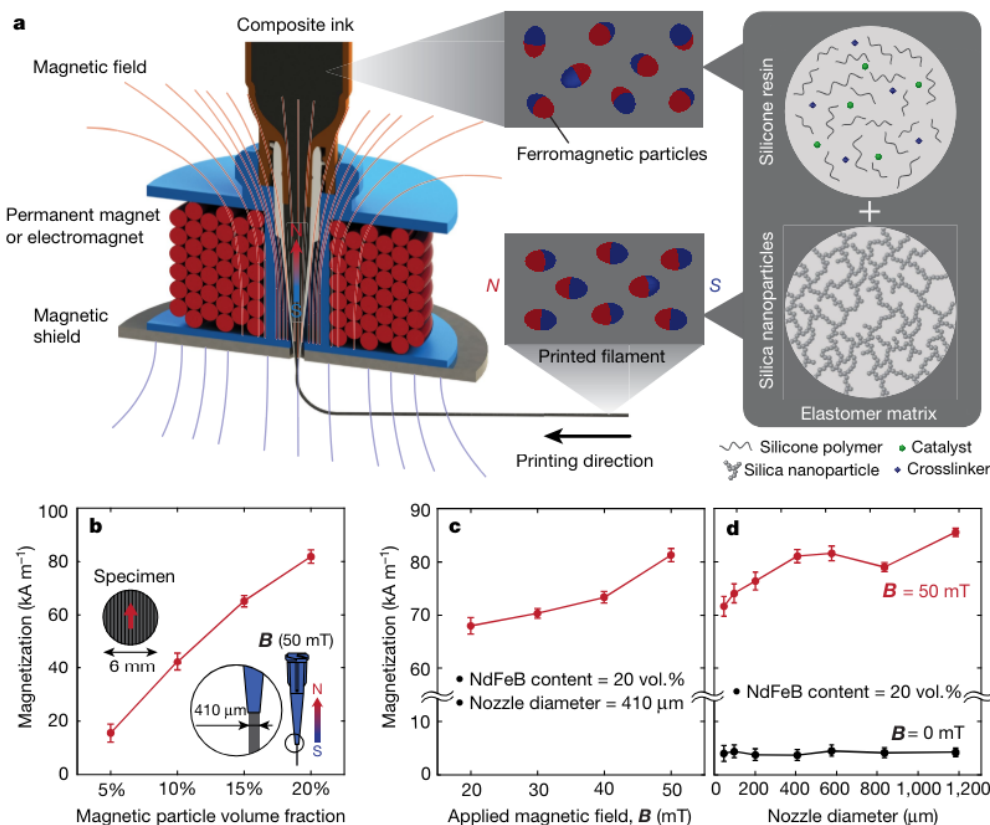


Figure 1-9: Process parameters of 3D printing ferromagnetic domains: a) Schematic of the printing process with alignment of the ferromagnetic particles in the ink; b) The magnetization versus the volume fraction; c) Effect of the magnetic field around the nozzle on the magnetization; d) Effect of the nozzle diameter on the magnetization (Kim et al., 2018).

By changing the nozzle diameter, the volume fraction of NdFeB particles and the strength of the magnetic field at the nozzle tip, the best parameters are determined for the highest possible alignment, referred to as the magnetic moment density [kA/m]. They discovered that the bigger nozzle diameter shows better results along with the absence of die-swelling effect, which happens when smaller nozzles are used. The volume fraction of the particles was set to 20 vol% and the magnetic field of 50 mT at the nozzle tip. How the field strength at the nozzle tip was measured or defined is not specified.

To visualize the fraction of alignment in the extruded samples, a comparison is done with and without the external magnetic field during extrusion. This showed the difference between aligned and randomized particles. When the sample printed in the absence of external field is magnetized under impulse fields (2.7 T), the maximum possible magnetic moment density is achieved. By comparing the maximum versus the 3D printed values for all the different volume fraction in particles they found that it was possible to achieve 63%-64% of the maximum achievable value when extruded using a field of 50 mT at the nozzle tip. Figure 1-10 shows the values between the different tests.

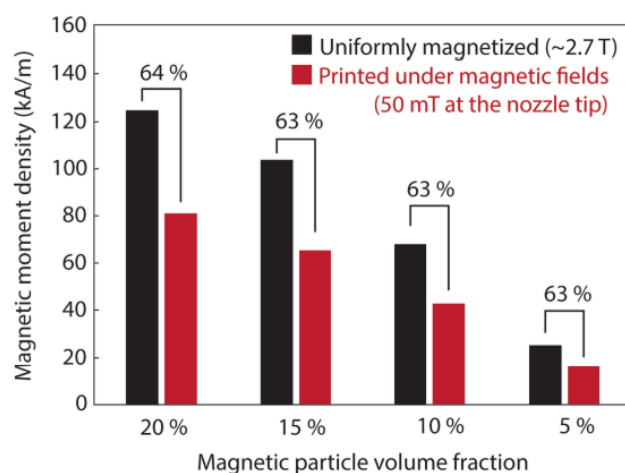


Figure 1-10: Magnetic moment densities for different NdFeB particle volume fractions (Kim et al., 2018)

The 3D printed structures are programmed with distinct ferromagnetic domains. When the structures are placed under a magnetic field, a torque is induced upon the ferromagnetic particles. This leads to macroscale movement of the structure as a response. Figure 1-11 depicts a two-dimensional example of such structure.

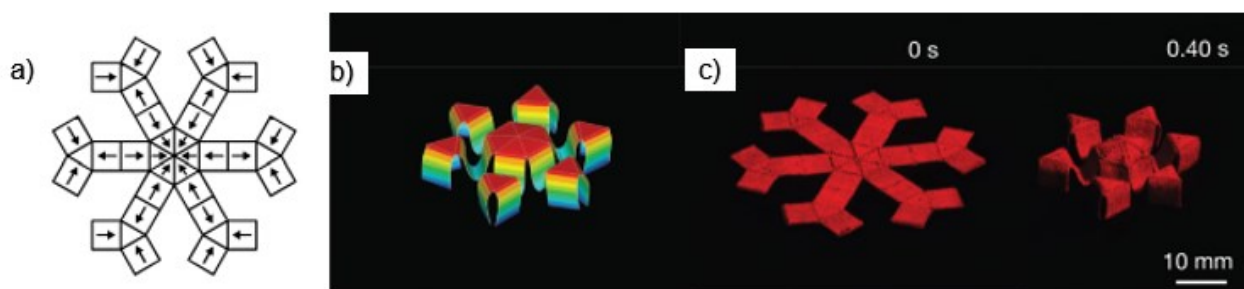


Figure 1-11: Example of a two-dimensional soft robotic structure: a) Schematic design; b) Finite-element simulation; c) Experimental results when applying a magnetic field of 200 mT (Kim et al., 2018).

In Figure 1-11a) the schematic with the arrow points indicating the north polarity of the magnetic domain. Section b) shows a finite-element simulation of the structure and section c) shows the actuation of the structure when placed under a magnetic field of 200 mT. The ferromagnetic particles align themselves with the external field, and thus movement inside the structure is created.

1.4.2 High-density copper components by paste-based 3D micro-extrusion

Kolli et al. investigated the possibility of manufacturing high-density copper parts by using 3D micro-extrusion in combination with a composite paste material to achieve a relative density of 98.8% of the theoretical density after sintering (Kolli et al., 2023). The goal is to find an alternative way than laser powder bed fusion (LPBF) for additive manufacturing of copper parts. The disadvantage of using LPBF with copper powder as the base material is the high optical reflectivity and thermal conductivity of copper. It is possible to achieve a relative density of 99.6% of the theoretical density using LPBF as is investigated by Qu et al. (Qu et al., 2021). Figure 1-12 shows an overview of the successive steps to achieve high density parts from (a) paste preparation, (b)(c) fibre extrusion, (d) drying and (e) sintering the parts.

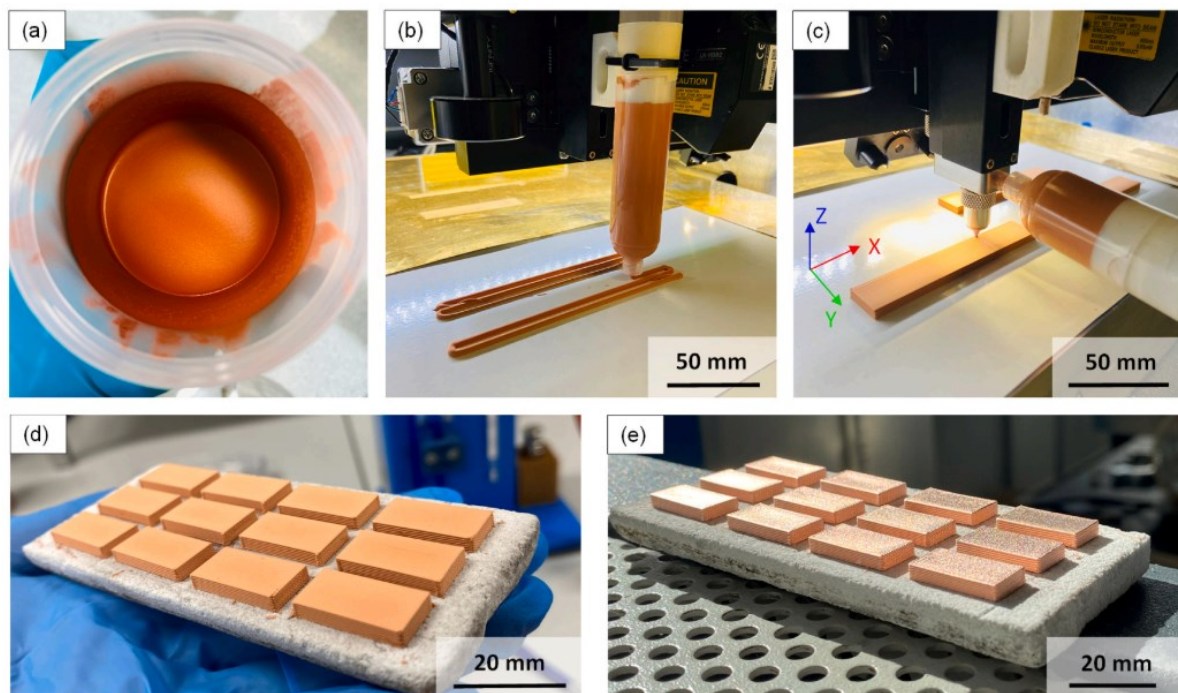


Figure 1-12: Process chain of micro-extrusion: (a) paste preparation; (b) and (c) controlled extrusion of the parts that are (d) dried and (e) debound and sintered (Kolli et al., 2023).

The powder loaded feedstock paste consists of copper particles and a binder solution. This paper uses hydroxypropyl cellulose (HPC) in 1-propanol with other organic additives to form the binder solution. These components are mixed using a planetary-centrifugal speed mixer (Hauschild Speedmixer DAC1100), which is able to degas the mixture in a vacuum. Two different compositions are chosen to see differences in the printability and the strength of the extruded part. Kolli et al. shows that 4 wt% HPC of 370.000 Molecular Weight (Sigma Aldrich) in 1-propanol (Sigma Aldrich) gives the best results (Kolli et al., 2023). The composition of the feedstock paste is presented in Table 1-1.

Table 1-1: Feedstock paste formulation for 4 wt% HPC + 1-propanol

	Cu powder	Binder	Lubricant
Wt%	94.81	4.36	0.76
Vol%	62.42	32.63	4.94

A syringe-type container is with the paste material. During the process, the plunger of the syringe is pushed with compressed air, called the extrusion pressure. An optimized set of parameters is found between the nozzle diameter, printing speed, extrusion pressure and printing strategy of the material to achieve high-density parts. In this case a unidirectional hexagonal stacking with sufficient overlap between the extruded material is used. Figure 1-13 presents an idea of different printing strategies with varying layer thickness (LT) and scan spacing (SP).

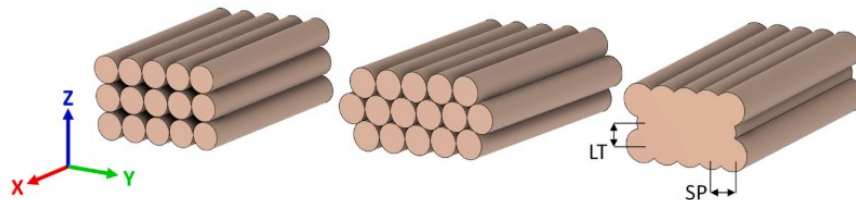


Figure 1-13: Schematic representation of printing strategies: unidirectional stacking (left), unidirectional hexagonal stacking (centre), unidirectional hexagonal stacking with overlap of the fibres (right) (Kolli et al., 2023).

The parts still contain the binder material after drying which needs to be removed to achieve higher densities. This is done by burning out the additives during the debinding step at a temperature of 550 °C for 5 hours in an Argon gas atmosphere. Followed by a pressure less sintering step of 1050 °C for 5 hours. The post-processing was preformed using a horizontal tube furnace (Carbolite, model: CTF 12/65).

The above process results in highly-dens parts, with up to 98.8% theoretical density. The results show that the mixing of the paste has a major influence on the packing density of the paste. Optical images in Figure 1-14 show cross-section of the sintered samples, which shows micrometer-sized porosities. It is clear that degassing the paste material only helps in the elimination of larger air bubbles but is not able to completely remove these micrometer-sized air bubbles from the paste mixture, which results in an estimated porosity of 3.4%.

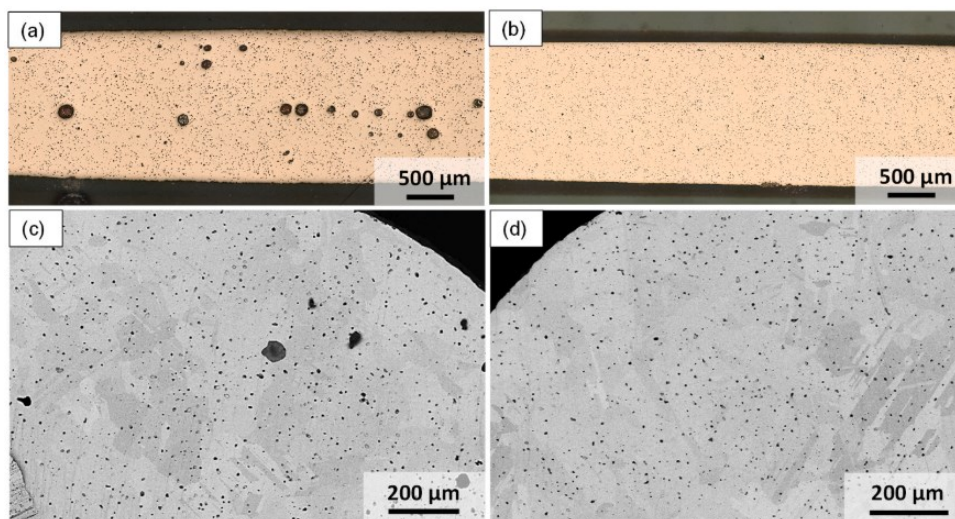


Figure 1-14: Optical microscopy images of the longitudinal section of as-mixed (a) and degassed (b) sintered copper fibre. The SEM micrographs of the cross-section of the as-mixed (c) and the degassed (d) fibres (Kolli et al., 2023).

1.5 Problem approach

The question is now, how it is possible to combine both methods discussed in section 1.4 to achieve crystal alignment during additive manufacturing of high-density ferromagnetic parts for electrical machines. The problem is split into two major sections: pre-magnetization of the Fe_{6.5}Si powder and magnetic field-influenced 3D extrusion.

This paper will make use of pre-sintered single crystal Fe_{6.5}Si powder with the Particle Size Distribution (PSD) depicted in Appendix A, which was determined using a LS 13 320 particle size analyzer (Beckman Coulter™). The shape and size of the powder from the PSD analysis, the d₁₀, d₅₀, and d₉₀ are measured to be 7.78 μm, 24.38 μm, and 47.81 μm, respectively. The as-purchased material used for the pre-sintering is presented in Figure 1-15. Pre-magnetization is done to the magnetic saturation of the powder to induce remanence inside the material. A custom magnetic circuit is designed and build where the powder can be inserted into.

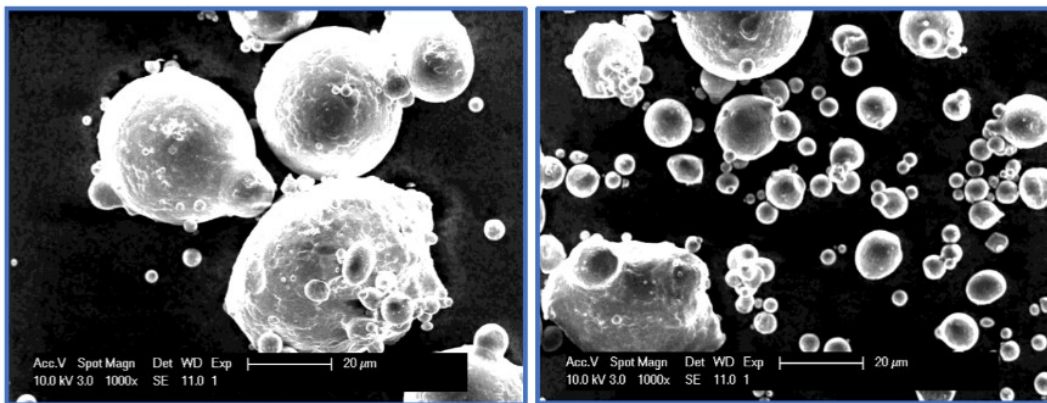


Figure 1-15: SEM image of the as-purchased single crystal Fe_{6.5}Si powder particles

The magnetic field-influenced 3D extrusion is done using paste-based material that uses a HPC and 1-propanyl binder solution. This enables extrusion of the material at room temperature and avoid the use of additional heating equipment. The magnetic field is present to invoke the remanence in the particles and to rotate them parallel to the magnetic field. As prove of concept, the magnetic field design is kept basic with no programable control of the field during printing. Either a permanent magnet or electromagnet can be used to apply the magnetic field.

Analyzing the green parts' properties is challenging due to their low strength. Therefore, the green parts undergo post-processing to debind the polymer binder material and sinter the particles to form a dense part. Small samples are tested by electron backscatter diffraction (EBSD) to see if crystal alignment is achieved.

2 Pre-magnetization of Fe_{6.5}Si powder

2.1 Introduction

The idea is to create remanence inside the single crystal Fe_{6.5}Si powder before 3D printing. Achieving the maximum remanence inside the crystals is done by completely saturating the powder in an external field. An estimated value for magnetization saturation, based on solid samples of previous research (Ouyang et al., 2019), is a flux density of 1.5 T in the powder. The goal is to create a closed magnetic circuit with a recess where the powder can be placed into. The design of a toroidal and rectangular electromagnet is described in this chapter.

2.2 Design requirements

The magnetization of the powder is done by a custom-designed setup of a magnetic circuit. The end result is based on criteria for operational difficulty, throughput of powder and also the manufacturing possibilities. One way to achieve this is to fill small capsules with powder so they can be first placed and then removed into the airgap of the magnetic circuit without wasting and letting the powder stick to other ferromagnetic material when it is magnetized. The concept is presented in Figure 2-1.

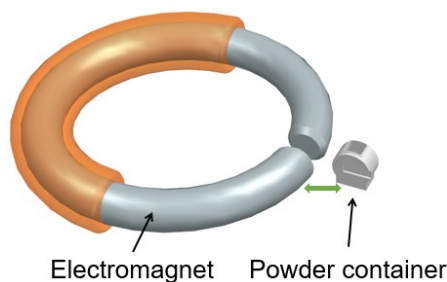


Figure 2-1: Concept representation of a magnetic circuit

The throughput of the powder is based on the size of the container and is important for practical and economic reasons. The time that the powder is exposed to air should be reduced to prevent oxidation by forming a SiO₂ layer around the Fe_{6.5}Si crystals. The enclosed volume of powder will be as large as possible to lower the amount of refilling the capsules.

The circuit should be able to put the powder under complete magnetic saturation, which is an estimated flux density of 1.5 T (Ouyang et al., 2019). It is possible that magnetization saturation may be lower because of the use of single crystal material which can rotate freely and do not share grain boundaries with other particles. To achieve a magnetic flux density of 1.5 T while using metals susceptible to saturation as the core material, one approach is to implement flux concentration where the magnetic field is locally concentrated, thus increasing its intensity. This is possible by an area reduction of the cross-section of the air gap in comparison with the core cross-section.

To monitor if this condition is reached in the powder, a flux measurement is done using a Tesla meter and a transverse Hall probe. This measurement is done by inserting the probe into the air gap where the flux density B is measured. The design of the capsule includes a thin slot for inserting the probe.

The flux generation can be achieved by permanent magnets or and electromagnet. The advantage of using the electromagnet is the capability to measure flux density over a wider range within the circuit by simply changing the current, making it possible to investigate the material properties of the powder. Using permanent magnets eliminates the use of extra current source but have a fixed value of flux density. At the design stage of the magnetic circuit the choice is made to use an electromagnet. This makes it possible to test different conditions and turn the field on and off. The electromagnet will be powered by a DC current source SM66-AR-110 (Delta electronica), which is able to give a maximum output of 55 A DC.

An important aspect is the ease of use during the operation and the possibility to create the circuit. Minimizing the length of the average flux path and preventing parasitic air gaps between different components is essential for good operation.

At last, the designs are simulated inside the Finite Element Method Magnetics (FEMM). The software in this chapter will simulate via the planar type, which can only calculate the magnetic fields in 2D.

2.3 Toroidal design

The first design is made of a single low carbon steel rod bent into a ring to form a toroidal shape. Constructing the electromagnet core from a single piece effectively prevents the formation of parasitic air gaps when core components are misaligned. This simplifies the setup and reduces the room for errors. To gain insight into potential core dimensions, the available rod dimensions in the lab were examined. Starting with the available rod diameters, a maximum diameter of 25 mm is selected. However, bending this into a toroid shape requires a lot of force. Therefore, a trade-off is made for a smaller diameter of 20 mm.

2.3.1 Analytical calculations

Before building the design, an understanding of the dimensions is needed, to verify that the flux densities are possible to reach. The magnetic circuit can be modelled by using Ampère's circuit law:

$$\oint_l \vec{H} \cdot d\vec{l} = N \cdot I \quad (2.1)$$

Which can be simplified:

$$H \cdot l_m = N \cdot I \quad (2.2)$$

The assumption is made that the field strength H is uniform along the circuit with mean length l_m of the closed loop. The excitation by the coil with N turns conduct a current I . Another component in the magnetic circuit is the reluctance $\mathcal{R}$, which stands for magnetic resistance. This depends on the relative permeability of the material used for each component, as well as the length and cross-section of the path.

$$\mathcal{R} = \frac{l}{\mu_0 \mu_r A} \quad (2.3)$$

The magnetomotive force (MMF) $\mathcal{F}$, that can be written as three different formulas:

$$\mathcal{F} = N \cdot I = \phi \cdot \mathcal{R} = H \cdot l_m \quad (2.4)$$

The magnetic circuit with the reluctances and source is solvable as shown in the schematic in Figure 2-2.

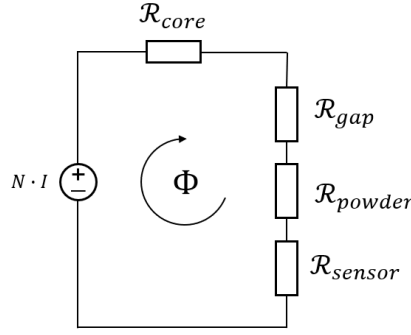


Figure 2-2: Magnetic circuit representation for a toroid

To solve the circuit in Figure 2-2, all parameters except the relative permeability of the powder $\mu_{r,powder}$ can be selected. According to previous research, which deals with high-density iron dust cores without binders, a core compressed under high pressure exhibited a permeability of 128 at 50 Hz (Yun et al., 2023). Another study that used FeSi powder noted that the permeability increases with increasing particle size, ranging from 25–75 μm , resulting in estimated permeability values of 20 to 48 μm , measured at magnetic field strengths of 3 kA/m, depending on the binder ratio used (Nowosielski et al., 2006). Considering the lack of compression in the capsule, it is anticipated that the permeability of the loose powder will be lower due to increased air between the particles. A possible advantage of using loose powder is that the particles are free to rotate, aligning themselves with the magnetic field and this way be magnetized in the easy direction of magnetization. For now, the following calculations are done using $\mu_{r,powder}$ equal to 5 as a constant value. The exact permeability of the powder will be determined by conducting tests once the setup is built. For the low carbon steel rod is a permeability of $\mu_{core} = 1404$ chosen.

The magnetic flux ϕ produced by the coil circulates around the metal core uniformly along its path. Like an electrical circuit the reluctances in series can be added to a sum $\mathcal{R}_{tot}$.

$$\mathcal{R}_{tot} = \mathcal{R}_{core} + \mathcal{R}_{gap} + \mathcal{R}_{powder} + \mathcal{R}_{sensor} = \frac{l_{core}}{\mu_0 \mu_{r,core} A_{core}} + \frac{l_{gap}}{\mu_0 A_{gap}} + \frac{l_{powder}}{\mu_0 \mu_{r,powder} A_{gap}} + \frac{l_{sensor}}{\mu_0 A_{gap}} \quad (2.5)$$

The used parameters for the lengths are as follows: $l_{core} = 400 \text{ mm}$, resulting in an inner diameter of $d = 110 \text{ mm}$. The length of the first air gap, due to the capsule wall thickness, is about $l_{gap} = 0.5 \text{ mm}$, while the airgap for the sensor is $l_{sensor} = 1.5 \text{ mm}$. Combining the two gaps for air, there will be a total of 2 mm airgap and 8 mm of powder in the circuit. Other dimensional values are visible in the technical drawing on Figure 2-3.

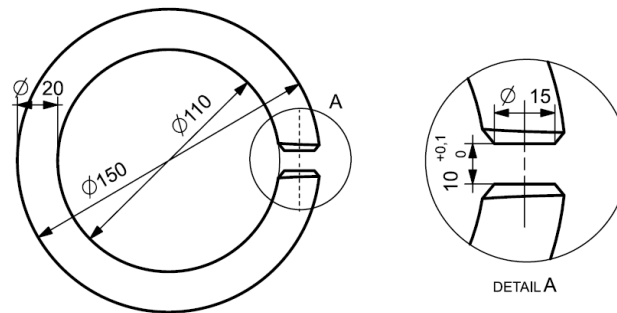


Figure 2-3: Technical drawing of the toroidal core with detail view of the air gap

The detailed view in Figure 2-3 shows the air gap as well as the chamfer designed to reduce the gap area and achieve flux concentration. The diameter of the gap is chosen to be 15 mm, to have a large enough volume of powder in the capsule, which makes the area reduction limited.

The cross-section of the core has a 20 mm diameter, while the gap area has a 15 mm diameter. However, due to the significant thickness of the air gap, fringing occurs in the gap area. This is the effect where the magnetic flux lines diverge or bulge outwards as they pass through a material with varying permeability, such as air or the powder. It is difficult to calculate the fringing effect as limited information is available, so mostly fringing is determined by simulations. A simple trick to adjust for fringing in air is by adding the thickness of the gap to the gap cross-section, as shown in equation (2.6) (Tumanski, 2016). The artificial increase in area lowers the flux density, and mimics divergence of the field. Because the gap will be filled with powder, the presence of the permeability of the powder will reduce the fringing effect. To simplify the situation, it is accepted that only the thickness of the container walls will have fringing. The most conservative calculation is when the two airgaps are connected, increasing the cross-section with 2 mm like is calculated in (2.7).

$$A_{gap,air} = \pi \cdot \frac{(d_{gap} + l_{gap})^2}{4} = \pi \cdot \frac{(0.015m + 0.010m)^2}{4} = 4.91 \cdot 10^{-4} m^2 \quad (2.6)$$

$$A_{gap,2mm} = \pi \cdot \frac{(d_{gap} + l_{gap})^2}{4} = \pi \cdot \frac{(0.015m + 0.002m)^2}{4} = 2.27 \cdot 10^{-4} m^2 \quad (2.7)$$

$$A_{gap,powder} = \pi \cdot \frac{d_{powder}^2}{4} = \pi \cdot \frac{(0.015m)^2}{4} = 1.767 \cdot 10^{-4} m^2 \quad (2.8)$$

$$A_{core} = \pi \cdot \frac{d_{core}^2}{4} = \pi \cdot \frac{0.020^2 m^2}{4} = 3.14 \cdot 10^{-4} m^2 \quad (2.9)$$

Solving (2.5) and filling in the values for $\mu_{core} = 1404$ and $\mu_{r,powder} = 5$ gives:

$$\mathcal{R}_{tot} = \frac{0,4 m}{\mu_0 \cdot 1404 \cdot 3.14 \cdot 10^{-4} m^2} + \frac{0.0005 m}{\mu_0 \cdot 2.27 \cdot 10^{-4} m^2} + \frac{0.008 m}{\mu_0 \cdot 5 \cdot 1.767 \cdot 10^{-4} m^2} + \frac{0.0015 m}{\mu_0 \cdot 2.27 \cdot 10^{-4} m^2} \quad (2.10)$$

$$= 14.94 \cdot 10^6 H^{-1}$$

Rearranging expression (2.4) to find the needed current in the coil too reach the wanted flux density results in the following:

$$I = \frac{\phi}{N} \cdot \mathcal{R}_{tot} = \frac{B \cdot A_{gap,powder} \cdot \mathcal{R}_{tot}}{N} = \frac{1.5 T \cdot 1.767 \cdot 10^{-4} m^2 \cdot 14.94 \cdot 10^6 H^{-1}}{100} = 39.6 A \quad (2.11)$$

The calculated current of 39.6 A is in range of the power supply and the other dimensions are a reasonable estimation for the setup dimensions.

2.3.2 Simulation toroidal

The FEMM simulation makes a triangulation and discretization in smaller triangles of the problem, called a mesh. Figure 2-4 shows the general setup of the FEMM model with the used dimensions of Figure 2-3 discussed in the previous section. Figure 2-5 shows the used mesh in this simulation.

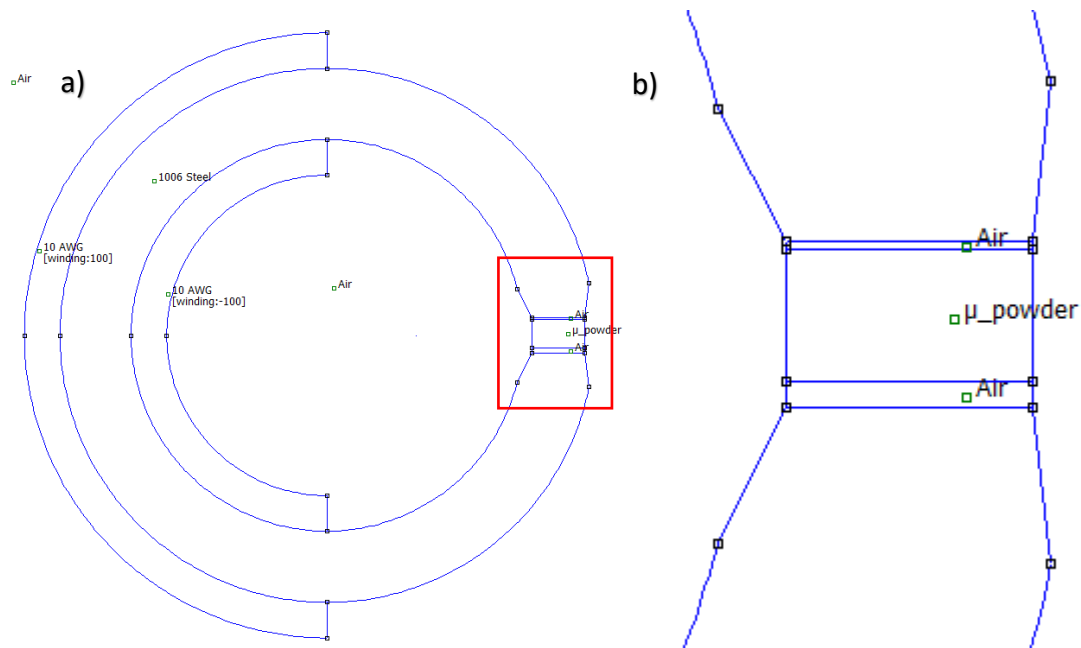


Figure 2-4: Situation setup of the FEMM model: a) Overview; b) Detailed view of the gap

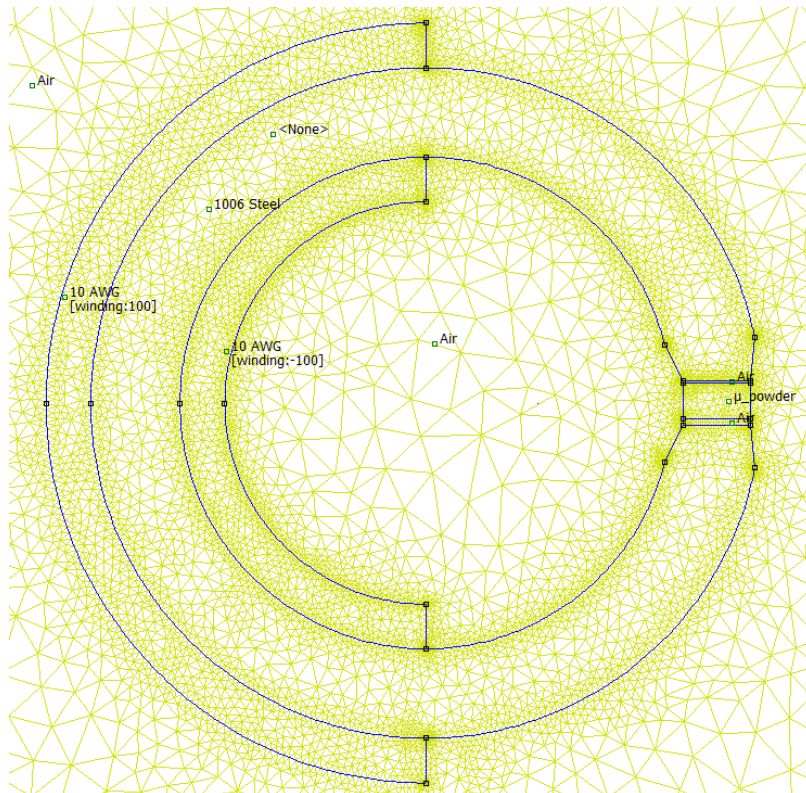


Figure 2-5: Mesh of the toroidal simulation

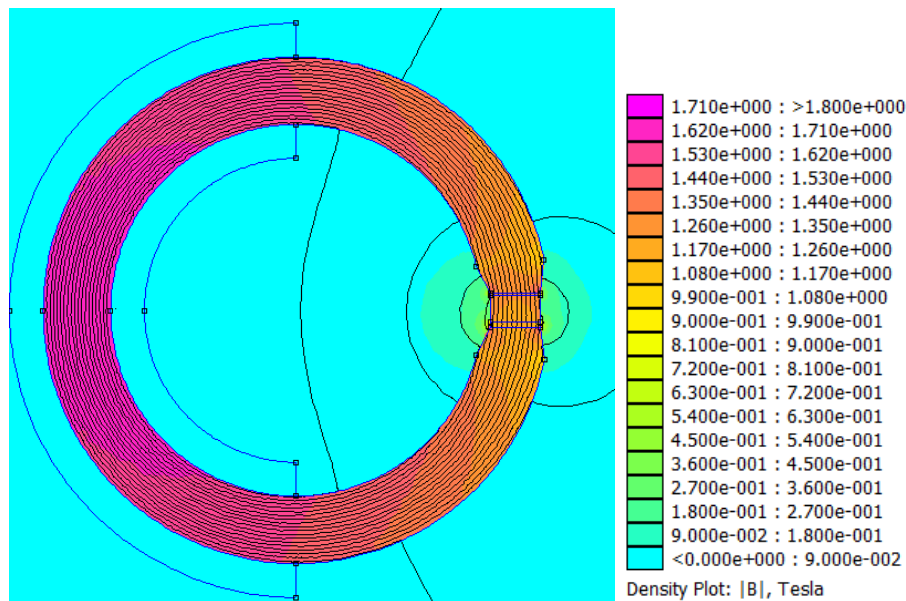


Figure 2-6: FEMM simulation results for 40 A

Figure 2-6 is the simulation for 40 A in the coil, resulting in a flux density of 1.2 T in the air gap with the powder permeability of $\mu_{\text{powder}} = 5$. The flux density in the core under the coil is at 1.65 T, which could cause saturation inside. This value in the air gap is lower than what the analytical calculation suggests, what was set to be 1.5 T.

2.3.3 Build overview

Once the concept is validated through simulations, construction of the circuit begins. The core is formed by bending a low carbon steel rod. Starting with the available rod diameters, a maximum diameter of 25 mm is selected. However, hand bending this into a toroid shape requires a lot of force. A trade-off is made for a smaller diameter of 20 mm, allowing for easier bending when locally heated with a torch to lower the Young's modulus and reduce the amount of force needed for plastic deformation. Accounting for the maximum bending radius of a rod of 20 mm diameter the inner diameter should not be too small, so 105 mm diameter is taken. This has the disadvantage that the core has a smaller cross-section so the reluctance of the system will increase, and less flux concentration is possible because the area reduction is smaller. To have a good volume of powder the choice is made to take a height of 10 mm and a diameter of 15 mm for the capsule.

The rod is spiralled around the tube in a spring shape to form a complete ring with uniform radius. After cooling, the excess material that was used to apply force for the bending, is cut off. The next step is to align the two ends by putting it under a press. The previous steps could not account for a precise 10 mm gap, but this can be achieved by a milling machine with a 10 mm diameter finger milling cutter. Passing the cutter through the gap creates a perpendicular and accurate gap. The last step of the core formation is to add the chamfers of the flux concentration. At this point, the precise dimension of the chamfer is difficult to machine because of the ring shape. The decision is made to do the area reduction by hand with a hand-held grinder. The only important dimensions are 15 mm diameter of the ends and that the surfaces are aligned above each other and not shifted. To have some guidance, a small piece of 10 mm thick and 15 mm diameter rod is glued in the gap. This will work as a reference to achieve a round surface at the two ends of the rod. Later the guide piece is removed. The end result of the toroidal core is visible in Figure 2-7.



Figure 2-7: Toroidal core with isolation tape applied

Inducing the magnetic flux is achieved by an excitation coil. From the calculations and simulation an estimation of 100 windings is made. Using a copper wire thickness of 1.25 mm, which is the biggest diameter that is still easily bendable by hand. The maximum current that it can handle is around 25 Ampère for short duration of ten seconds to conduct the tests. When increasing the current or duration the heating of the wire would destroy and deteriorate the protective isolation layer on the winding and leading to wire contact between each other, making a short circuit. Because the current source can provide up to 55 Ampère, an additional 100 windings are added parallel to the existing winding. The final toroid has a total of 200 windings, but in two parallel wires. It is important to remember in this chapter, that when 50 A is injected, each wire receives 25 A. The end assembly of the toroidal core with connection wires is depicted in Figure 2-8. The further calculations will use 100 windings with the 50 A injection because this is the reading on the current source, therefore no recalculation is needed.



Figure 2-8: Toroidal electromagnet design

2.3.4 Measurements

The finished toroidal core can now be tested to verify if it matches the simulations that were conducted. To solve equation (2.14), one more variable is unknown. This is the flux density B in the air gap. By using a Tesla meter probe, a precise measurement is possible.

2.3.4.1 Teslameter

The measuring device used in all the following measurements is the FH 55 Gaussmeter or Teslameter from Magnet-Physik. This meter is used to get an estimation of the order of magnitude of the flux density. The corrected accuracy of the meter is 0.25% to 3 T, which means a difference of 4 mT in the range of 1.5 T. Because the measurements are only used as an indication, the error is neglected so no error bars are included during this paper.

The complementary Hall probe exists in two different configurations. In Figure 2-9 is the axial and transverse Hall probe that measure the flux density B under a different angle. The axial probe must be held parallel with the field lines, see the arrow B , and touch the surface with the tip of the probe. The transverse probe is held perpendicular to the field lines with the side of the probe touching the surface of the sample. The location of the sensor in the transverse probe is located 2 mm from the end of the slat, and has a thickness T of 1 mm.

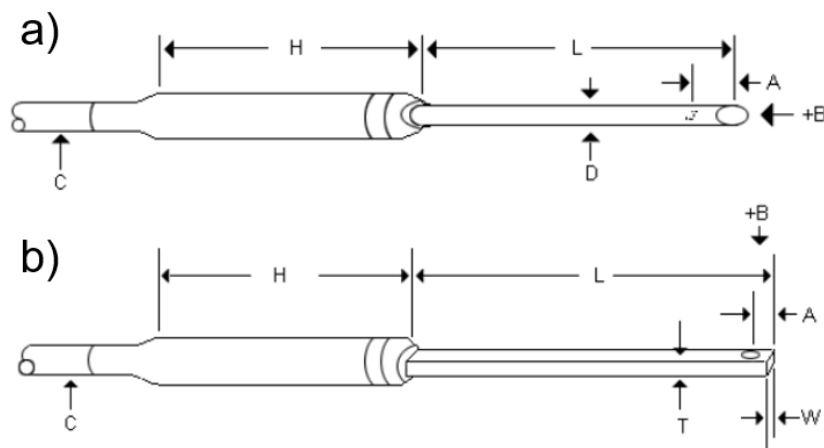


Figure 2-9: Hall probes: a) Axial; b) Transverse (Magnet-Physik, 2018)

2.3.4.2 Initial tests using the axial Hall probe

For the initial test, only the axial probe is available in the lab. To try taking measurements, the probe must be positioned at an angle to fit the flat tip within the air gap. By calculating this angle of 45° , it is possible to find the actual flux density inside the air gap. A schematic representation of the setup is visible in Figure 2-10.

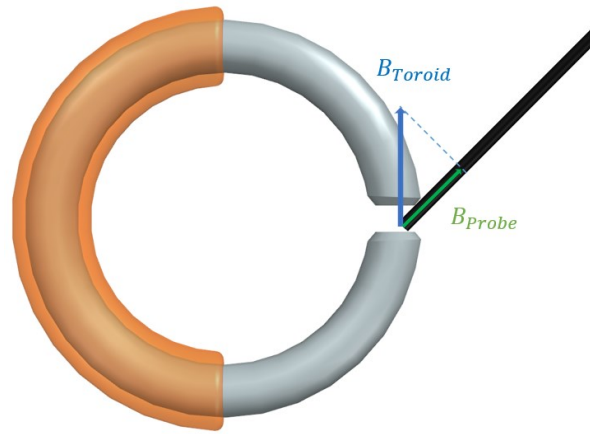


Figure 2-10: Measurement setup with axial probe under a 45° angle

When the measured flux density is known, the actual B in the circuit can be found using:

$$B_{toroid} = \frac{B_{Probe}}{\cos 45^\circ} \quad (2.12)$$

In Figure 2-11 is a CAD model of the capsule with the cross-section and the circular clearance for inserting the round axial probe during the measurements.

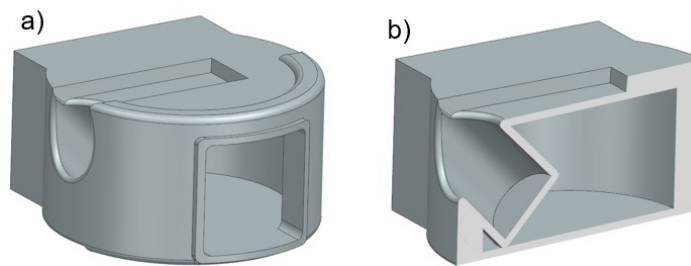


Figure 2-11: a) CAD model of the powder capsule; b) cross-section

To verify that this approach is reasonable, the probe is also placed under the smallest possible angle. Perfect alignment with the field lines is not possible, but a comparison is possible. The results for a test with 13 A injected in the coil are presented in Table 2-1 for different angles.

Table 2-1: Flux density measurements using the axial Hall probe

Material in the gap	B at 45° angle	B at 5° angle	Calculated B in the circuit
Air	98 mT	150 mT	138 mT
Powder	83 mT	/	125 mT

Table 2-1 includes the results for the test with the capsule filled with powder. It is expected that the presence of the powder will reduce the reluctance of the air gap, because of the ferromagnetic properties. However, the measured value of 83 mT is lower than the flux observed for only air. It is concluded that the measurement is not representative of the flux in the circuit, as it is not possible to achieve a lower flux density when the reluctance is reduced. The reason why the measurement is lower, is because of the non-uniformity of the magnetic field inside the capsule, caused by distortion in the cutout where the probe is inserted. This is not the case with air where there is uniformity due to lack of material preference. Filling the capsule with the powder causes the field lines to diverge and prefer the

material with higher permeability, which is the powder. This is verified with a simulation inside FEMM that is only an indication, where it is visible how the field lines avoid the probe sensor, Figure 2-12.

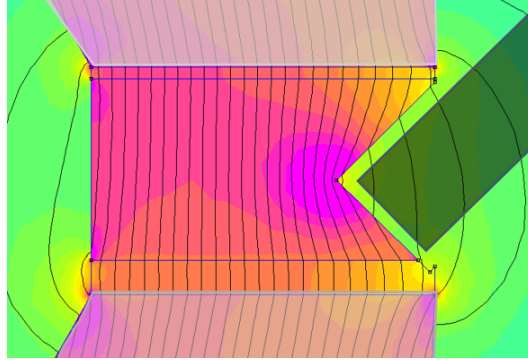


Figure 2-12: FEMM simulation for indication of distortion with the core (grey) and the probe (black) and powder in the air gap

2.3.4.3 Second test using the transverse Hall probe

To ensure the measurement of the field is conducted without distorting the uniformity of the field lines, the transverse Hall probe as in Figure 2-9b) is used. A slot is created where the probe aligns perpendicular to the field lines. To make sure this condition is reached, the enclosed volume of powder has 2 parallel planes, as shown in Figure 2-13. Although the thickness of a wall is only 0.5 mm the probe would create an area with more air gap so the field lines would have the same distortion as previously. Therefore, a thickness of 1.5 mm is maintained in the capsule to ensure uniform thickness in the powder of 8 mm.

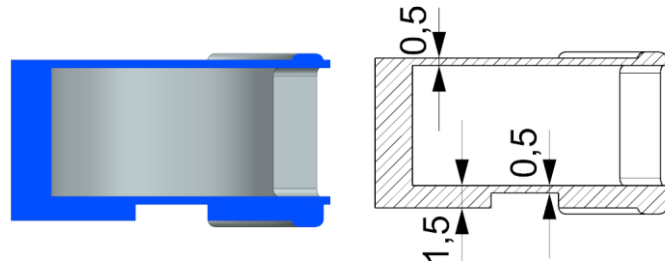


Figure 2-13: CAD rendering and technical drawing of the cross-section of the 15 mm diameter capsule

2.3.5 Results

The measurements of flux density inside the gap with a powder filled capsule are done ranging from 6 A to 40 A and presented in the Figure 2-14. Finding the last unknown variable $\mu_{r,powder}$ is possible when the equations are rearranged as follows:

$$\mathcal{R}_{powder} = \mathcal{R}_{tot} - \mathcal{R}_{core} - \mathcal{R}_{gap} - \mathcal{R}_{sensor} \quad (2.13)$$

$$\mathcal{R}_{tot} = \frac{N \cdot I}{B_{gap} \cdot A_{gap}} \quad (2.14)$$

$$\mu_{r,powder} = \frac{l_{powder}}{\mu_0 \mathcal{R}_{powder} A_{gap}} \quad (2.15)$$

The above equations enable the analytical calculation of the $\mu_{r,powder}$ for different field strengths by changing the current. The result is also presented in Figure 2-14.

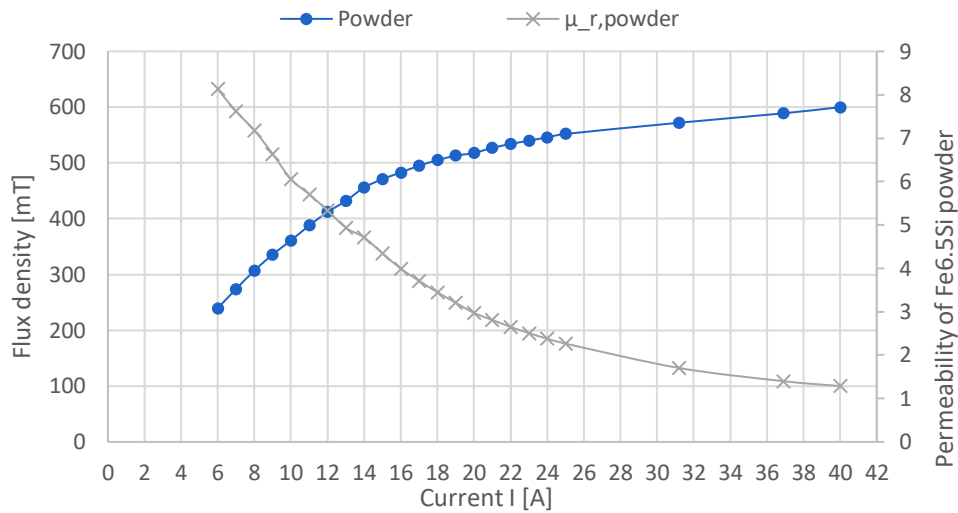


Figure 2-14: Toroidal measurements for the powder filled capsule of 10 mm thickness

The results show similar behaviour as saturation of a ferromagnetic material. The linear and non-linear relation between the current and flux density is visible in the measurements. What is unexpected is the level of saturation, which is expected to be higher than 0.6 T for strong ferromagnetic materials.

The calculation of the $\mu_{r,powder}$ is linked to the same current levels. The decrease of permeability is expected once the linear behaviour of the material is not maintained. Note that the changing permeability of the material was not accounted for in the design process and that it was estimated that the permeability would stay constant of $\mu = 5$, which is incorrect.

To see the calculated result for $\mu_{r,powder}$, the FEMM simulation is solved using the calculated permeability for the matching current levels. This is to compare the measured result with what is expected from the simulation. The measurement in the powder, the calculated $\mu_{r,powder}$ and the simulated values are presented in Figure 2-15.

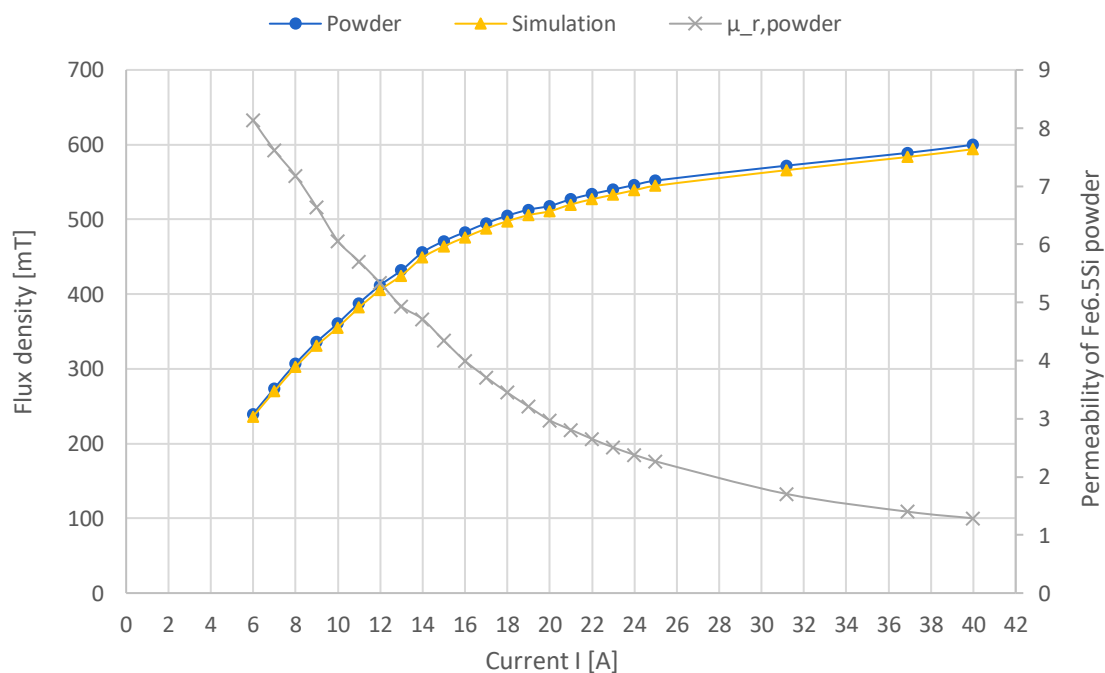


Figure 2-15: Flux density in the air gap for powder filled capsule

The results of the measurements differ from the analytical calculation because there was no accounting for the nonlinear material characteristics. Additionally, the assumption is made that the flux density is uniform in the core. This is not the case as is visible in the simulations in Figure 2-6, because of the gradually increase in reluctance the flux density gradually decreases based on the travelled distance. Because the coil is at the opposite end of the toroid, the gap will have a lower flux density than expected.

A few mistakes are being made in the calculation of the permeability. The first simplification is that the linear permeability of the 1006 steel is used to calculate the powder permeability. This will likely not be correct because the used core material will not show only linear behaviour in the tested range, but also saturate under the tested conditions. Now the complete change in permeability is assigned to the powder, which in reality will be a combination of the powder and the core. Solving this problem is not possible without knowing the exact nonlinear material properties of the core material. This can then be used to get the relative permeability for each field strength in the core, which will influence the reluctance to calculate the reluctance of the powder.

2.3.6 Summary

The measurements on the physical design show large deviations with the simulated model. The simulations are done during the design stage of the toroid and suggested that flux densities of 1.5 T are possible to reach. This is not the case with the physical setup.

An explanation for the difference is found mostly in the dimensions and material choice. Because the properties of the low carbon steel are not exactly known, the magnetic properties are most likely not ideal. The addition of carbon and other elements into the material will worsen the magnetic conditions of the steel. Only based on this information the saturation of the core will be significantly lower than 1.5 T. The saturation of the core at lower flux density levels than 1.5 T was partially expected and accounted for with the flux concentration by reducing the gap area, but because the reduction is limited from 20 mm to 15 mm diameter, this effect is minimal.

The material properties were also affected by the building process of the core. Cold deformation of the crystal structure in the rod significantly lowers the magnetic properties of the material. So, by bending the rod to the toroidal shape, the plastic deformation resulted in a lot of distortion in the crystal structure, making the magnetic properties worse. Recrystallization of the core could recover damage inside the material, but this means heating the material above 700 °C, which will destroy the copper windings, having to rebuild the toroidal electromagnet.

2.4 Rectangular design

For the success of crystal alignment, it is important to reach higher values of B in the circuit so complete saturation in the powder is reached. The physical changes needed on the toroidal core are significant which makes it impossible to modify this design. The only way to success is by redesigning the circuit with the previous information and insight in mind. This section will discuss the thought process of designing the new rectangular core as well as the simulations and measurements.

2.4.1 Improvements

The biggest difference between the toroidal and the rectangular design is the increase in cross-section. It is also important that the effect of flux concentration is significantly larger than in the previous design. Fiorillo investigated the dimensions of the pole tips of an electromagnetic system (Fiorillo, 2004). The optimal taper angle is determined to be $\beta = 54.74^\circ$ to obtain the maximum possible flux density inside the air gap, at the cost of area reduction of the gap cross-section. Figure 2-16 shows an example of the flux density increase when the system has a relation between the gap distance l_g and the core diameter D . Note that tapering the poles only increases the B when otherwise saturation behaviour would occur, the values in the linear part of the material are the same.

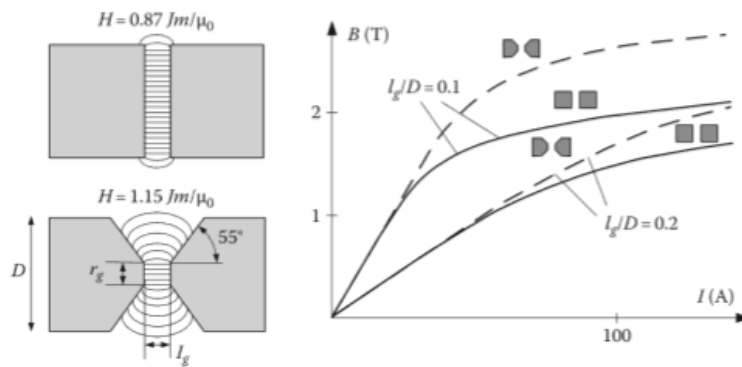


Figure 2-16: flat and tapered poles of an electromagnet (Tumanski, 2016)

The second improvement is the choice of material to use as the core material. Electrical steels have known saturation point around 1.5 T which can slightly differ depending on the NGO or GO types. For the design only DC-characteristics are important, which means that the type of electrical steel is less important. For this design leftover pieces of rectangular plates are used. They have dimension of 120 x 100 mm with a thickness of 0.36 mm.

The third improvement is adding more flexibility in the setup by making it possible to change the air gap distance by reconfiguring the circuit. This is not possible with the toroidal design where the ring shape of the core has a fixed gap thickness.

2.4.2 Analytical calculations

The following calculations are done without the powder permeability in mind, and only the achievable flux in the air gap. This eliminates the uncertainty of the powder behaviour. While the permeability of the powder will be close to one, the same as for air, for high flux densities.

Using the pre-cut electrical steel plates already define the dimensions of the magnetic circuit. To limit the amount of work to cut all the material plates to shape, one cut is done through the middle of the plate to have two identical pieces of 120 x 50 mm. These rectangular plates are layered upon each

other to form the laminated core blocks for the magnetic circuit, which needs five identical blocks. There is enough material to achieve a stack height of 18 mm for all the blocks. By adding a different type of electrical steel with a thickness of 0.50 mm the thickness of the core is brought to 20 mm. The average length and cross-section of the core are determined in equation (2.16) and (2.17). In addition, the reduction in gap area is reduced to a square of 20 x 20 mm.

$$l_{core} = (0.12 \text{ m} \cdot 4) + (0.025 \text{ m} \cdot 4) = 0.580 \text{ m} \quad (2.16)$$

$$A_{core} = (b \cdot h) = (0.05 \text{ m} \cdot 0.02 \text{ m}) = 0.001 \text{ m}^2 \quad (2.17)$$

$$A_{gap} = (b \cdot h) = (0.02 \text{ m} \cdot 0.02 \text{ m}) = 4 \cdot 10^{-4} \text{ m}^2 \quad (2.18)$$

The reluctance of the circuit is calculated based on the previous equation (2.5) with an air gap of 6 mm and the electrical steel permeability $\mu_{core} = 7493$:

$$\mathcal{R}_{tot} = \frac{0.580 \text{ m}}{\mu_0 \cdot 7493 \cdot 0.001 \text{ m}^2} + \frac{0.006 \text{ m}}{\mu_0 \cdot 4 \cdot 10^{-4} \text{ m}^2} = 11.998 \cdot 10^6 \text{ H}^{-1} \quad (2.19)$$

Rearranging expression (2.4) to find the needed current in the coil with an estimated windings of 200, to reach the wanted flux density, looks as follows:

$$I = \frac{\phi}{N} \cdot \mathcal{R}_{tot} = \frac{B \cdot A_{gap} \cdot \mathcal{R}_{tot}}{N} = \frac{1.5 \text{ T} \cdot 4 \cdot 10^{-4} \text{ m}^2 \cdot 11.998 \cdot 10^6 \text{ H}^{-1}}{200} = 35.99 \text{ A} \quad (2.20)$$

This current of 35.99 A is in range of the power supply maximum output and is a reasonable setup for the dimensions.

2.4.3 Simulation rectangular

Figure 2-17a) shows the general setup of the FEMM model with the used dimensions discussed in the previous section, and Figure 2-17b) shows the used mesh in this simulation. Figure 2-20 represents the final dimensions in a technical drawing.

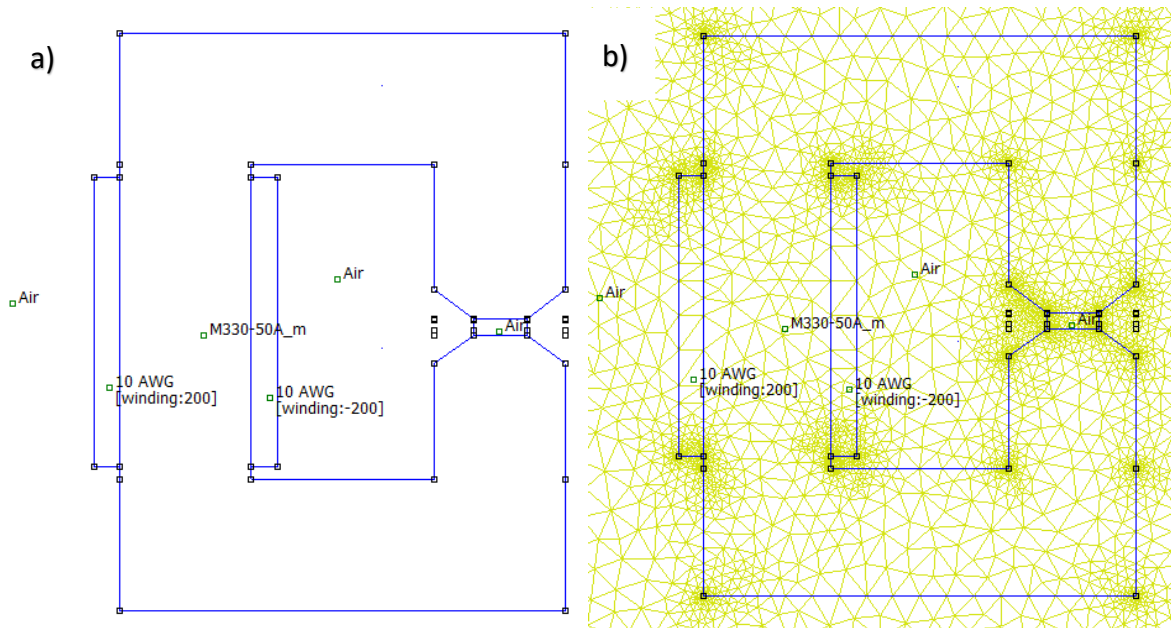


Figure 2-17: FEMM model: a) with materials; b) applied mesh

The difference with the previous simulation for the toroidal design, is that now the nonlinear material properties are used for the core material, which is shown in Figure 2-18.

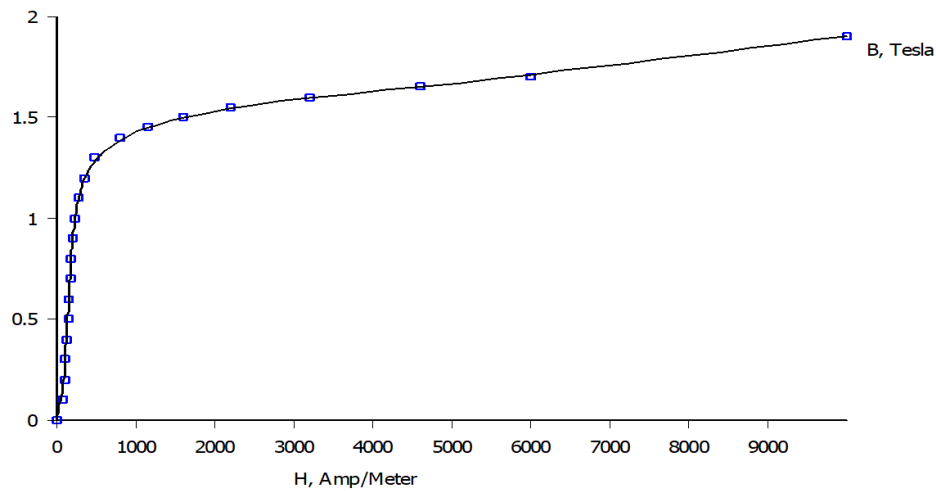


Figure 2-18: B-H curve for the M330-50A_m core material

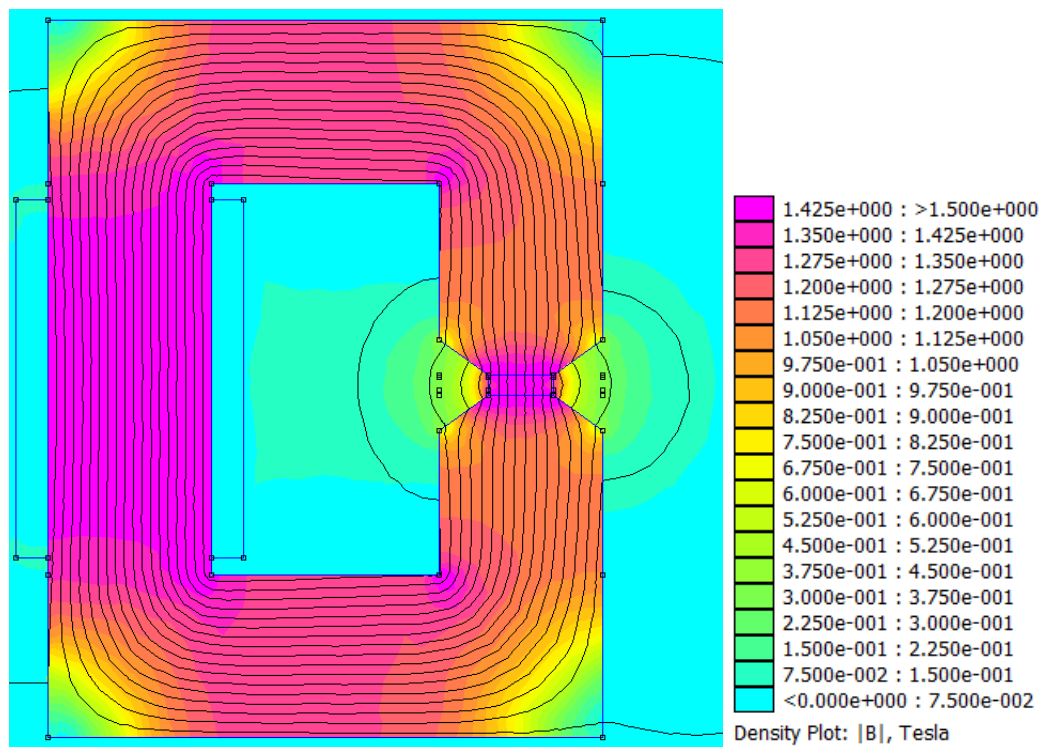


Figure 2-19: Simulation results for 35.99 A

Figure 2-19 shows the results for the simulation of 35.99 A, what is the needed current for reaching a flux density of 1.5 T in the 6 mm air gap. The flux density by the simulation is 1.436 T in the air gap. The same simulation for 25 A gives a flux density of 1.022 T. The difference in the simulation could be linked to the effect of the flux concentration and the fringing effect of the gap, what was not accounted for in the analytical calculations. It is also visible that the flux density under the coil is 1.46 T what is close to the saturation point of the electrical steel and is gradually decreasing along the travelled path. However, the values in the airgap remain reasonable, and it is still possible to achieve 1.5 T in the air gap when the current would increase, or powder would be added.

2.4.4 Build overview

Starting with the layout of the magnetic circuit that was based on the available electrical steel plates in the lab, dimensions of the five laminated core blocks are 120 x 50 x 20 mm. By cutting the plates in the middle, stacks are formed of the loose plates. The creation of the core blocks is done using two different operations of cutting the plates using a large metal scissors and machining one of the end surfaces to achieve two flat and parallel surfaces to avoid parasitic air gaps. Figure 2-20 shows the dimensions of the core and the operations indicated by colour, for cutting (red) and machining (blue).

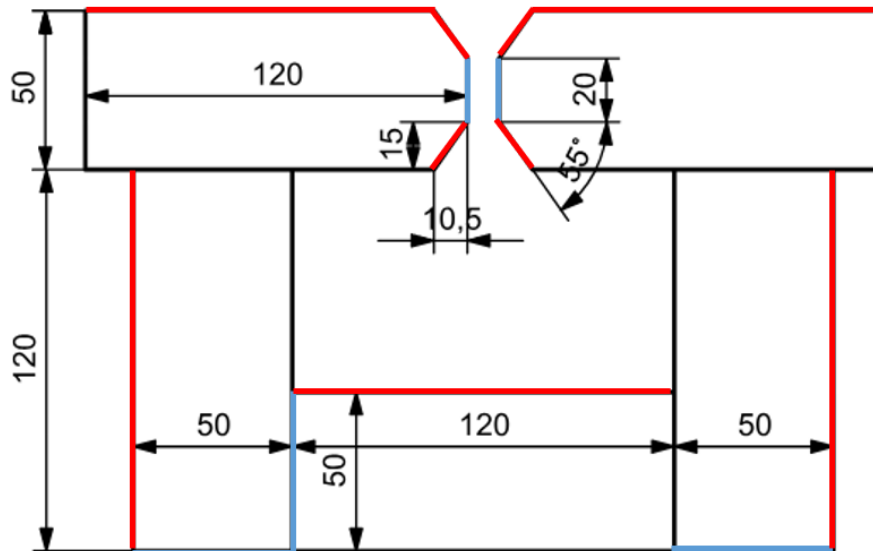


Figure 2-20: Technical drawing of the rectangular design with the cut and the machined sides indicated in red and blue, respectively

During the configuration of the blocks, attention went to orientation of the blocks so that the magnetic field lines do not cross machined or cut edges to minimize the influence of the cutting edge effect by mechanical deformation. The laminated core plates are surrounded with bolts and washers to temporarily fix them by a clamping force. Figure 2-21 shows the top surface of the blocks after machining to achieve a true flat surface and avoid parasitic airgaps.

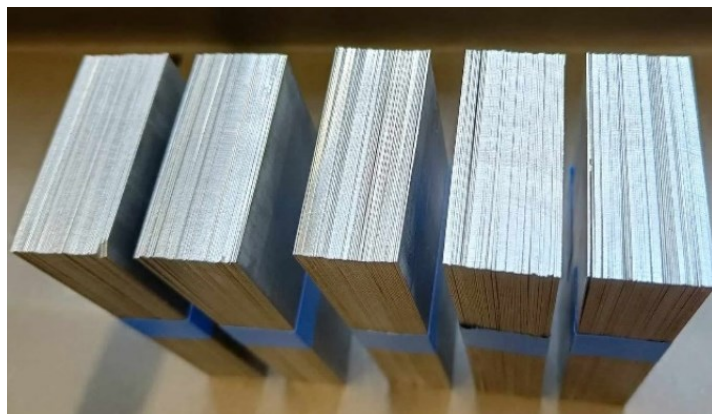


Figure 2-21: Top surfaces of the core blocks for the rectangular design

The copper wire of 1.25 mm diameter for the circuit is placed directly around one of the core blocks. Bending the wire on the sharp corners of the steel plates would cut into the insulation of the wire itself, making a short circuit with the core material, which needs to be avoided. As a counter measure for the sharp edges, extra filing of the corners and a special insulation strip of Nomex is placed over the corners

of the core block. This material has a high mechanical toughness to prevent the edge cutting through the isolation. And extra tape to hold everything in place. All these steps are needed to prevent damage to the copper wire when put under the high tension because of winding the wire. Figure 2-22 shows the insulation of the core block with 3D printed end caps to provide support for the wire.

Applying the copper windings around the core there is only enough space to fit around 70 windings next to each other. To fit 200 windings, the wire is done in three passes of each around 66 windings and then connected into series. Additional insulation is provided on the copper wire where a lot of bending is done to prevent damaging the coating of the wire and creating a short circuit. The end result of the windings and the complete magnetic circuit is presented in Figure 2-23.

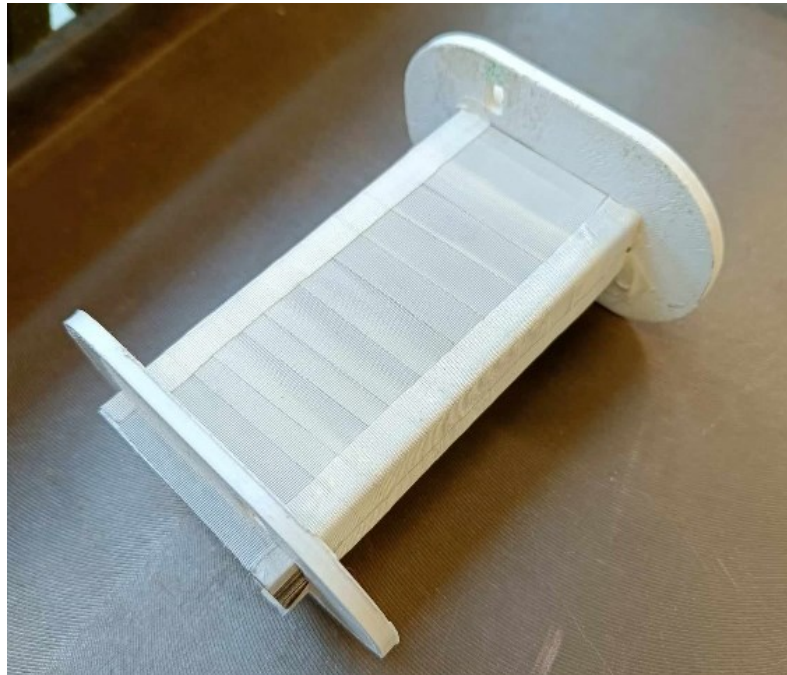


Figure 2-22: Insulated core block with Nomex and tape

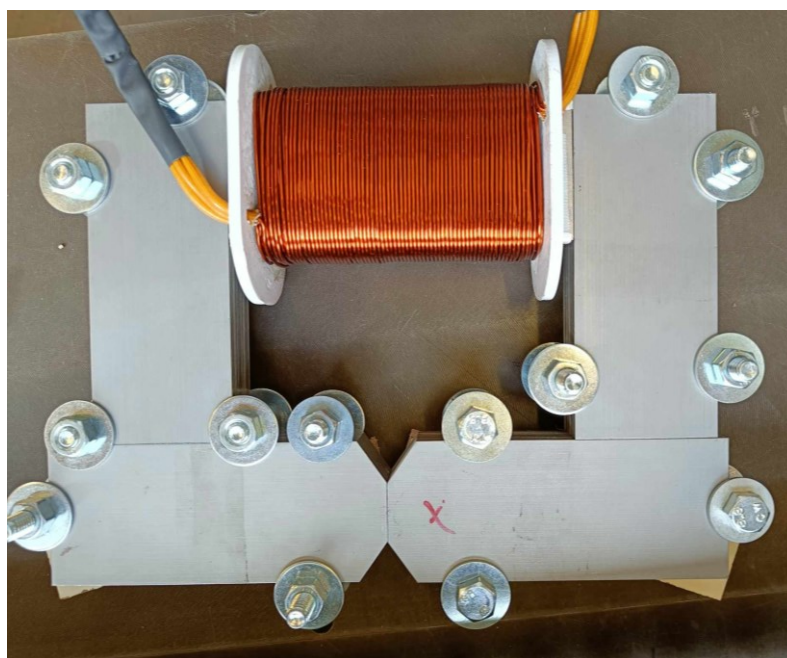


Figure 2-23: Physical magnetic circuit of the rectangular design

2.4.5 Measurements

The measurements are presented in the following Figure 2-24 for different conditions of the gap and to keep an overview, terms are assigned to each condition that will be used throughout this work:

- **Setting 1:** air, total thickness 6 mm
- **Setting 2:** powder-filled capsule with 4 mm powder, total thickness 6 mm
- **Setting 3:** powder-filled capsule with 2 mm powder, total thickness 4 mm

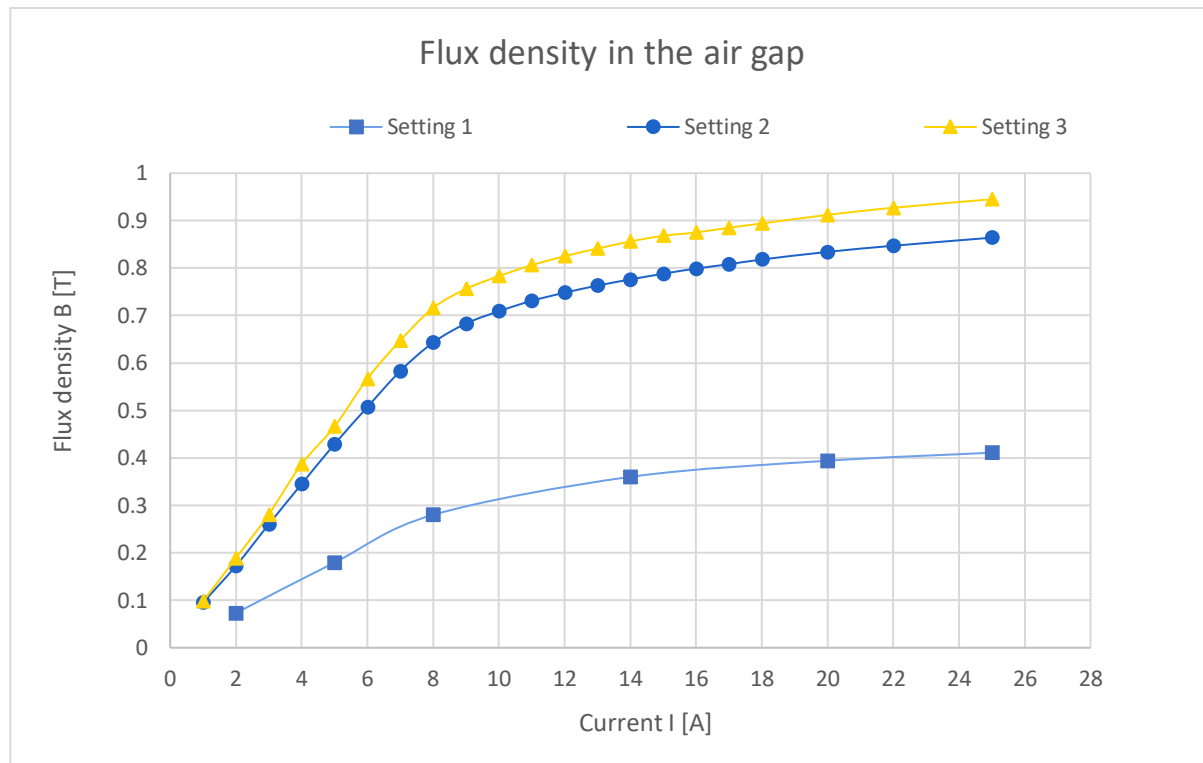


Figure 2-24: Flux densities in the gap for different conditions of the rectangular design

From the results it is visible that saturation occurs again. The level of saturation is below the expected values of 1.5 T that is achievable for most electrical FeSi steels. Even when the reluctance is reduced in the system by changing the thickness of the gap to 4 mm for Setting 3, only a slight increase is visible in the flux density. For all the settings the saturation knee happens for the same current of around 8-9 A.

A possibility is that the FeSi steel laminates under the windings saturate and limit the effect of increasing the current in the coil, but based on the FEMM simulation from 2.4.3 the flux density under the winding is not saturated yet. For Setting 1 at 25 A, the simulation gives a flux density of 1.022 T in the air gap, which is 0.6 T higher than the measured value in the setup, which is 0.4 T.

2.4.5.1 Anhysteretic curve of magnetization of the core material

The saturation of the core material consisting of FeSi steel laminates should be closer to the theoretical saturation level of 1.5 T. The physical measurements are not reaching these values. To understand why, the saturation curve of the material is directly measured by using Faraday's law by conducting an Epstein frame measurement. By reconfiguring the rectangular setup, the tapered ends are eliminated and a rectangular path for the flux lines is created, as is shown in Figure 2-25.

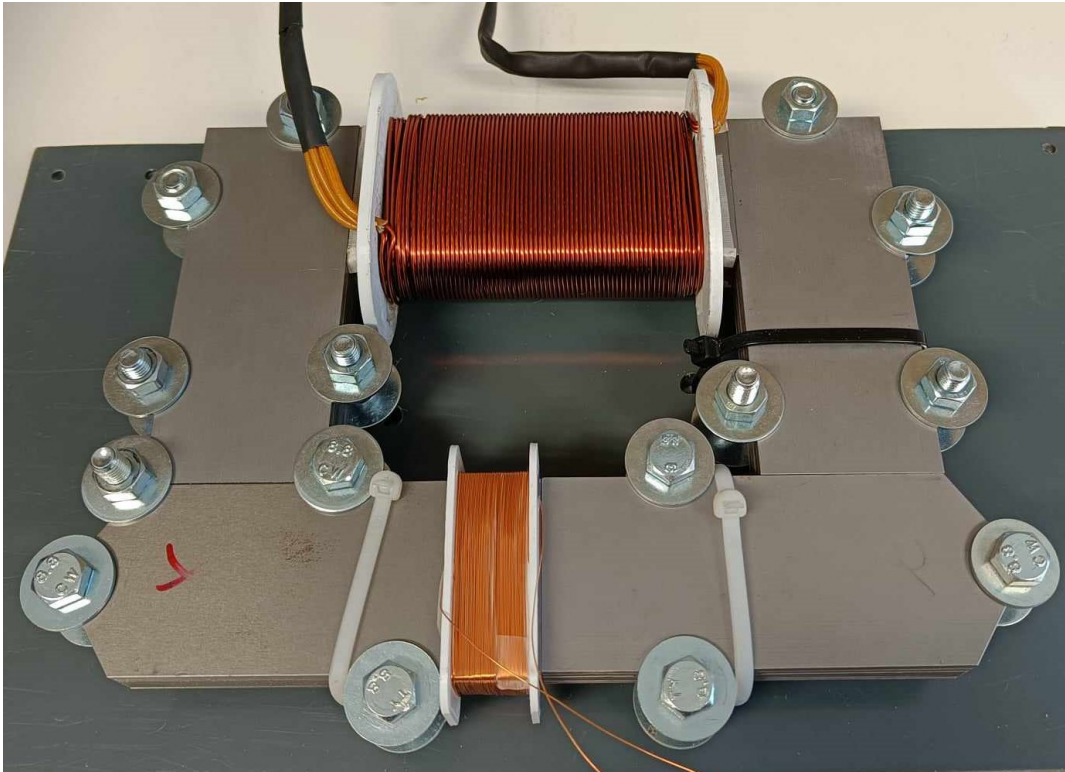


Figure 2-25: Reconfiguration of the rectangular core with a secondary measuring coil of 50 windings

The reconfiguration is to eliminate the air gap and taper during the measurement, essentially creating an Epstein frame but with different dimensions. Adding a second coil will measure the induced voltage due to the magnetic induction $B(t)$. This ensures that the secondary voltage $V_{sec}(t)$ is directly proportional to the $B(t)$:

$$V_{sec}(t) = -N_2 \cdot A \cdot \frac{dB(t)}{dt} \quad (2.21)$$

To get an estimation for the secondary voltage during the measurement, a calculation is done for a secondary coil with $N_2 = 50$ turns, the cross-section of the core A , and a changing flux density from positive to negative 1.5 T on a 50 Hz net.

$$V_{sec} = -50 \cdot (0,020 \text{ m} \cdot 0,050 \text{ m}) \cdot \frac{(1,5 - (-1,5) \text{ T})}{0,02 \text{ s}} = -7,5 \text{ V} \quad (2.22)$$

The results of the anhysteretic magnetization curve are shown in Figure 2-26. The process and algorithm of measuring the curve are standard procedure and not discussed further.

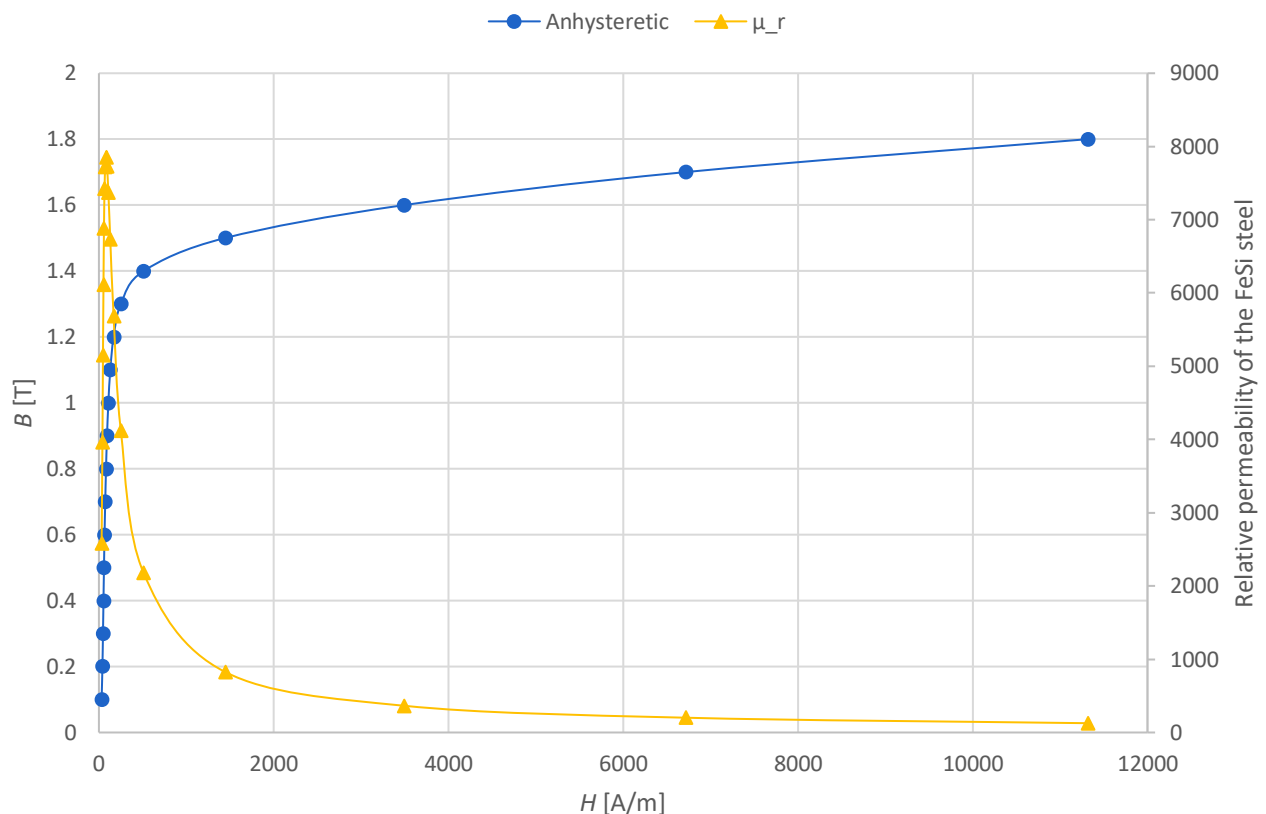


Figure 2-26: The measured anhysteretic magnetization curve and the permeability of the core material

The material properties of the core are what is expected from electrical steels, so it is still unclear why the measured values are lower than expected. This is a cumulation of several factors:

- **FEMM simulation limitations:** The current FEMM simulation only considers a 2D scenario, overlooking significant fringing effects in the 6 mm air gap, especially at the system's top and bottom.
- **Parasitic air gaps:** Despite efforts to smooth connection surfaces and aligning the laminates during assembly, uncertainty remains regarding parasitic air gaps where blocks touch each other. The influence of these gaps can be larger than expected.
- **Cutting edge effect:** Mechanical-induced plastic deformation during the cutting process disrupts grain boundaries of the material, potentially deteriorating magnetic performance. This effect can be up to 1 mm thick, but research by Wu et al. suggests a more probable range of around 250 μm depending on the cutting force (Wu et al., 2022).
- **Anisotropic orientation in NGO:** Manufacturing processes may introduce slight anisotropic orientation in the NGO, although its impact is expected to be minimal.

The results of the core material anhysteretic BH-curve are implemented in the FEMM simulation to improve the simulation values for further improvements.

2.4.5.2 Improving the setup

Modifications are needed to achieve higher flux densities in the air gap. A first approach is to see how the circuit will react when permanent magnets are added to provide a passive increase in the flux density. Two round magnets of thickness 10 mm are added between two blocks of electrical steel as presented in Figure 2-27.

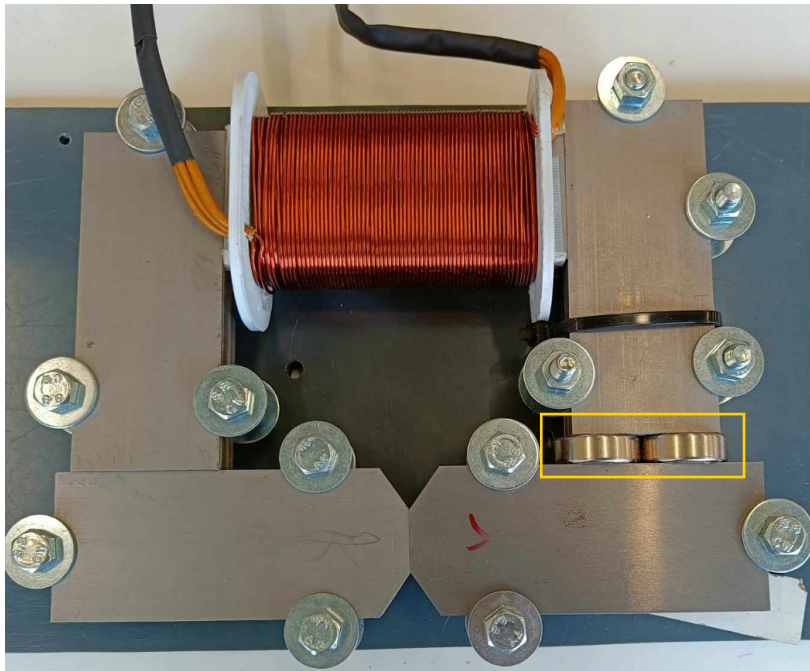


Figure 2-27: Addition of permanent magnets in the right part of the rectangular circuit

To boost the flux even higher, extra windings are added in series as close as possible to the air gap to minimize the leakage flux. The end result of two extra coils with each 41 windings is presented in Figure 2-28.

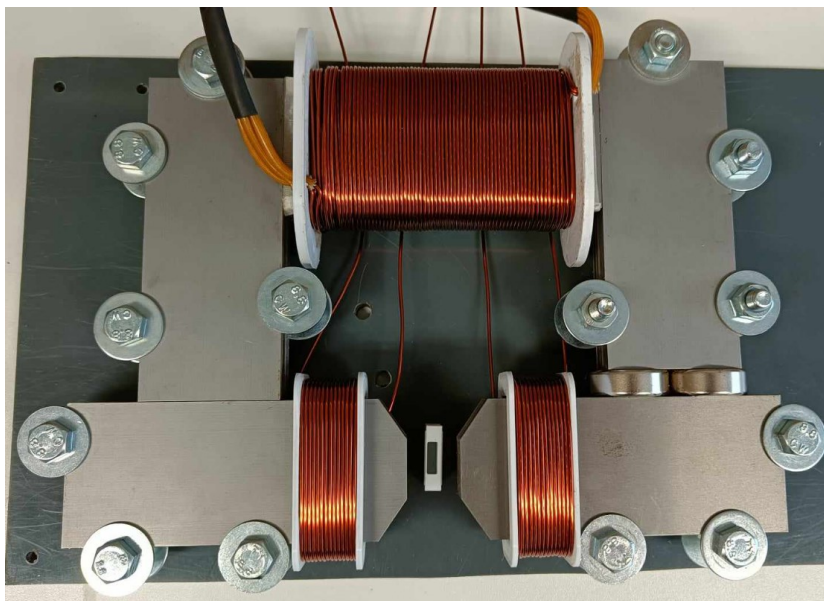


Figure 2-28: Addition of permanent magnets and two extra coils in the rectangular circuit

The additions of permanent magnets, extra coils and parasitic air gaps are also implemented in the FEMM simulation, to get an estimation of the flux density improvement of the system. The situation for a current of 25 A and a 6 mm air gap is presented in Figure 2-29.

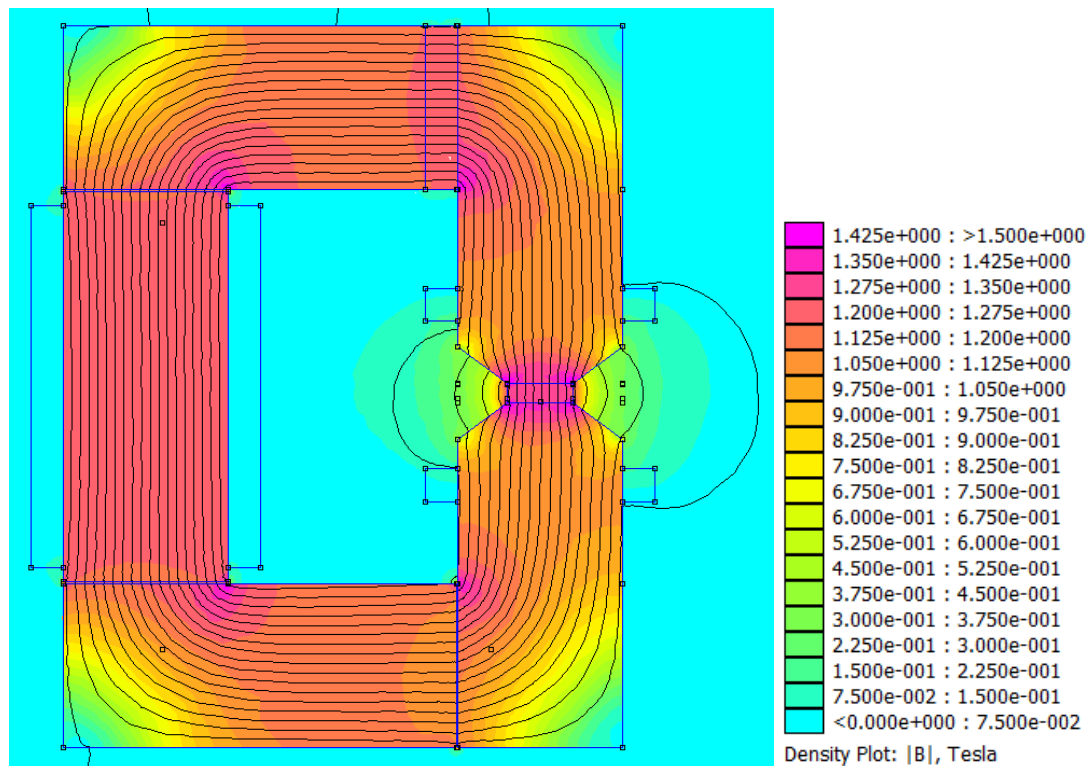


Figure 2-29: Updated FEMM simulation with additional coils (right) and permanent magnets (top) for 25 A

Measurements are made in both situations to see how the flux density B is improved in co-operation with the coil. To keep an overview, terms are assigned to each condition that was done in section 2.4.5 for the previous measurements (pg. 29):

- **Setting 4:** permanent magnet with the powder-filled capsule, total thickness 6 mm.
- **Setting 5:** permanent magnet with additional coils with the powder-filled capsule, total thickness 6 mm.
- **Setting 6:** additional coils for the powder-filled capsule, total thickness 6 mm (magnets removed).
- **Setting 7:** additional coils with air, total thickness 6 mm.

The settings 4-6 are all executed using a powder filled capsule with a 6 mm thickness. The measured results are presented in Figure 2-30 together with setting 2 as reference for the unmodified setup.

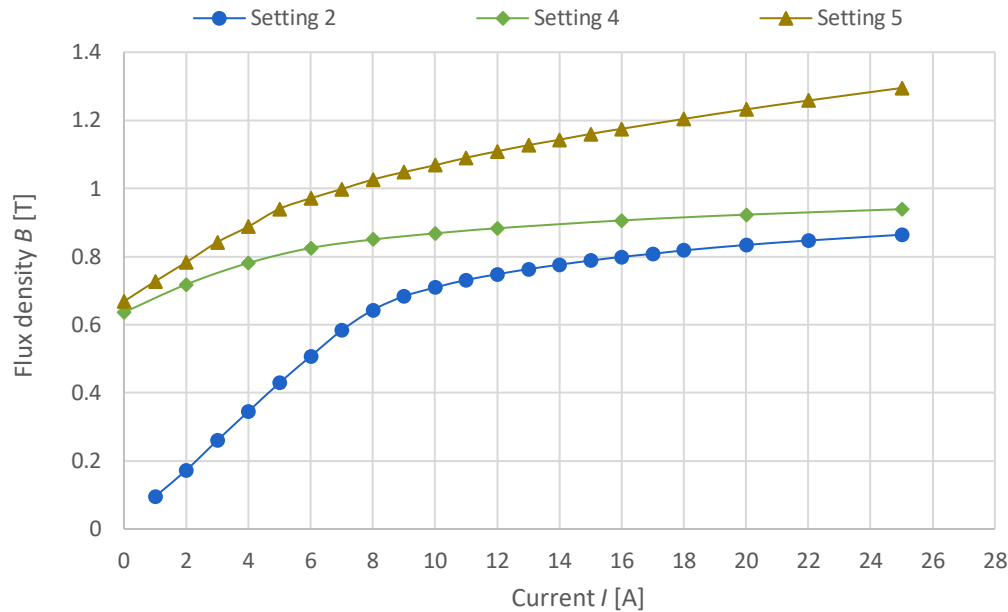


Figure 2-30: Comparison of flux density B in the gap between different settings

The addition of permanent NdFeB magnets passively generates a flux density of 0.668 T in the system when no current is active in the coil. For higher currents of 25 A and setting 4, only a small increase of 75 mT is seen in the flux density of the air gap as the saturation behaviour of the main coil is still present. The disadvantage is the low permeability of the NdFeB magnet which is around $\mu_r = 1.05$. This creates an additional reluctance for the electromagnetic system to overcome. Hence, the addition of permanent magnets has diminishing returns in combination with the main excitation coil. The problem when using strong permanent magnets is the constant attraction force between the parts of the circuit. This makes manipulating the system when changing powder capsules challenging.

Setting 5 adds an additional of 82 extra windings close to the air gap in two coils as shown in Figure 2-28. The extra coils have the largest contribution to the B field, with the 1.295 T at 25 A. The most important aspect is that the excitation happens close to the air gap. The B for high current values in setting 5 does not show any sign of strong saturation in Figure 2-30. To see if there is potential to increase the B with increasing the current, a special function on the Tesla meter is used, called the peak function. This measures the maximum value of a short magnetic field pulse that is longer than 150 μ s. This is ideal to use in this case where the heating of the coils could destroy the setup, which prevented measurements for the higher currents above 25 A before.

The setting 6 and 7 are executed without the permanent magnets for values of 30 A to 55 A. The measurements are shown in Figure 2-31. As a frame of reference, the same measurement values are added to see the improvement in flux density of the additional coils. Setting 1 and 2 are compared to the situation with additional windings, setting 7 and 6 respectively, with the matching situation but with additional coils for air (setting 7) and powder (setting 6).

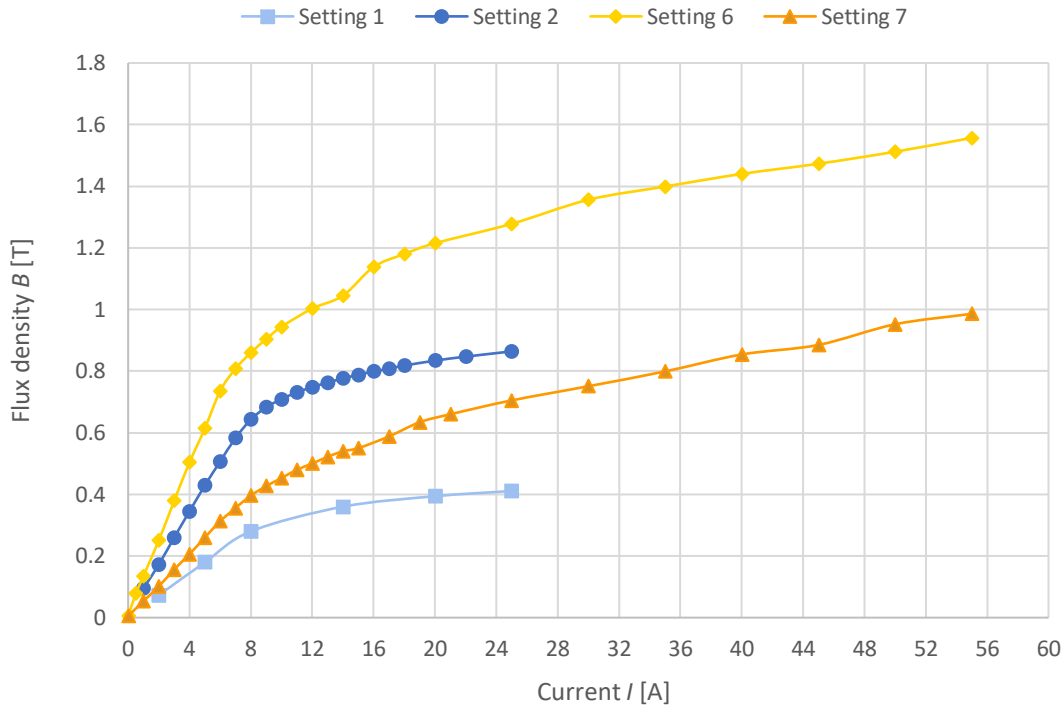


Figure 2-31: *B* measurements with high current points using the peak function

Setting 6 presents the maximum value that was reached for 55 A, $B_{max} = 1.566 \text{ T}$. The measured value in the gap with a powder-filled capsule of 4 mm powder exceeds the wanted magnetic saturation level of 1.5 T. The measurements for the high currents made use of the step function of the teslameter, which resulted in small inaccuracies. The measurements of setting 7 are compared to the simulated values to validate the updated and final simulation model, which is presented in detail in Appendix B. This is done for the 6 mm air gap in the system and the results are shown in Figure 2-32.

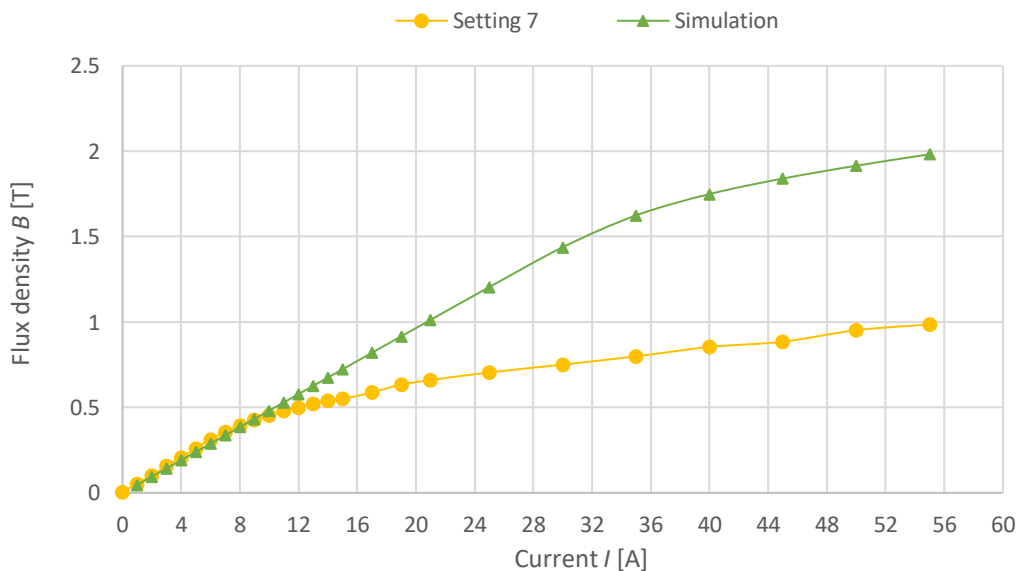


Figure 2-32: Comparison between the measured flux density and the simulated flux density in the 6 mm air gap

The updated simulation model shows a good estimation for low field strengths in the linear region, but large differences for higher field strengths when saturation occurs.

2.5 Conclusion

The executed simulations often show different values for the higher flux densities. Nonlinear behaviour of the ferromagnetic material proved to be difficult to get right in the simulations. The flux density in the toroidal design was insufficient because of multiple reasons. First the cross-section with a diameter of 20 mm of the ring is too small and leaves no area reduction to achieve flux concentration in the air gap. Also, the material choice is not ideal because of the bad magnetic properties as well as the distortion of the grain structure by cold deformation.

A second attempt to achieve higher flux densities is done. With the experience of the toroidal design, the design of the rectangular core is made. The biggest improvements included the increase in cross-section, larger flux concentration and the choice of electrical steel laminates with better magnetic properties. The measurements of the physical system shows large differences again. Extra investigation is done by measuring the anhysteretic magnetization curve of the core material by conducting an Epstein frame like test. The results showed that the core material has expected behaviour and that the error with the simulation is due to a combination of different factors: the lack in 3D simulation of the FEMM program, the parasitic air gaps, and the cutting edge effect reduce the flux density in the system.

Different improvements in the magnetic circuit are tested. The best improvement is adding extra copper windings closer to the air gap. This is to limit the leakage flux in the system and reduce the travelled path for the flux density. Because limited space is available, the two coils consist of each 41 windings, making the total amount of 282 windings in series for the magnetic system. When injecting 55 A in the coils, a maximum magnetic flux density $B_{max} = 1.566 \text{ T}$ is reached. The rectangular design can put the Fe6.5Si powder under magnetic saturation for short periods of time.

When the measurements are compared to the updated simulation model, there is a good estimation for low field strengths in the linear region, but large differences for higher field strengths when saturation occurs. This is because of the same reasons that are mentioned earlier.

3 Magnetic field-influenced 3D extrusion

3.1 Introduction

Additive manufacturing (AM) or 3D printing is a technology that is already extensively used as rapid prototyping (Cardon, 2023). The main advantage is achieving geometric and material complexity that is not possible to manufacture using conventional techniques. Objects out of Fe_{6.5}Si steels are difficult to shape using subtractive material removal processes due to high brittleness of the material.

Several types of AM are available when metal objects are produced starting from a metal powder material. Two distinctive differences are made: a direct and an indirect process. The direct process builds the object out of only the metal powder by selective laser melting (SLM) or sintering (SLS) the particles together. The indirect process makes use of a sacrificial binder to form a polymer matrix that holds the metal particles in place. This binder material can be in a solid state or partially dissolved by a liquid to form a slurry or paste which is possible to extrude (Cardon, 2023).

Generally, both direct and indirect processes require post-processing of the parts to achieve higher densification. The possible downside when using the indirect process is that the binder material needs to be removed after extrusion by a separate thermal treatment. When done correctly the two heat treatments can be joined in one longer process.

Figure 3-1 shows the complete process of the extruded part. Extruding material that exists of the Fe_{6.5}Si particles in combination with the binder is referred to as the green part. This is mostly a material extrusion process where after printing this binder is removed during the debinding step to form the brown part followed by a sintering step to end with a high dense part, referred to as the white part (Cardon, 2023; Gonzalez-Gutierrez et al., 2018).

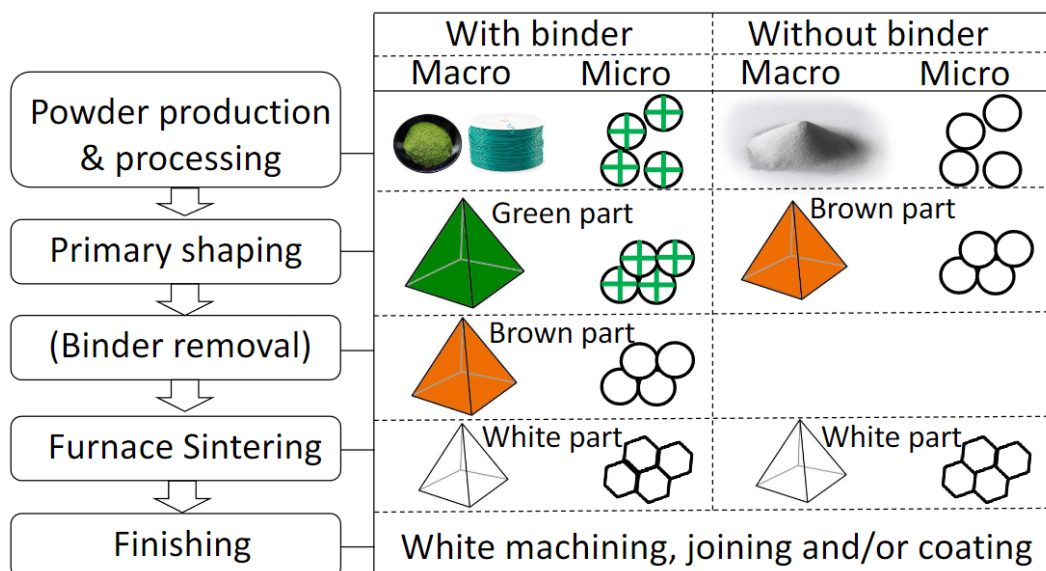


Figure 3-1: Schematic visualizing the journey of powder-based AM (Cardon, 2023)

3.2 Material extrusion

This work will use the indirect material extrusion process for the AM of the parts. The term is broad and can be split into different types, as shown in Figure 3-2 (Gonzalez-Gutierrez et al., 2018).

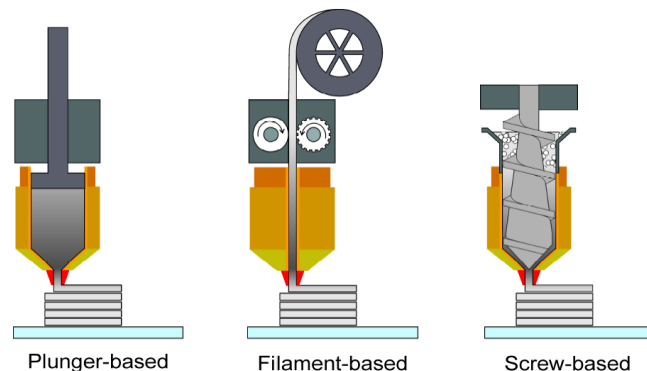


Figure 3-2: Different types for extrusion-based additive manufacturing (Gonzalez-Gutierrez et al., 2018)

The plunger-based system utilizes pressure or a lead screw mechanism to drive linear motion on a plunger within the cylindrical body, enabling material extrusion from a nozzle. It is crucial that the material is soft enough throughout the entire reservoir body to extrude. When thermoplastic materials are used as a binder, the reservoir needs to be around 200°C in case of polylactic acid (PLA). This could cause problems with the homogeneous temperature inside the reservoir because of the insulating properties of the polymer. Additionally, the heating needs to be maintained during the complete duration of preparation and the extrusion. Schyns et al. stated that this could lead to thermal degradation of the polymer through chain scission when shear stress is applied (Schyns & Shaver, 2021). Degradation of the polymer will have a negative impact on the result of the extruded part because fluctuation in chain length results in change in viscosity (Cardon, 2023). Another option is to use a solvable binder in paste form, which solidifies once the material is extruded.

The second type is the filament-based extrusion. This is the 3D printing type most known for its simplicity that makes use of thermoplastic filaments out of PLA, acrylonitrile butadiene styrene (ABS), etc. Recent years have seen an increase in commercial availability of composite materials with particles dispersed within the polymer, designed for filament fused fabrication (FFF). Gonzalez-Gutierrez et al. refer to these materials as highly-filled polymeric materials, capable of accommodating up to 40 vol% of metal particles and being formed into filaments (Gonzalez-Gutierrez et al., 2018). The challenge lies in the complexity of the filament creation, especially for small material quantities.

The third type is the screw-based extrusion that makes use of thermoplastic pellets. The principle is the same as a screw extruder that is used in injection moulding machines, but applied on a smaller scale so that it fits on the printing head. The screw has a melting zone to melt the pellets, metering zone that creates high pressure to eliminate entrapped air bubbles and a feeding zone where it exits the nozzle (Cardon & Marchesini de Oliveira, 2023). A study of Singh et al. uses a metal injection moulding (MIM) copper feedstock with 93.54 wt% of copper (Singh et al., 2021). The feedstock enters the screw-based system for extruding highly dense copper parts. The composite material filled with metal particles accelerates the erosion of the screw, which becomes a problem for the wear of the system.

3.2.1 3D micro-extrusion

This paper utilizes 3D micro-extrusion with a plunger-based system, in combination with a paste prepared in a syringe-type container. The plunger actuation is achieved by using compressed air. The advantage of this system lies in the ease of switching between paste-filled syringes. Additionally, the preparation of filling of the syringe can be done independently from the printer machine.

This process is ideal for extruding samples when only small amounts of material are available, and the metal particle content can be significantly higher. The filament-based extrusion needs larger amounts of material for filament fabrication and the particle loading is lower because of the needed strength in the filament. A screw-based system is less ideal because of the increased erosion between the screw and abrasive particles, causing screw wear in the system during operation.

Printing strategies are not investigated in detail. The unidirectional hexagonal stacking with overlap on the fibres is used, as was discussed in section 1.4.2. Although, the printing strategy has an important role in the end result of the extrusion of the samples. Heller et al. designed simulations to see the internal flow of the deposited material. Figure 3-3 shows different strategies where the Falling Flow would have the preferred strategy to limit distortion in the material flow.

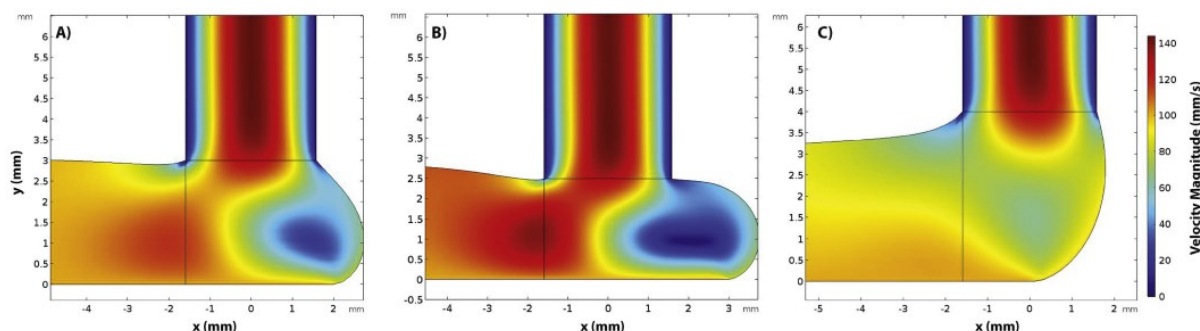


Figure 3-3: Simulated shape of the deposition and velocity (mm/s) of material: A) Level Flow; B) Bull Nose Flow; C) Falling Flow (Heller et al., 2019).

3.2.2 Paste formulation

In this study, a binder solution of hydroxypropyl cellulose (HPC) in combination with 1-propanol is utilized (Kolli et al., 2023). The 1-propanol solves the HPC as a binder solution that has good properties for wetting the powder substrate and avoids lumping of the particles (Dürig & Karan, 2019), which improves the flowability of the mixture. After extruding the paste, the dissolved 1-propanol will vaporize in the air, leaving the Fe_{6.5}Si powder in the solid HPC matrix to form the green part. In this state the green part is very brittle with low strength and must be handled with care for further post-processing.

Using a soluble binder simplifies the extrusion setup significantly compared to using a thermoplastic binder. The approach makes it possible to extrude the material in room temperature and does not need additional heating elements during extrusion. A drawback is that the viscosity of the paste is not controllable by changing the temperature like a thermoplastic polymer. By adding a small amount of lubricant materials in the paste composition the viscosity can be improved but it cannot be changed after paste preparation.

The exact paste composition is protected by VITO that prepared and provided the paste. An estimation for the composition is found in the work of Kollie et al., that is discussed in 1.4.2. The difference in metal powder will change the use of lubricants but the large similarities of particle content of 94.81 wt% or 62.42 vol% are assumed to be the same order of magnitude with small variations.

3.3 External field setup

During the paste extrusion, an external field is provided around the nozzle that will potentially align the pre-magnetized particles. Previous studies (Kim et al., 2018) have demonstrated the potential of this approach for soft robotics, as mentioned in chapter 1.4. Applying the external field is possible in two approaches: by using permanent magnets or by using the electromagnetic principles:

Permanent magnets:

Using a permanent magnet eliminates the need for an external power supply to maintain the magnetic field. The disadvantage of permanent magnets is the lack of dynamic control over the field during the printing, which may not be an issue during the proof of concept stages where stationary fields suffice. However, the inability to adjust the field strength limits the system's flexibility when experimenting with various settings to observe differences in crystal orientation.

Electromagnet:

An electromagnetic system has more flexibility in adjusting the field strength by changing the amount of current through the wire. A drawback is that the coil needs connection wires to an external current source, which could prove problems during the movement of the print head. An important consideration is the capability of electromagnets in generating a strong field, as they require more space around the nozzle to achieve equivalent field strength compared to permanent magnets.

The first idea is using the highest possible field strength to see if alignment is possible. The easiest way is to use permanent magnets that have good capability for high field strengths and eliminate the use of the extra power source. The magnetic field should be positioned near the end of the extrusion nozzle to prevent loss of alignment caused by the velocity gradient because of shear rate within the small nozzle.

Another important part for the setup is the magnetic protective shield. The extruded samples may not experience magnetic fields when they are on the print bed (Kim et al., 2018). This will have a possible influence on the alignment of the crystals when they exited the nozzle. By using a ferromagnetic plate, the magnetic field lines can be guided away from the extruded fibres to protect them from unwanted fields.

The permanent ring magnet is commercially available in various sizes. The syringe nozzle has an outer diameter and height of 10 mm each, serving as defining dimension for the magnet to fit over the nozzle. The NdFeB magnet used in this work has an outer diameter of 27 mm, inner diameter of 16 mm, and a thickness of 5 mm. By adding two magnets together some flexibility is possible to change the magnetic field strength.

3.4 Manual extrusion

The fundamental test is done by manually extruding single thickness fibres straight out of the syringe nozzle, which has an opening of 2 mm diameter. The extruded fibre thickness is around 2 mm that gives the green part enough strength to handle for later post-processing. For this experiment, very minimalistic control is needed for the placement of the nozzle in relation to the previous extrudate. The paste used for this test is made with Fe_{6.5}Si powder that is pre-magnetized above 1.2 T and paste preparation as stated in 3.2.2. Because the amount of pre-magnetized paste for extrusion is small, around 7 cubic centimetres, the extrusion setup is tested by using a non-magnetized dummy paste.

3.4.1 External field simulation: permanent magnet

The dimensions of the setup are also defined using the axisymmetric simulations in FEMM, with the axis of symmetry on the left side of the simulation view. Figure 3-4 shows the result that will be used for the final design.

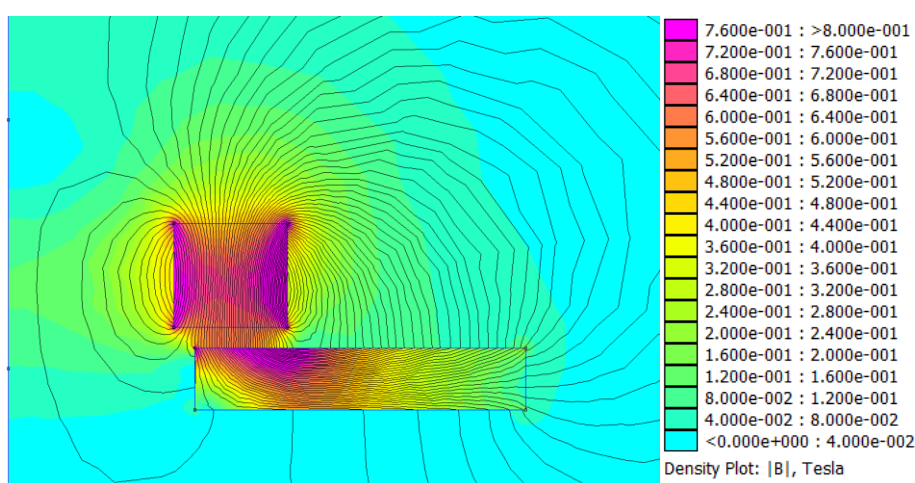


Figure 3-4: Axisymmetric simulation with the left side as rotation axis

To fit the selected magnet from 3.3 to the syringe nozzle, a connector piece is designed to join the ring magnet to the syringe body, which has a diameter of 25 mm. The assembly, including the magnet and magnetic shield, are depicted in a rendering of the CAD model in Figure 3-5.

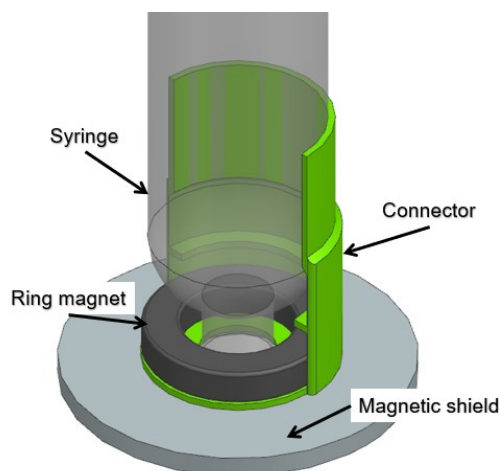


Figure 3-5: rendering of the CAD model from the setup with the different components

Note that a high number of different configurations is possible by slightly changing the position of the magnet, the thickness and size of the magnetic shield and the size of the hole where the nozzle is guided through. To simplify the problem an estimation is made for the following: the thickness of the shield is 3 mm with a diameter of 50 mm and an 18 mm diameter hole in the middle. The hole in the shield is slightly larger than the 16 mm hole of the magnet to leave area where the field lines can loop around the magnet in air and not directly into the shield. This is to avoid distortion of the field lines when they come near the shield. The maximum magnetic flux density B in the nozzle area in air is around 120 mT, exceeding the 50 mT used during the extrusion of NdFeB particles (Kim et al., 2018).

The setup for the field is build and additional measurements of the field strength in the ring magnet with shield are measured. On Figure 3-6, both the measured and simulated B values are shown. The positive direction of the flux density is oriented downward. Additionally, this comparison estimates the leakage flux under the shield.

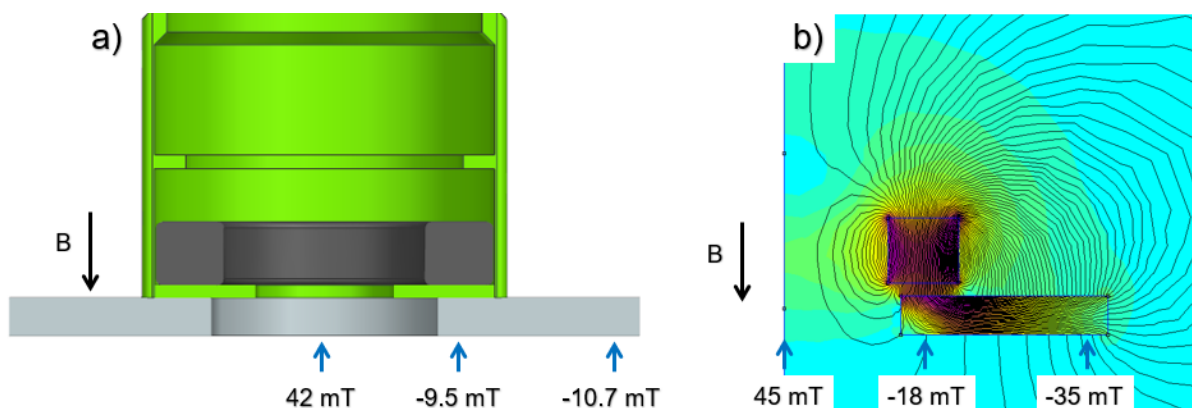


Figure 3-6: Flux density points indicated by arrow tips: a) Physical design; b) Axisymmetric simulation

The difference between the measurement and simulation may originate from small measuring mistakes when using the axial Hall probe. Alignment and positioning are important to receive accurate results. Note that this comparison is only intended to get an estimation of how the magnet setup works in a physical setup and that the measured B values are lower than simulated which is beneficial for the shielding of the extruded parts.

3.4.2 Extrusion: permanent magnet

To facilitate fibre extrusion during printing, several preparatory techniques are employed. Initially, a wooden stand is constructed to secure the syringe at a fixed height above the table. The stand is firmly clamped in place. Additionally, a wooden plank serves as the print bed, onto which the fibres are deposited. To ensure a non-stick surface, Teflon-coated paper is used as print bed surface, avoiding adhesion of the green parts.

Manually extruding fibres demands the use of both hands: one to exert pressure on the syringe and the other to smoothly move the print bed beneath the nozzle. To simplify coordination, a lead screw is used for applying pressure, reducing the distance travelled by the plunger to minimize the impact of hand variations and eliminate downward force on the syringe. Using the lead screw, the forces are all acting on the syringe and not on the stand. The lead screw is made of a threaded rod, a nut, and a 3D printed part to fix the nut to the upper part of the syringe, as shown in Figure 3-7. The rod makes direct contact with the plunger. Using a wrench to turn the rod creates an additional lever arm to increase the moment and the possible pressure.

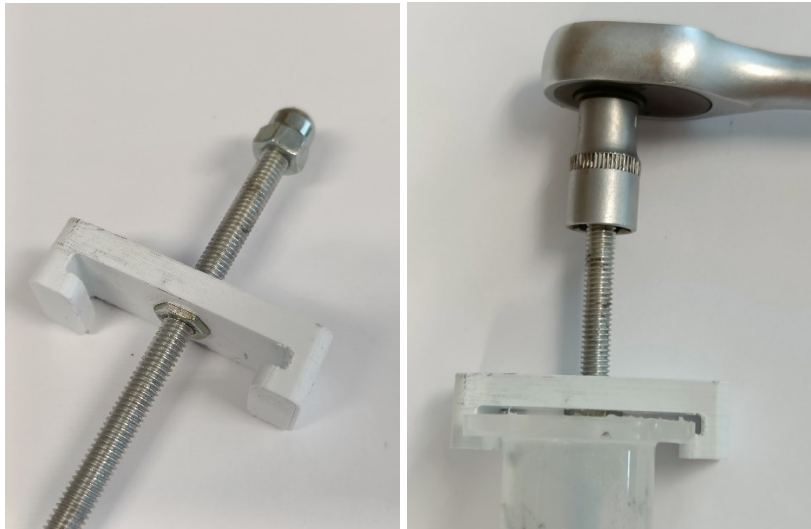


Figure 3-7: lead screw system mounted on syringe

The design from the FEMM simulation is made and is presented in Figure 3-8.

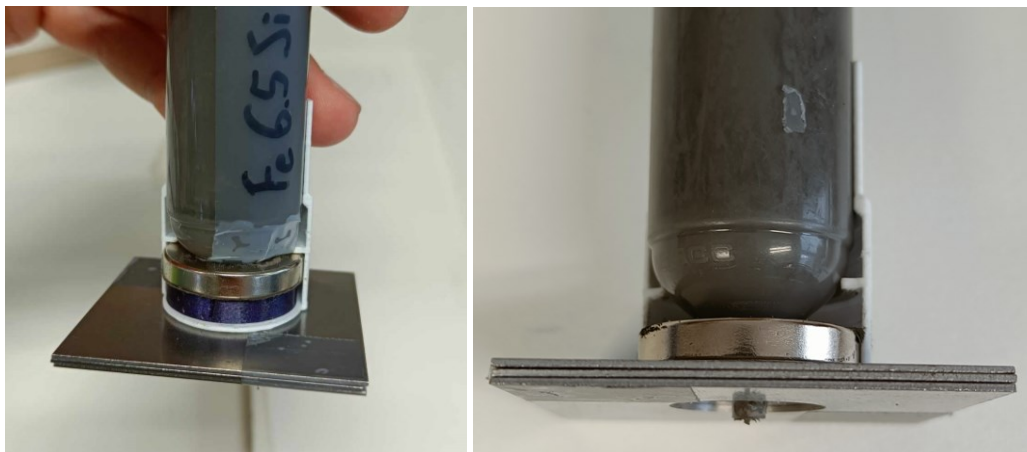


Figure 3-8: Connecting the magnet to the syringe

Upon first extrusion attempt, it is evident that it is exceedingly difficult to extrude the material when the magnet is close to the syringe. The paste material exhibits an increase in apparent viscosity when under the influence of a magnetic field. When the paste is not under the influence of the magnetic field it could flow freely out of the nozzle opening, but when the magnet is at the nozzle or even close to the body of the syringe, the movement of the paste stops. Even large pressures exerted with the additional moment of the lead screw can not overcome the additional resistance in the paste.

The reason why extrusion is not possible is because of the overlooked behaviour of the ferromagnetic paste when exposed to an external magnetic field. The magnetic field of the permanent magnet is too strong, which creates an interaction force between the ferromagnetic particles. Relatively little information is available on this magneto-rheological response.

Jiao et al. gives a perspective on the change in apparent viscosity because of the influence of a magnetic field (Jiao et al., 2021). By using magnetic nano particles (MNP) of Fe_3O_4 with a size around 20-30 nm added in a cementitious-like suspension to control the viscosity of the extrudate during printing. They found that the MNP inside a suspension have an interaction on each other when placed in a magnetic field. More concise the influence of the magnetic attraction force F_{mag} has a larger effect then the hydrodynamic force. The big difference between the paper and this situation is that they only

use a small amount of MNP, around 3wt% of the suspension. This greatly differs from the 95 wt% Fe_{6.5}Si particles in the tested paste composition. An assumption is that the possibility for increase in viscosity is very large because of the large amount of ferromagnetic material.

The lack of experimental data of the paste's viscosity under different magnetic field conditions makes it difficult to make an estimation on the behaviour. With the use of simulation software this could be calculated, but information about the particle size, surface and shape of the particle is needed alongside with the interaction between the binder material and the particles itself. This makes simulating the viscosity of the paste a complex problem which is not solved in this paper.

3.4.3 External field simulation: electromagnet

The alteration in ferromagnetic paste behaviour significantly impacts extrusion, with increased apparent viscosity directly correlated to the magnetic field strength. To find an optimum between the external field strength for crystal alignment and the increase in apparent viscosity, a dynamic system is needed. Using a small electromagnet at the nozzle on different current levels, it can be experimentally determined at what field strength the viscosity overcomes the extrudability of the paste.

The axisymmetric simulation helps to determine the dimensions of the electromagnet. The limited space at the nozzle only leaves place for 80 windings of a 0.6 mm diameter copper wire. These defining properties limit the current through the wire to 5 A for short duration during the extrusion of 30 seconds to prevent overheating the electromagnet. Important to note is that the influence of the paste permeability is brought into account which was not done previously. The value of the permeability determined by experiments, $\mu_{r,powder} = 15$ and is explained later. The simulation for 5 A is presented in Figure 3-9.

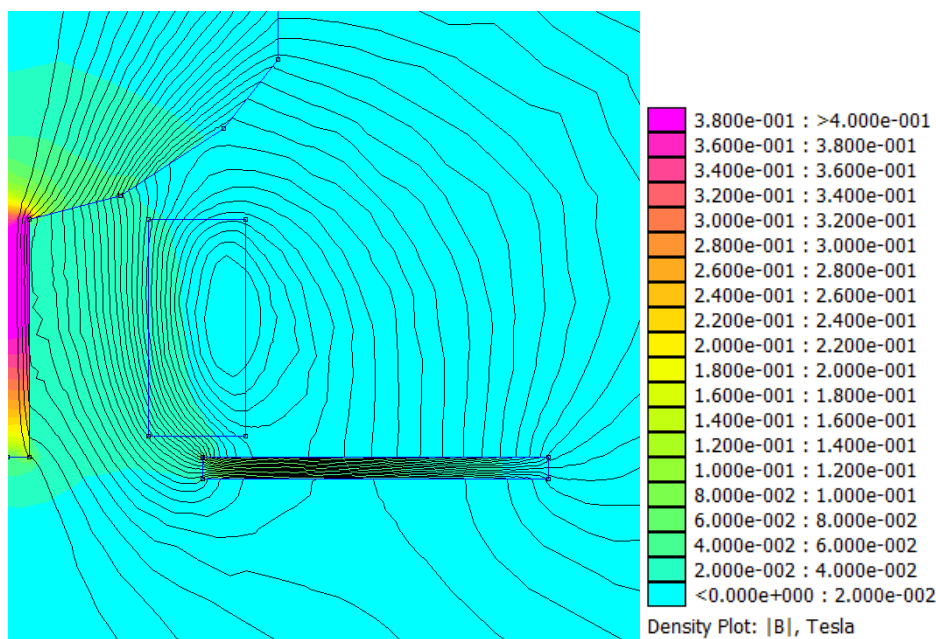


Figure 3-9: Axisymmetric simulation of the electromagnet with 5 A for manual extrusion

A CAD rendering of the complete setup is presented in Figure 3-10.

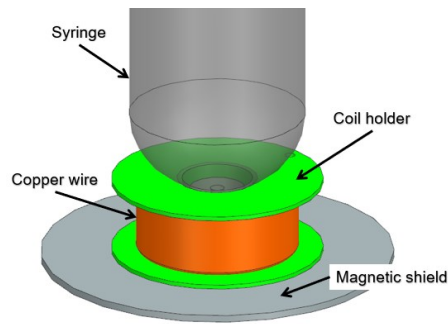


Figure 3-10: CAD rendering of the electromagnet

The difference between the electromagnet setup and the previous setup for the permanent magnet is the thickness in shield, this is reduced to 1 mm. Because the flux density B created by the coil is significantly lower than the magnet, less material is needed to guide the field lines away from the extruded fibres. Additional measurements of the flux density with the shield are measured, like it was done in Figure 3-6. For the electromagnet both the measured and simulated B values are shown in Figure 3-11.

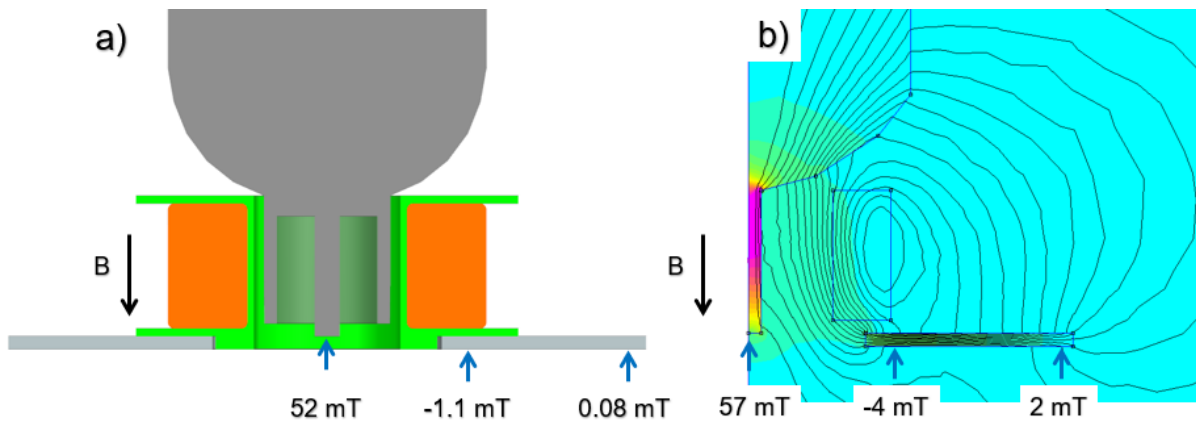


Figure 3-11: Flux density points indicated by arrows for 5 A: a) Physical design; b) Axisymmetric simulation

The simulation above accounts for the permeability of the paste material which has a large influence on the magnetic field lines. By measuring the flux density at the physical nozzle tip for different current settings, the permeability in the simulation can be changed to match the measured flux density at the nozzle tip.

This method provides an estimation of the permeability for the powder $\mu_{r,paste}$. Importantly, due to low field strengths involved for extrusion, saturation of the material does not occur, which is beneficial and does not exacerbate the situation complexity. Table 3-1 shows the measurements at the nozzle tip that are measured using the axial Hall probe for different current settings up to 5 A.

Table 3-1: Measured and simulated flux densities for the electromagnet with paste

Current [A]	Probe at nozzle tip [mT]	Simulation at nozzle tip [mT]	Simulation in tube [mT]
0.5	5.99	5.8	43
1	12.76	12	86
2	24.6	23	172
3	37.2	35	259
4	46.1	47	354
5	56	57	430

The final result for $\mu_{r,paste} = 15$ is used in the simulation to match the measured values at the nozzle tip. This gives an approximation of the real situation. The advantage is that a value can be found inside the paste material, which cannot be measured from the outside otherwise. For each current setting the highest value in the syringe nozzle is determined and presented also in Table 3-1 with the maximum of 430 mT for 5 A inside the electromagnet.

It is observed that the nozzle tip measurements varied by a few mT when using the dummy paste versus the pre-magnetized paste. This is possibly due to variations in particle fillings, the different origin of the material or the pre-magnetized condition.

3.4.4 Extrusion: electromagnet

To gain a sense of the extrusion process, the first test involves using a dummy paste. The complete setup for the extrusion test is presented in Figure 3-12.

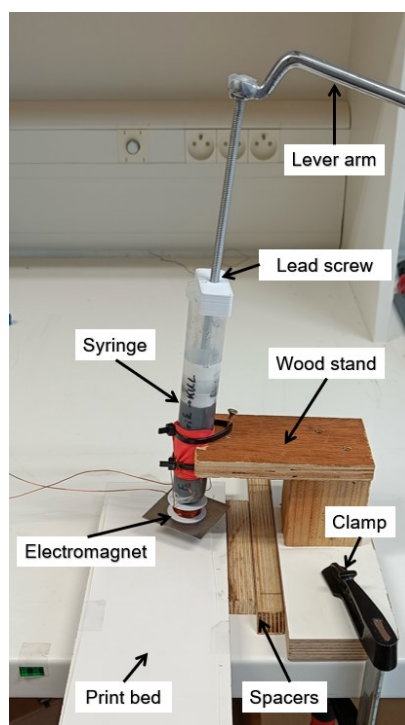


Figure 3-12: Complete setup for manual extrusion with electromagnet

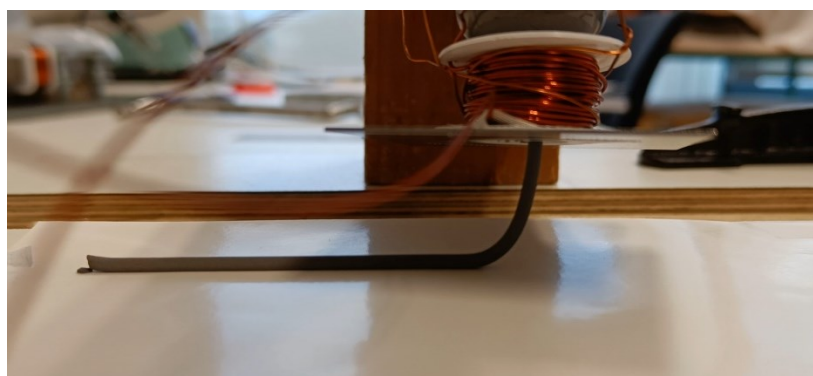


Figure 3-13: In-Situ extrusion of a fibre using a 1 A electromagnet

Figure 3-13 presents a sideview of the extrusion process for a fibre. The height of the nozzle opening versus the print bed is around 20 mm. The cohesion of the paste keeps the fibre connected without breaking, which makes it possible to let the extruded material hang at the nozzle when done carefully. By moving the print bed to the left, the fibre can rest on the surface with minimal distortion.

During the experiment, it was observed that the fibre extrusions achieved smooth results for 0.5 to 3 A. However, when higher field strengths are tested, material flow becomes more difficult and discontinuous. It seems as though the paste has to overcome static friction initially. Once the flow initiates, extrusion proceeds smoothly for a defined duration. If the backpressure on the paste is not maintained by turning the lead screw, extrusion halts, and the system has to overcome the pressure again.

To achieve extrusion for higher currents and field strengths, information is found about 3D printing highly viscous paste materials. Gunduz et al. investigated a solution for the current problems for AM with paste-based materials (Gunduz et al., 2018). Highly-filled solid loading pastes form a viscous paste and due to the wall friction in the converging nozzle extrusion is difficult. The high pressures needed to overcome the resistance cause problems in: binder separation, flow hysteresis, heating, nozzle erosion, and extrudate break-up. A possible solution is to apply ultrasonic vibrations to the nozzle. The shear rate inside the material is drastically increased and reduces the apparent viscosity of the paste.

This principle was mimicked by adding an electrical toothbrush at the nozzle opening. The vibrations make it possible for material to exit the nozzle opening when the backpressure is high. Because the lack of hands and control in this setup, only a small piece of fibre was extruded this way under a magnetic field with 4 A in the coil. Below in Table 3-2 is a list of the number of extruded samples and the fitting conditions and field strengths that the fibres are extruded from.

Table 3-2: Manually extruded fibre samples

Current [A]	Number of samples [normal]	Special condition
0	1	/
0.5	1	/
1	3	Fast extrusion: 1
2	1	Fast extrusion: 2
3	2	Fast extrusion: 1
4	0.5	Vibrations: 0.5

In Table 3-2 the special conditions are also mentioned. One aspect of extruding the paste is the additional shear rate inside the nozzle. It is known that the paste is shear thinning which reduces the viscosity for higher shear rates. By increasing the extrusion speed, the viscosity will be lower inside the nozzle tube. To test if this has influence on the crystal alignment, some fibres are extruded under these conditions. For the setting with 4 A inside the coil only a small piece was extruded with and without vibrations. The Figure 3-14 shows the extruded green fibres on the print bed.

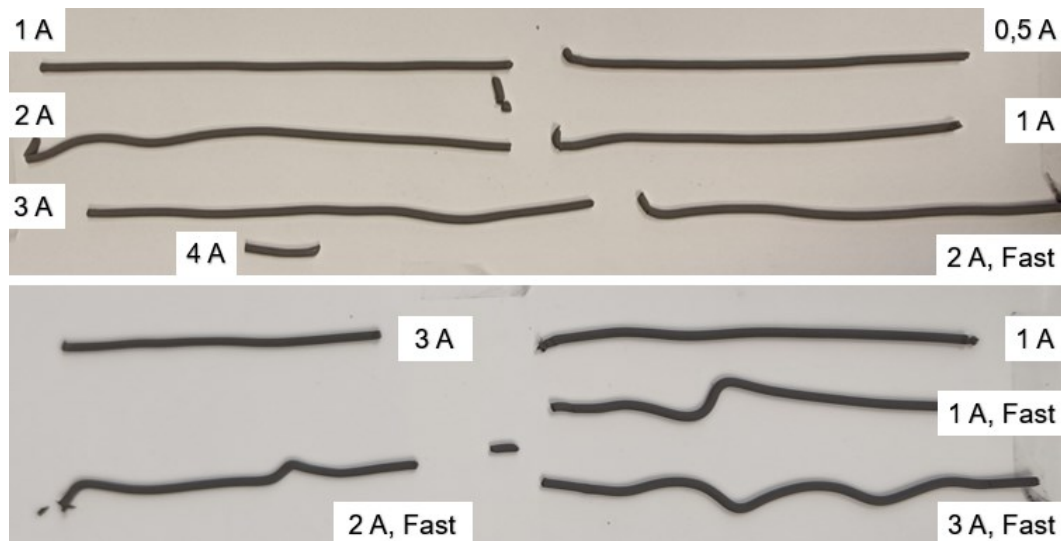


Figure 3-14: Manually extruded fibre samples

Note that the fibres for higher current settings and faster extrusion are wavier. This is because the hand movement is faster in these situations and influences the stability of the setup, which was not sturdy enough and could move the syringe, hence the small wave formation in the fibre.

3.5 State-of-the-art extrusion at VITO

Manually extrusion has limitations on controlling the flow, accuracy, thickness, and placement of the fibres. To accommodate these limitations, a test is done at VITO on a high end 3D micro-extrusion 3D printer with an XY accuracy of 0.1 mm (LUTUM 5, VormVrij). The syringe is directly mounted onto the print head equipped with a 580 μm conical nozzle. This finer nozzle and his narrow tube will improve the shear rate in the paste material, thus lowering the viscosity of the paste inside. The narrow 25 mm long nozzle design creates more space for the electromagnet design around the nozzle. This section describes the design of an external field setup that is used during the 3D micro-extrusion process. The paste is made with Fe6.5Si powder that is pre-magnetized to 1.6 T.

3.5.1 External field simulation: electromagnet

To find the dimensions for the setup, the same approach is used as before, starting with the axisymmetric FEMM simulation. For consistency, the same amount of 80 windings is used for the coil and the copper wire of 0.6 mm diameter. Because the additional space, the coil height is increased to 14 mm with an inner diameter of 12 mm to reduce the outer diameter of the coil, thus achieving higher flux density in the nozzle. The magnetic shield has an area of 30 x 30 mm and thickness 1 mm with a hole diameter of 6 mm. The presence of the paste material, $\mu_{r,paste} = 15$ is also considered.

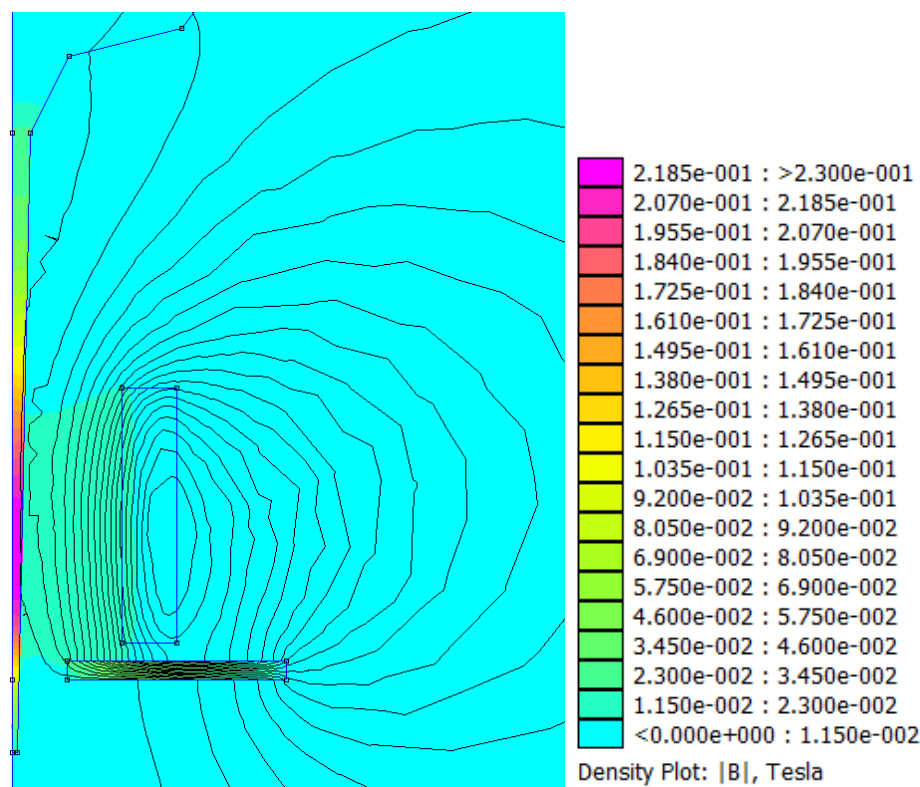


Figure 3-15: Axisymmetric simulation for the 580 μm conical nozzle for 3 A

Figure 3-15 shows quite different results from the simulation for the smaller nozzle in Figure 3-9. In this situation the maximum flux density is only present in the tube of the nozzle itself, which was not the case for the other simulation where the field strength reached higher values in the body of the syringe. A CAD rendering of the setup is shown in Figure 3-16.

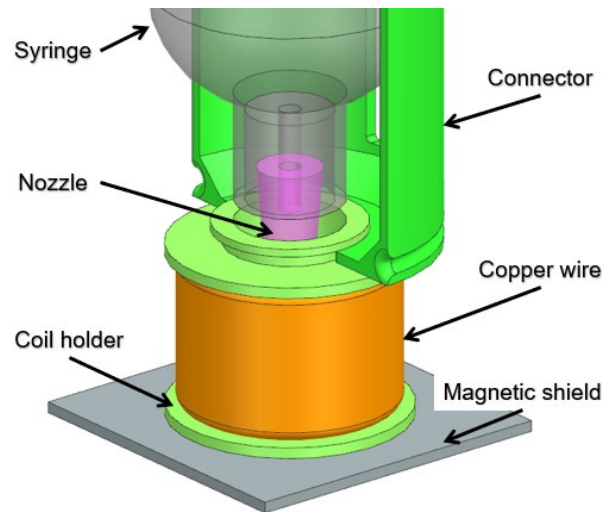


Figure 3-16: CAD model of the setup at VITO

The setup is built by 3D printing the connector and coil holder piece and glueing the magnetic shield to the coil. This ensures a flat surface on the bottom, so it is possible for a small clearance between the shield and the extruded material. The complete assembly of the setup is presented in Figure 3-17.

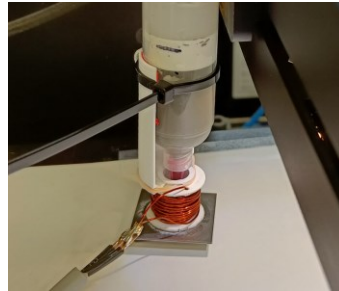


Figure 3-17: Complete assembly of the electromagnet for the extrusion process at VITO

Validation of the model is done by comparing the simulation with the measurements of the physical setup like what is done in Figure 3-11. The results are presented in Figure 3-18.

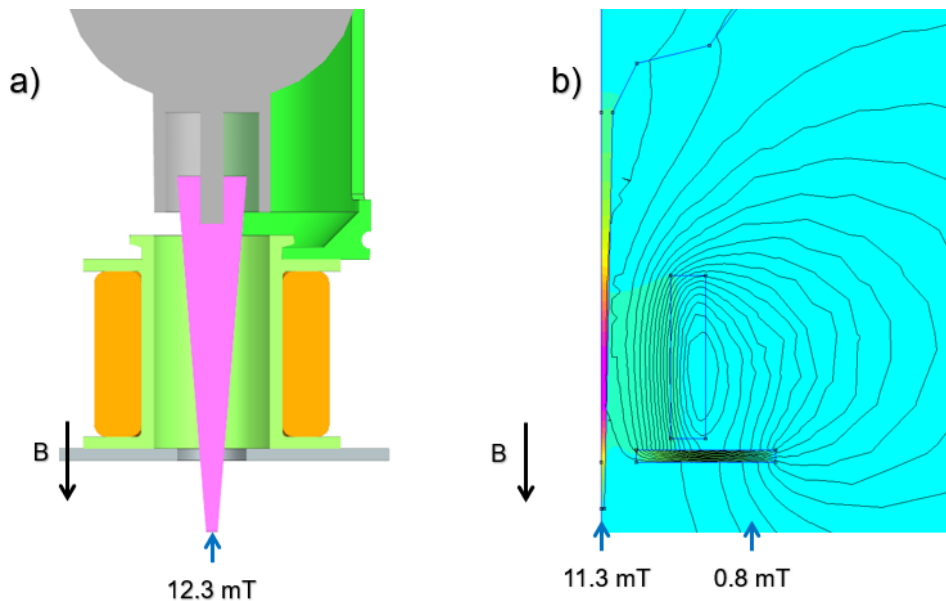


Figure 3-18: Flux density points indicated by arrows for 5 A: a) Physical design; b) Axisymmetric simulation

The flux density measurements for different current settings along with the simulated values are presented in Table 3-3.

Table 3-3: Measured and simulated flux densities for the electromagnet around the conical nozzle, with simulation values of the other setup from Table 3-1 between brackets

Current [A]	Probe at nozzle tip [mT]	Simulation at nozzle tip [mT]	Simulation in tube [mT]
1	1	1.6	77 (86)
2	2.5	3.4	153 (172)
3	3.9	5.2	230 (259)
4	6.54	6.8	308 (354)
5	12.3	11.3	384 (430)

Taking the measurements from the 580 μm nozzle is difficult because of the small measuring area. Even small position errors of the probe or placement of the coil cause large differences in the results. This is also visible in the FEMM simulation where the value at the nozzle quickly changes. The small amount of material in the nozzle tube drastically lowers the measurable flux density at the nozzle, which means that the errors have a larger influence when matching the simulation. Because the $\mu_{r,paste} = 15$ is unchanged, the values in the nozzle tube can be linked to the other setup and simulation values from Table 3-1, as is presented in the last column of Table 3-3. Comparing the values from the other setup shows an increasing difference for higher currents.

Comparing the magnetic field conditions between the first manual extrusion test from 3.4.4 and this extrusion test is important so the results can be compared between the thick 2 mm nozzle extrusion and the conical nozzle extrusion. For this reason, the selected conditions are 1 A and 3 A in the electromagnet, because the simulation shows similar values in the nozzle tube. Although a difference exists between the two testing conditions, efforts are made to minimize this to the best extent possible, so comparison of the results is still possible.

3.5.2 Extrusion: electromagnet

This section will explain the setup and the test procedure for the extrusion test using a 3D printer. The coil and connection parts are 3D printed in PLA and assembled. The complete setup is visible in Figure 3-19.

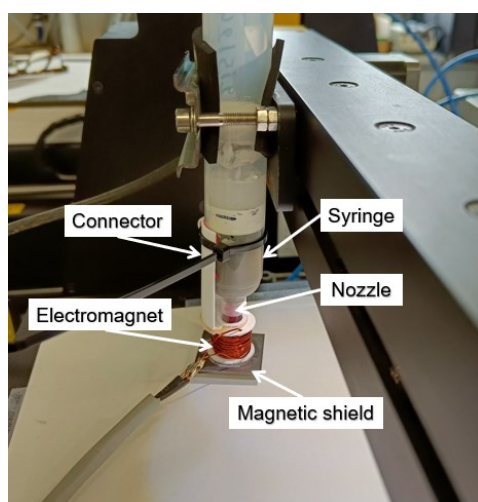


Figure 3-19: Assembly of the electromagnet around the conical nozzle

During the extrusion, the DC-current in the electromagnet is maintained at the same level, which means that the magnetic field control is static for the extrusion of the sample. To avoid having a sample with alternating fibre orientations, it is preferred that the extrusion direction is the same for all the deposited fibres, as shown in the cross-section in Figure 1-13. It is preferred that a continuous flow of the material is maintained to achieve a stable flow. So, to avoid interruptions in the extrusion by starting and stopping for relocating the next fibre deposition, the printed sample will use a spiralling printing strategy. The end results will be a smaller rectangular piece from the sample with dimensions 15 x 10 x 2.4 mm for later analysis by EBSD as shown in Figure 3-20.

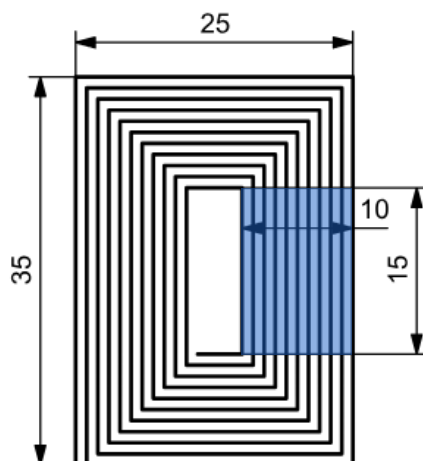


Figure 3-20: Spiral printing strategy with the number of fibres not to scale

The magnetic field is provided by an external power supply and monitored with a multimeter to detect fluctuations because of the sensitivity of the settings. Figure 3-21 shows the setup for 3 A and 1.1 V in the electromagnet with the multimeter in series.

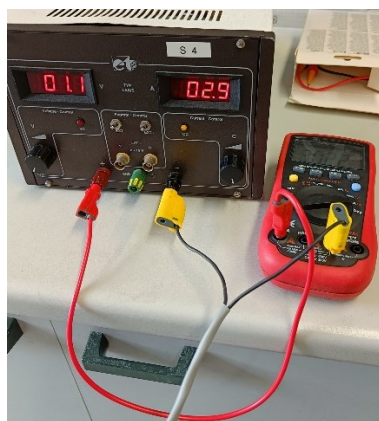


Figure 3-21: Power supply to provide DC current for the electromagnet with the multimeter

The extrusion force on the plunger is exerted with pressurized air on the back of the syringe. The adapter piece is connected to the pressure supply and creates an airtight seal, as shown in Figure 3-22. The control system can set the pressure at the wanted level to match the extrusion rate of the material with the speed of the print head. The influence of the magnetic field on the apparent viscosity of the paste material requires a different backpressure depending on the field strength. Test conditions for the magnetic field include currents of 1 A and 3 A in the coil, with a printing speed of ~5 mm/s, resulting in pressures of 1.08 bar and 1.38 bar for the respective samples. This means that the increase of magnetic field strength from 1 A to 3 A results in a 28% increase in extrusion pressure.



Figure 3-22: Example of the syringe with the adapter and micro-nozzle equipped (Nordson, 2018)

Additional settings for the 3D printing program are the layer thickness (LT) of 400 μm , the scan spacings (SP) of 400 μm to ensure sufficient overlap and prevent the formation of voids, owing to the rounded shape of the nozzle and deposited material, see section 1.4.2.

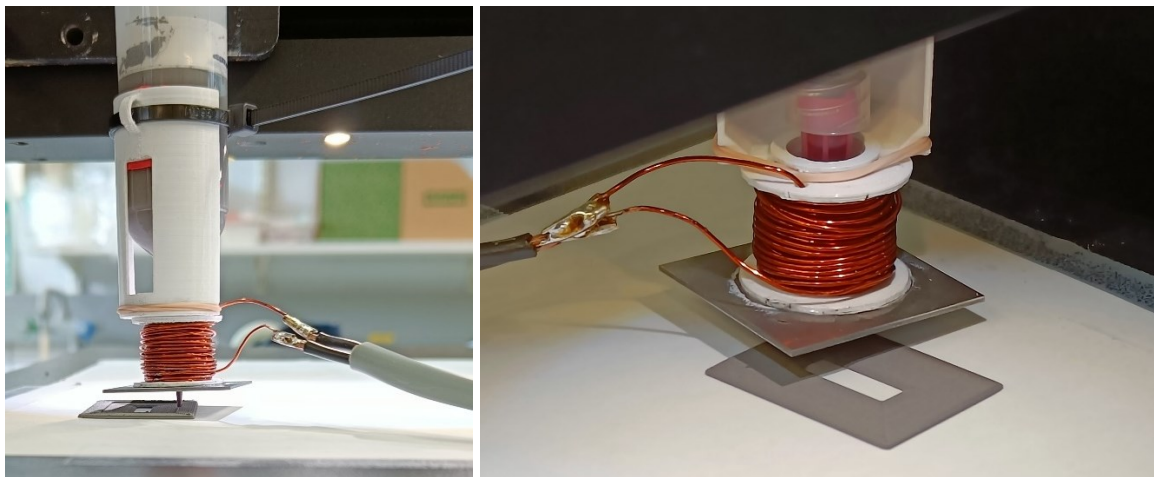


Figure 3-23: Side and top view of in-situ extrusion of the first layer

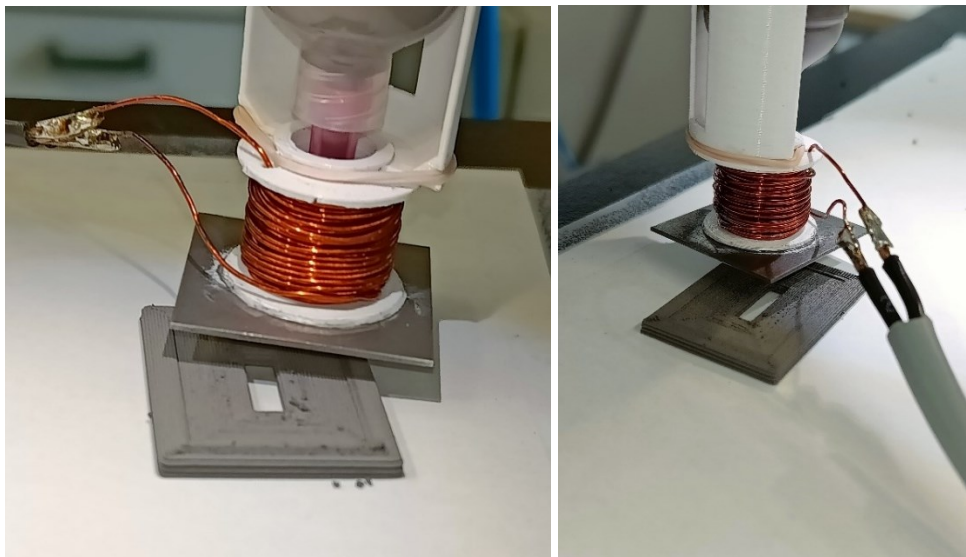


Figure 3-24: In-situ extrusion view of the sample at higher layer thickness, with grain formation and scratching

Figure 3-23 shows a side and top view of the in-situ extrusion process of the first layer. The flow rate for the first layer matched the print speed, which results in a very smooth layer. Figure 3-24 represents the process at a later stage after some layers are deposited. When the material is deposited in the middle of the spiral, an excess amount of material was deposited in the corners of the spiral. This is

seen in the small grains that are being formed on the top layer of the sample. This is detrimental for the end result because it will add impurities in the structure. Some of the grains are pushed out of the system with the next nozzle pass, but a large amount is removed by gently blowing compressed air on the surface. This must be done carefully to avoid excessive drying of the top layer, which would result in bad layer adhesion for the following material. Some layers also demonstrate scratches in the extruded material. It is unclear what caused this, but a possibility is the quality of the nozzle, which can have a small imperfection that slightly scrapes the extruded material when moving in one direction and not in the other. In general, the outside of the sample showed smoother results.

During the extrusion of the sample when using 3 A in the coil, the copper wire generated a small amount of heat. The prolonged duration of extrusion generated a heat buildup at the electromagnet. This started to melt the thermoplastic material of the coil holder. To avoid further heating of the system, additional convection is created over the copper wire. Figure 3-25 shows the result for the extruded spiralled samples at 1 A and 3 A in the electromagnet.

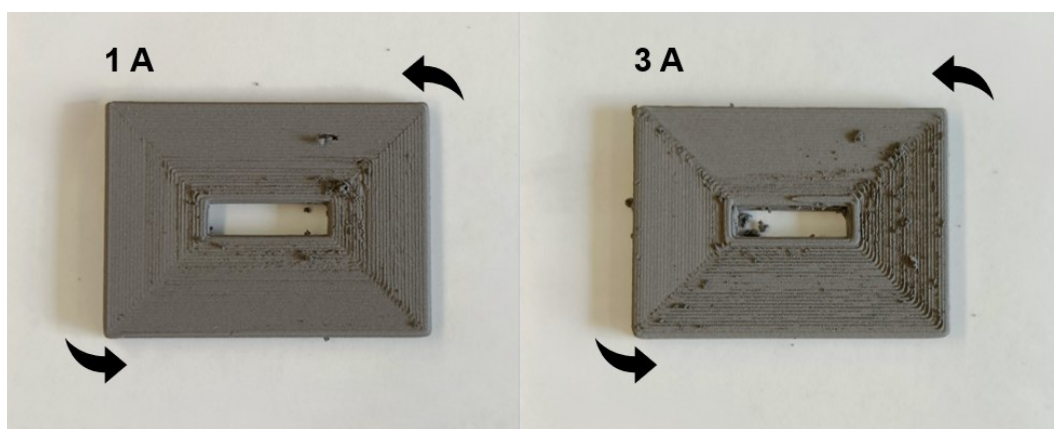


Figure 3-25: End result of the spiralled samples with micro-extrusion at VITO

The samples have a final height of 2.8 mm and 2.4 mm for 1 A and 3 A, respectively. One layer takes about 10 minutes to extrude, with a total duration of around 70 minutes for each sample.

3.6 Post-processing of the green samples

The extruded green fibres and spiralled samples from section 3.4.4 and 3.5.2 need to undergo thermal treatment existing of a debinding and sintering step. The complete process overview is given in the following schematic on Figure 3-26.

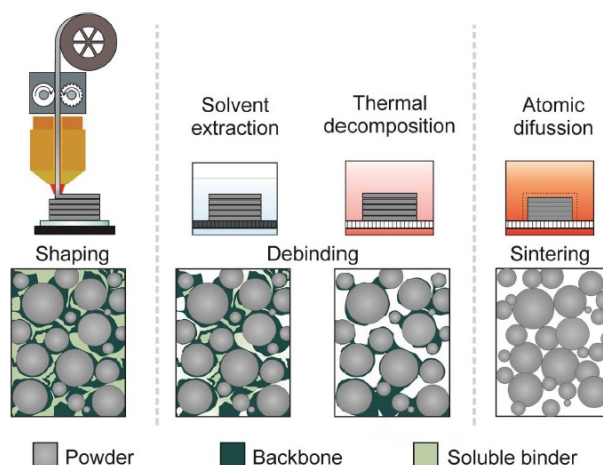


Figure 3-26: Schematic representation of the shaping, debinding, and sintering (Gonzalez-Gutierrez et al., 2018)

3.6.1 Debinding

After the solvent material is evaporated out of the samples, the debinding step completely removes the polymer matrix from the green sample by thermal decomposition. At this point it is referred to as the brown part. The strength of the samples during the thermal treatment process is shown in Figure 3-27.

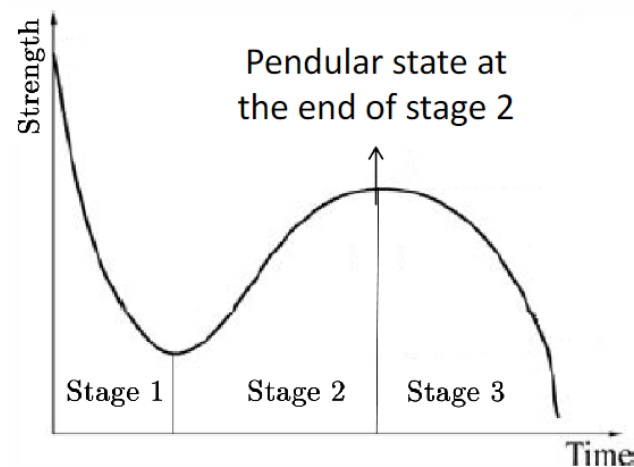


Figure 3-27: Strength of the part during the debinding step (Cardon, 2023)

Starting from the strength of the green part the process starts heating the part. The polymer binder will start to melt and liquify in case of a thermoplastic binder or degrade in case of a thermoset. At the end of stage 2 only a small amount of binder material is still present, which creates small bridges between neighbouring particles, called the pendular state. At the end of stage 3 all the binder material is removed, and the only acting force on the particles is the Van der Waals forces (Cardon, 2023). These very weak forces keep the particles together until the sintering process commences.

3.6.2 Sintering

An important question remains if the debinding step destroys and neglects the orientation of the crystals. The shrinkage during the process because of the binder removal and the weak strength of the Van der Waals forces could cause shifts in the material orientation that was potentially achieved during extrusion. To minimize the risk in changing the crystallographic orientation during post-processes, the sintering step will only go until the minimum needed stage, called pre-sintering. By partially sintering the particles together, shrinkage is limited to about 10%. This is an estimation based on the research discussed in 1.4.2 for high-density materials.

The complete process is executed in one step inside a horizontal tube furnace (Carbolite, model: CTF 12/65) with an argon gas atmosphere. To eliminate the presence of oxygen during the process, titanium material is added. The process starts heating to 500 °C with an increase of 0.5 °C/min, stays 1 hour at 500 °C to then increase to 1150 °C at a rate of 5 °C/min and stay 2 hours at 1150 °C. At this point, the part is sintered and cooled down at a rate of 5 °C/min to room temperature which does not have to be precise. Normally the sintering temperature of FeSi is around 1350 °C, but in this process, sintering is only partially wanted, hence the lower temperature of 1150 °C. The temperature progression is presented visually in Figure 3-28 and takes about 25 hours to complete.

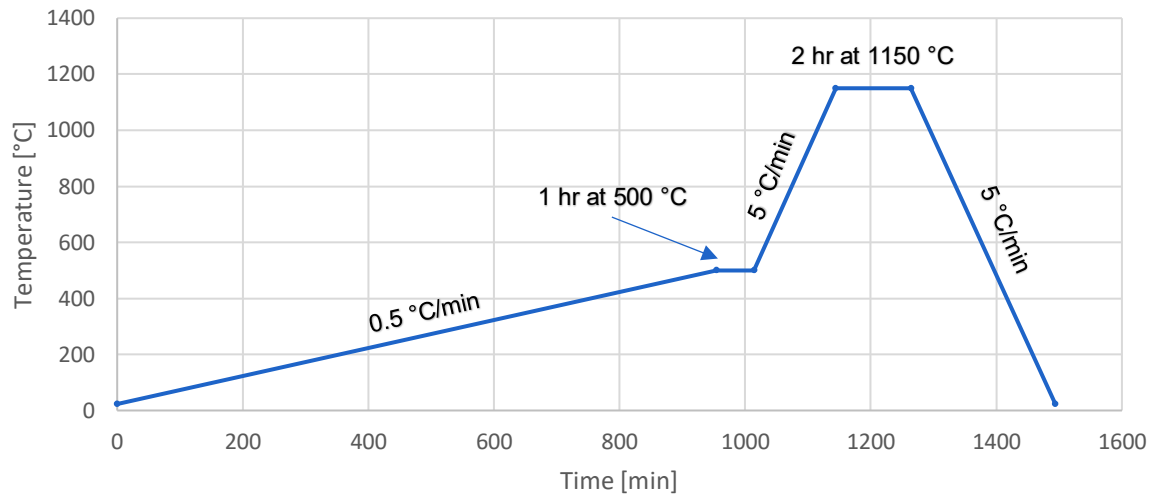


Figure 3-28: Temperature progression for the post-processing step

3.7 Conclusion

This chapter discusses the different ways in which extrusion is possible. The choice is made to use an extrusion-base principle by using a paste-based material that is a composition of Fe_{6.5}Si particles with an HPC polymer matrix.

Two different extrusion tests are conducted, one manual extrusion and one using a state-of-the-art 3D printer setup. Manual extrusion is done because it does not require a complex system to see if fundamental crystal alignment is possible. The test with the 3D printer at VITO enables for better control of the flow rate, and deposition of the material.

The goal is to keep test conditions between the manual and the 3D printer similar so a good comparison can be made. By limiting the changes in the setup, the differences in the results can be linked to the change in nozzle diameter or printing speed. The differences between the two test setups are listed in Table 3-4.

Table 3-4: Differences in test conditions between manual extrusion and 3D micro-extrusion at VITO

Conditions	Manual extrusion	3D micro-extrusion at VITO
Pre-magnetization level	> 1.2 T	1.6 T
Powder batch	Batch 1	Batch 3
Nozzle	Short, 2 mm diameter	Long, conical, 580 µm diameter
Field strength [3A]	259 mT	230 mT
Magnetic shield	18 mm diameter hole	6 mm diameter hole

For both tests, simulations in FEMM are made of the relation between permanent or electromagnet, paste material, and the shield material to protect the extrudate. The simulation is done to see the magnetic field strength and the flux density in the nozzle, and to quantify the influence of the magnetic field. By changing the current in the electromagnet different strengths are tested.

Building the setup with the permanent magnet showed the significant increase in apparent viscosity. It is clear that the field strength has a maximum limit when a free flow of material is desired. The influence of the magnetic field becomes a trade-off between crystal alignment and the change in apparent viscosity.

Determining the optimum situation for crystal alignment, different field settings are tested by using an electromagnet for both the manual and the 3D micro-extrusion. The electromagnet uses 80 windings in a 0.6 mm diameter copper wire and a maximum current of 4 A because higher currents were not able to extrude as a result of the apparent viscosity increase.

The manual extruded fibres have a diameter of 2 mm and are extruded for various conditions. The 3D micro-extruded spiralled samples are conducted for 1 A and 3 A in the coil with 15 x 10 x 2.8 mm dimensions.

The post-processing for the samples is done for the same process. To avoid change in crystallographic texture during the sintering process, the sintering temperature is lowered to limit the grain growth of the particles. This is called pre-sintering to only achieve partial necking of the particles to form a solid sample that can be analysed by EBSD in later stages.

4 Results

4.1 Introduction

This section will discuss the results of the sintered samples that are extruded under the influence of a magnetic field. The scanning electron microscope (SEM) used for EBSD measurements is a Philips XL 30 FEG with a 1.4 megapixel resolution (1392 (H) x 1040 (L)), a data collection rate of up to 200 indexed patterns per second, and an EDAX-TSL Digiview V, with a 25 kV beam. The program TEAM: Texture & Elemental Analytical Microscopy is used for the data computation in combination with Orientation Imaging Microscopy (OIM).

Analyzing the samples is a time consuming and labour intensive process. EBSD measurements need a high surface quality because the thickness of entering by electrons is only tens of nanometers. This is why the surface roughness needs to be low or else this will interfere with the diffraction of the electron scatter. This is the reason not all the samples are analysed by EBSD. To have the highest possible chance of finding good results a priority list is made to see which samples would give the most information. The examined samples consist of a small amount of powder to investigate the single crystal condition, the manual extruded fibres, and the 3D micro-extruded spiralled samples, as shown in Table 4-1. This chapter shows the results for sintered samples as well as the EBSD results.

Table 4-1: Overview of the priority list for sintering and EBSD analysis for the analysed samples

	Sintered	EBSD analysis
Loose powder	5 g of pre-magnetized powder (>1.5 T)	Encapsulated in epoxy
Manual extrusion	Samples: 0 – 1 – 1F – 2F – 3 – 4V – 4	Samples: 1 – 4V
3D micro-extrusion	Samples: 1 A – 3 A	Sample: 3 A

4.2 Loose powder

To investigate the single crystal condition of the used Fe_{6.5}Si powder an EBSD measurement is performed on a small amount of pre-magnetized (>1.5 T) powder. The powder from the second batch is sintered in a crucible until low amount of necking occurs between the particles. This process is only intended to form a weak connection between the particles and form a ridged object. The voids that are present after sintering are filled with an epoxy. The prepared sample is visible in Figure 4-1.



Figure 4-1: Loose powder sintered and prepared for EBSD

The result of the EBSD measurement for the loose powder is presented in Figure 4-2.

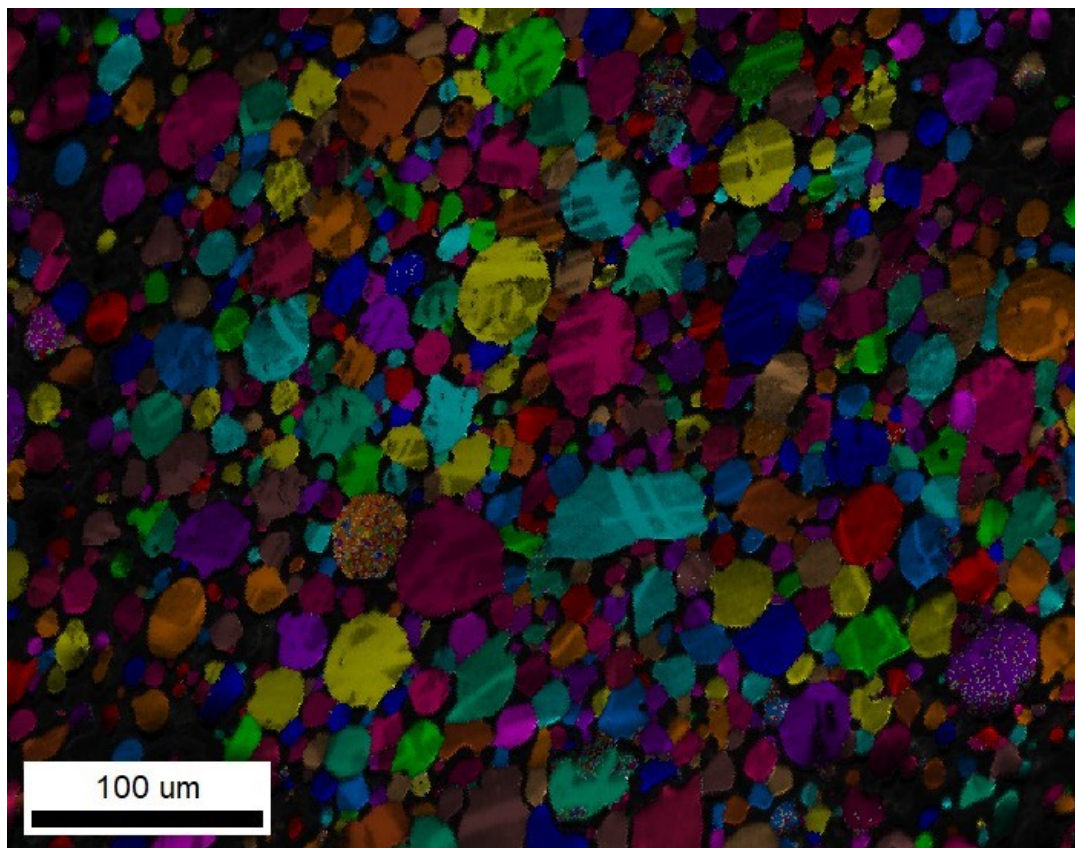


Figure 4-2: EBSD for loose powder

The coloured zones represent the different grains, and the distinct colours represent a crystal orientation, which is not important in this test. What is important is the fact that every grain only shows one colour with no grain boundaries that indicate the single crystal condition. From Figure 4-2 it is visible that there are very large grains present in the structure. This is because the second batch of powder contained larger grains due to a difference in the milling process, which was not done via cryogenic milling. When focused on the smaller grains, that give a better representation of the wanted material condition, some polycrystals are present, as shown in Figure 4-3.



Figure 4-3: Close up of the loose powder EBSD with indicated polycrystals

The driving force for diffusion, necking of the material during sintering, is the available surface area compared to the enclosed volume. When a small crystal is connected to a large crystal, the speed of diffusion for the small crystal will be significantly higher, essentially stealing material of the larger crystal. This is detrimental for the process, because the larger crystal will win orientation preference over the small crystal during magnetic field-influenced extrusion, but the small non-oriented crystal will benefit in grain growth during the sintering process.

The milling of the powder after sintering is difficult to break the small particles of the larger particles. More investigation is needed to separate the smaller particles before sintering to make sure that the larger particles are single crystal without parasitic satellite particles.

Achieving a perfect single crystal condition for the used Fe_{6.5}Si powder will be difficult, and small imperfections will be present in the material. It is possible to conclude that the first EBSD results show no significant grain growth of these parasitic particles. This means that the negative effect of the polycrystals is not as pronounced.

4.3 Manual extruded fibres

Sintering can be done for multiple samples at the same time, but surface preparation for EBSD is only done for sample 1 and sample 4V. These conditions are extrusion with a 2 mm nozzle in a flux density of 86 mT and 354 mT in the nozzle tube based on the simulation, respectively. Sample 4V is extruded under the influence of additional vibrations to improve the flow rate of the material. Figure 4-4 shows the samples before and after sintering.

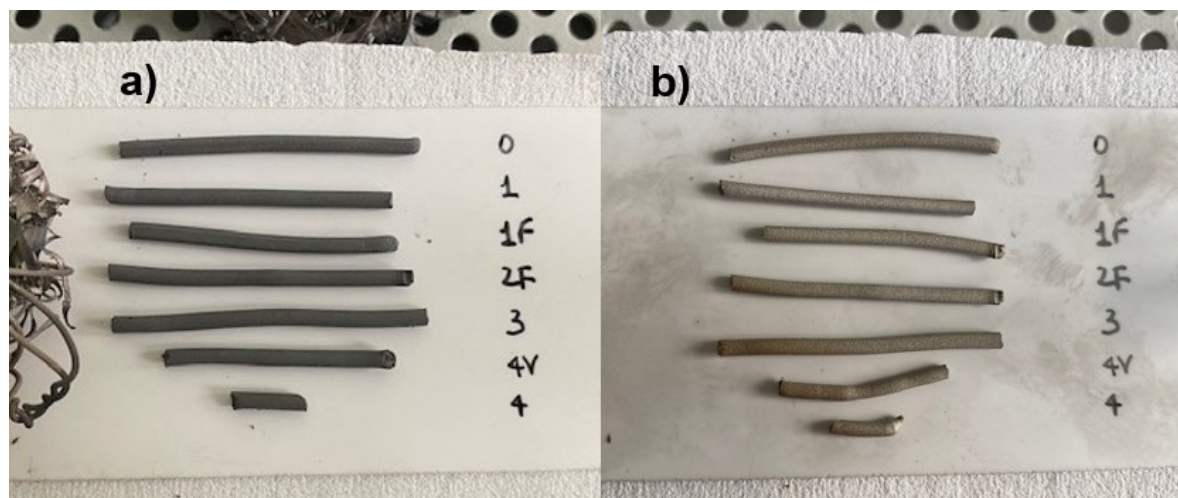


Figure 4-4: Fibre samples cut to size: a) before sintering; b) after sintering

The samples 1 and 4V are grinded and prepared for EBSD as presented in Figure 4-5 along with the sample orientation of the measurements. This means that the extrusion direction (ED) is aligned with the Axis 2 and the normal direction (ND) is aligned with the Axis 3.

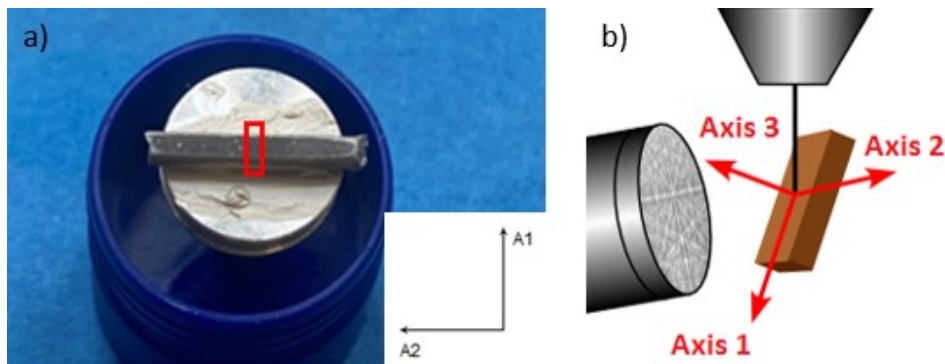


Figure 4-5: a) Prepared fibre sample for EBSD, with the analysed zone indicated; b) the sample orientation (OIM)

A SEM image of the area is visible in Figure 4-6 with the corresponding axis. The high number of porosities are intentionally to avoid changing the crystallographic orientation of the grain growth during the sintering process by using the low level of sintering. The grey zones represent single grains that end in grain boundaries.

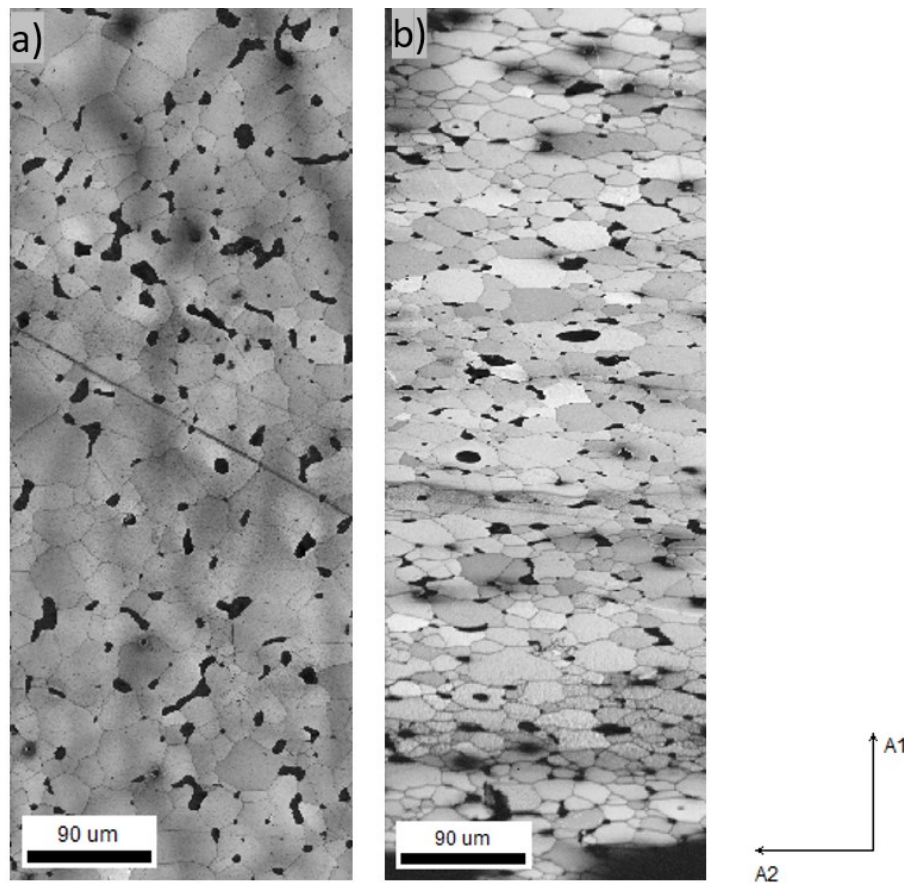


Figure 4-6: SEM image of the area: a) sample 1; b) sample 4V

4.3.1 Sample 1

The EBSD measurement is executed with a step size of 0.8 μm. Figure 4-7 represents the inverse pole figure of the A2, extrusion direction. The legend shows the corresponding colour to the relative orientation of the crystal versus the sample orientation. Red means the [001] direction, which is the wanted orientation in the ED because this is also the easy magnetization direction. The voids in the sample result in noise in the inverse pole figure.

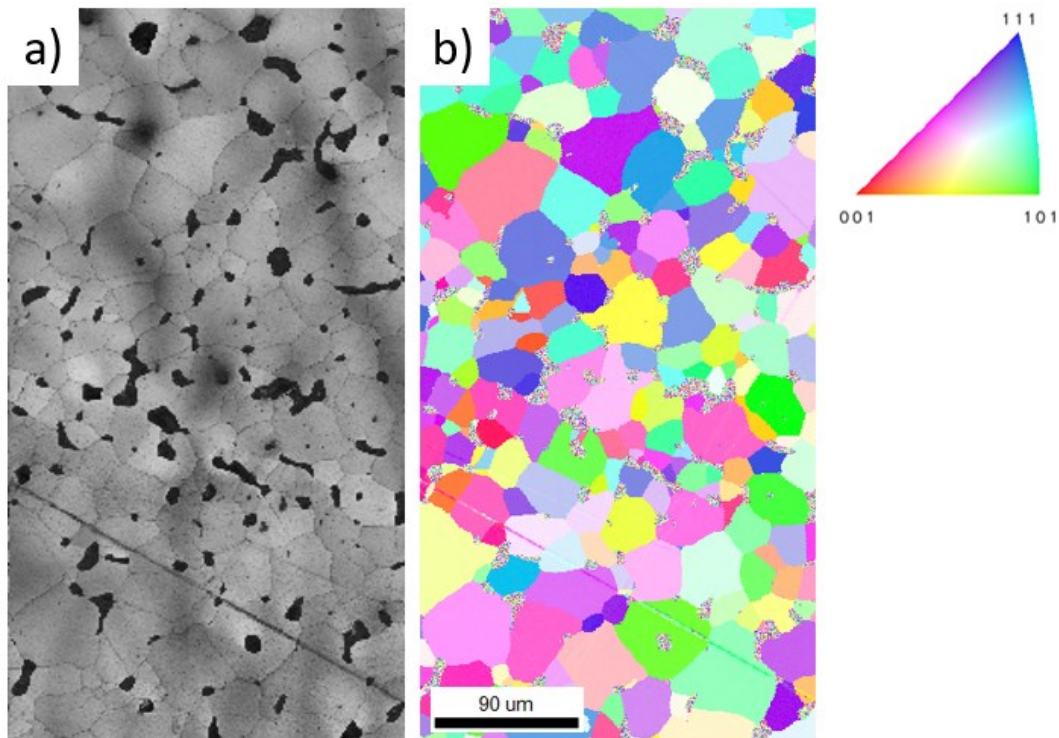


Figure 4-7: Sample 1: a) Part of the SEM image; b) Inverse pole figure of the A2, extrusion direction

A first look at the crystallographic orientation of the sintered sample shows that the used powder is single crystal. This can confirm that the sintering step does not affect this condition significantly.

Figure 4-8 represents the pole figure which is a stereographic projection of the poles of sample 1 for three orientations [001], [110], and [111] that show the intensity of the alignment. These pole figures show the texture inside a material when the intensity is located around one of the axis. When the intensity is high, around 10 – 20, the material is called textured. The results in this pole figure are more randomized and no texture is present in the sample. If texture is visible a high intensity of red would be located around the A2 axis of the [001] pole figure.

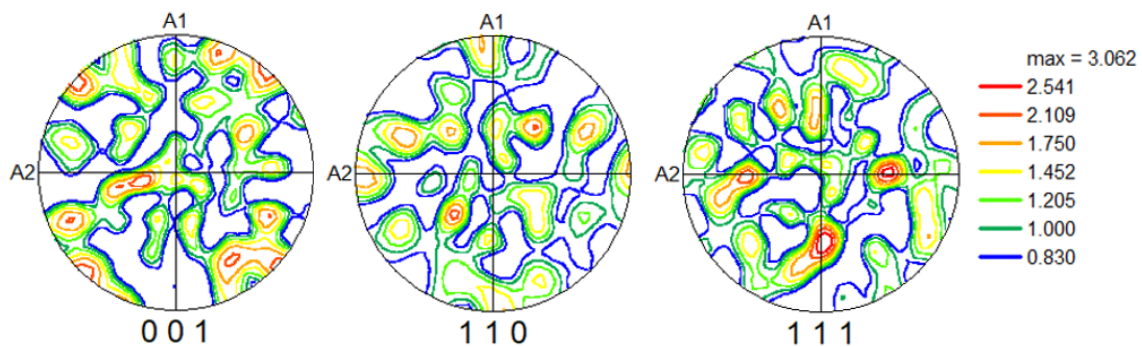


Figure 4-8: Sample 1 pole figure

Figure 4-9 shows the intensity of each orientation linked to the sample axis, which is at the top left of the legend. The extrusion direction of the sample shows no intensity around the [001] direction for crystal orientation.

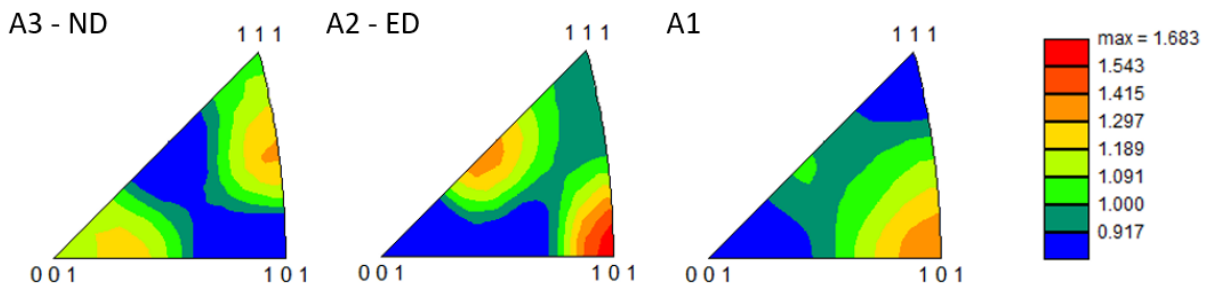


Figure 4-9: Sample 1 inverse pole figure

4.3.2 Sample 4V

The EBSD measurement is executed with a step size of 0.8 μm . Figure 4-10 represents the SEM and inverse pole figure of the A2, extrusion direction. The same information applies to the inverse pole figure of sample 1 in section 4.3.1.

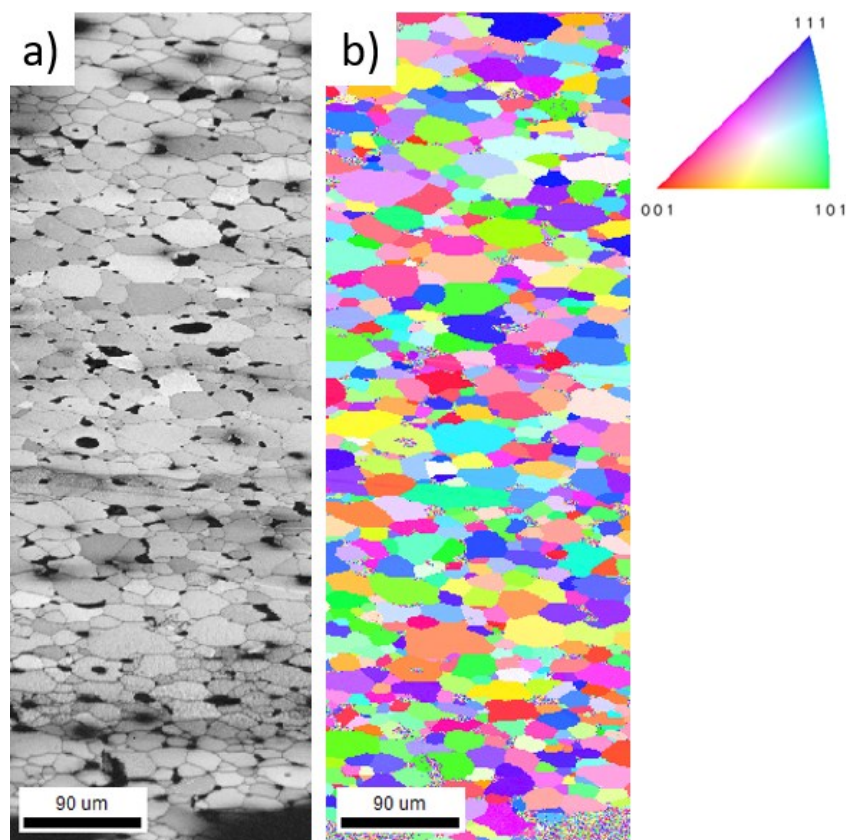


Figure 4-10: Sample 4V: a) SEM image; b) Inverse pole figure of the A2, extrusion direction

Figure 4-11 represents the pole figure which is a stereographic projection of the poles of sample 4V for three orientations [001], [110], and [111] that show the intensity of the alignment. The results in this pole figure are more randomized and no texture is present in the sample. If texture is visible a high intensity of red would be located around the A2 axis of the [001] pole figure.

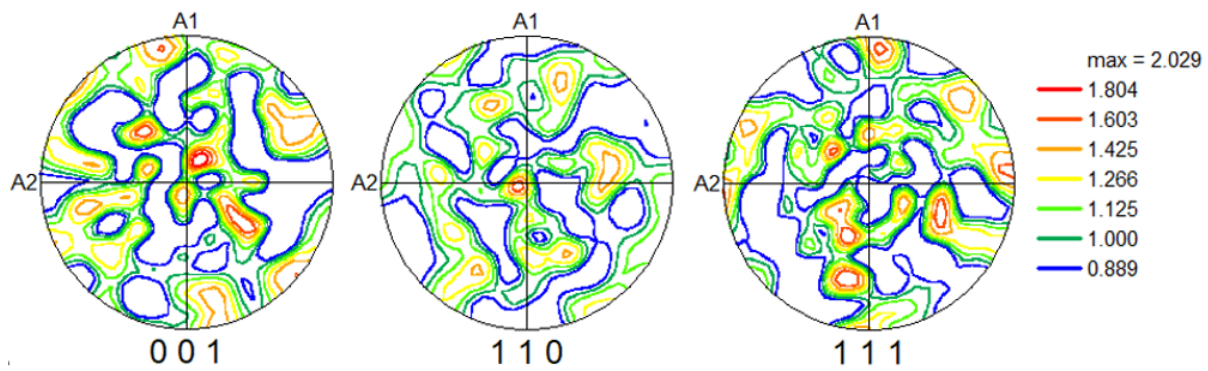


Figure 4-11: Sample 4V pole figure

Figure 4-12 shows the intensity of each orientation linked to the sample axis, which is at the top left of the legend. The A2 – ED of the sample shows no intensity around the [001] direction for crystal orientation, but a small amount of [111] orientation.

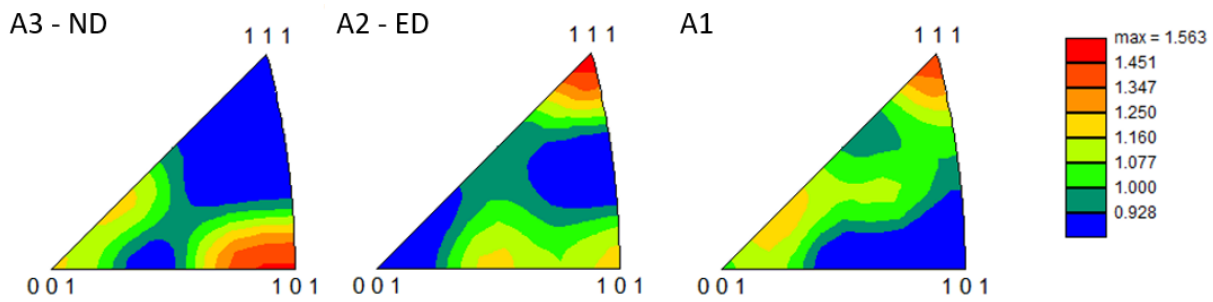


Figure 4-12: Sample 4V inverse pole figure

4.4 Micro-extruded spiralled samples

Both sample 1 A and 3 A are sintered using the same temperature progression stated in section 3.6.2, but this section will only discuss the EBSD measurement for sample 3 A. The conditions are extrusion with a 580 μm nozzle in a flux density of 230 mT in the nozzle tube based on the simulation. Figure 4-13 shows sample 1 A and 3 A after sintering and before cutting into sections.

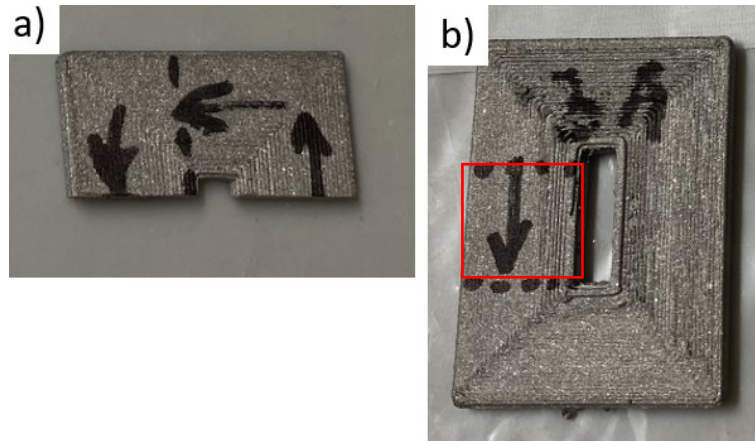


Figure 4-13: Samples after sintering with the arrows indicating the extrusion path: a) 1 A that is cut; b) 3 A

4.4.1 Sample 3 A

Figure 4-14 shows the sample 3 A after cutting and polishing mounted in a holder for EBSD measurements, with indications to state the global orientation of the sample. The following section will always have the same sample orientation for consistency. For simplicity, the bottom layer of the sample is at the top and the top layer of the sample is at the bottom. As stated previously, the outside of the spiralled sample has a smoother finish during extrusion, which is indicated at the left of the images.

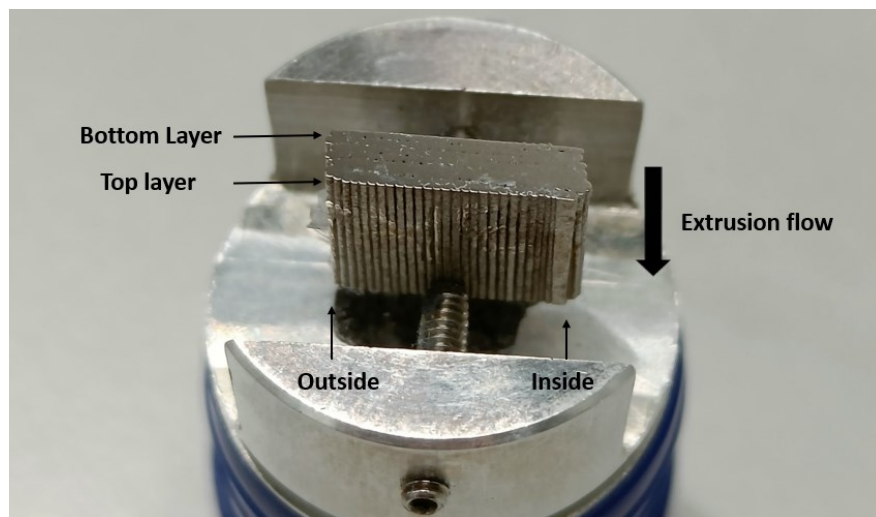


Figure 4-14: Sample 3 A after cutting and polishing for EBSD in sample holder

The large cross-sectional area of sample 3 A enables to perform multiple EBSD measurements at separate locations. A total of six areas is examined, that are visualised in Figure 4-15. Figure 4-16 shows the colour coded legend for the inverse pole figure that will be used for all the presented EBSD measurements for the ND.

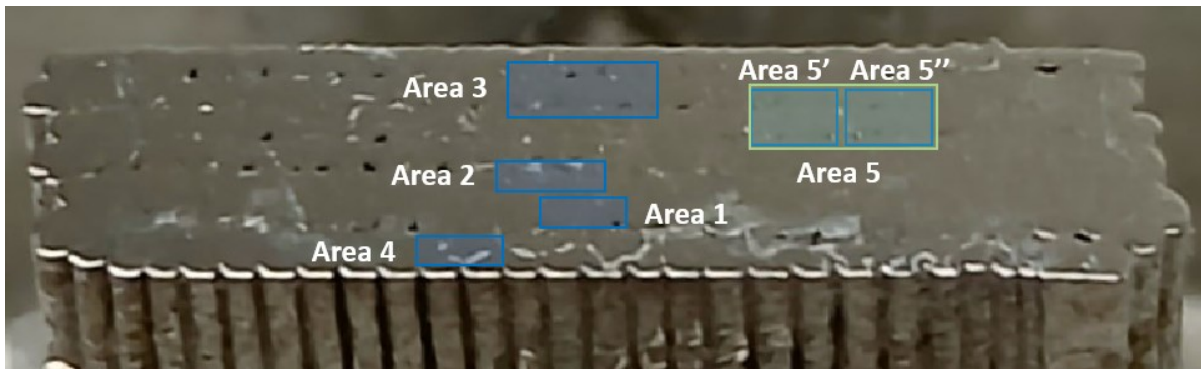


Figure 4-15: Locations of the examined areas

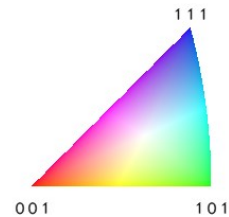


Figure 4-16: Colour coded legend for the inverse pole figure

The individual EBSD measurements are presented in Appendix C. As an example the results for a small area 1 is presented in Figure 4-17 and Figure 4-18.

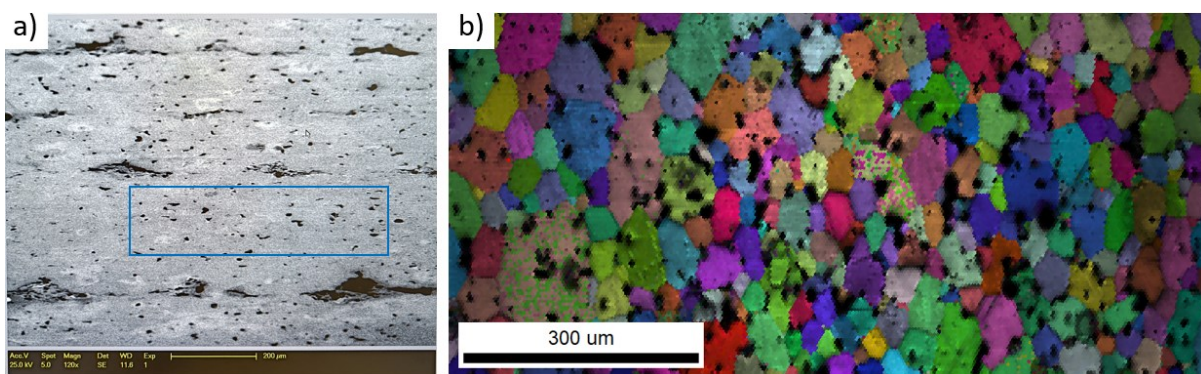


Figure 4-17: Sample 3 A, area 1, magnification 120x: a) SEM; b) Inverse pole figure of ND, step size 2 μm

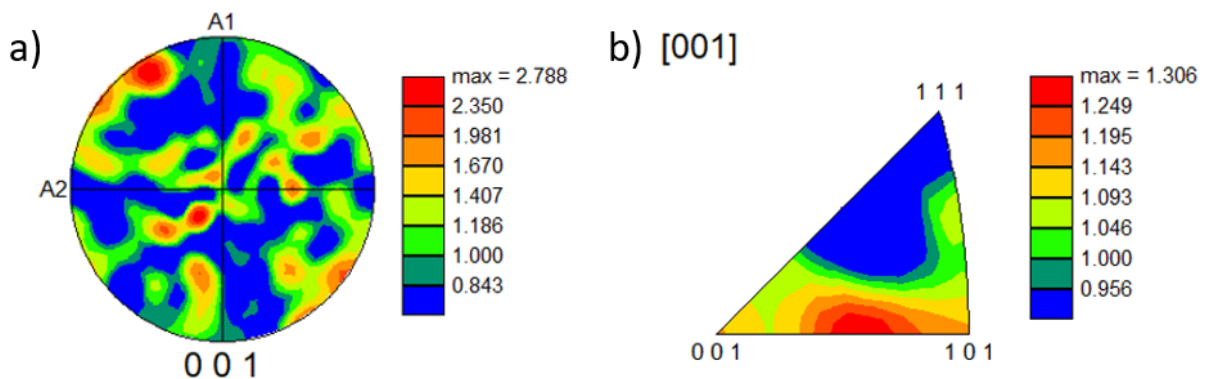


Figure 4-18: Sample 3 A, area 1: a) pole figure; b) inverse pole figure ND

Only the results are discussed for the ND, which is the extrusion direction perpendicular to the examined plane, other pole figures or inverse pole figures would only present the results of the randomized orientation because there was no influence of the magnetic field in these directions. Based on the results, area 1 shows a low intensity in crystal alignment in the [001] and [101] direction.

To increase the statistical significance of the measurements multiple areas are combined, as for area 5' and 5'' are stitched to one larger area 5 to have more data points. Area 5 covers an area of around 2 mm², with the inverse pole figure presented in Figure 4-19 and the pole figure and inverse pole figure intensity in Figure 4-20.

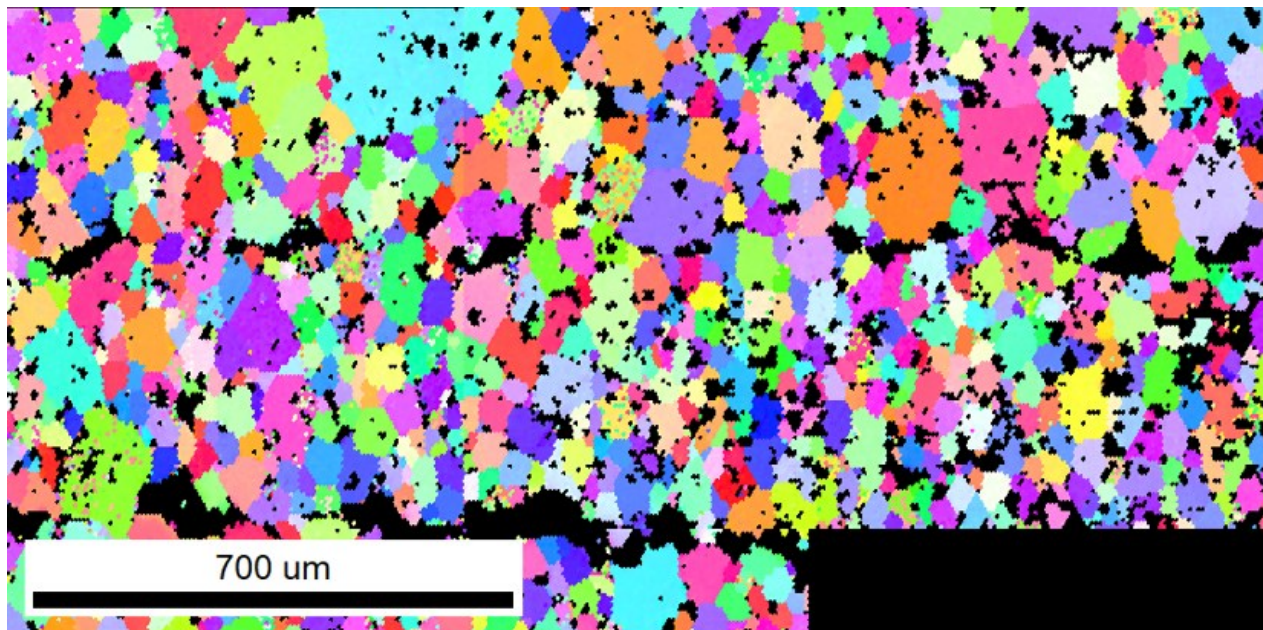


Figure 4-19: Sample 3 A, area 5, magnification 100x, Inverse pole figure of ND, step size 6 μm

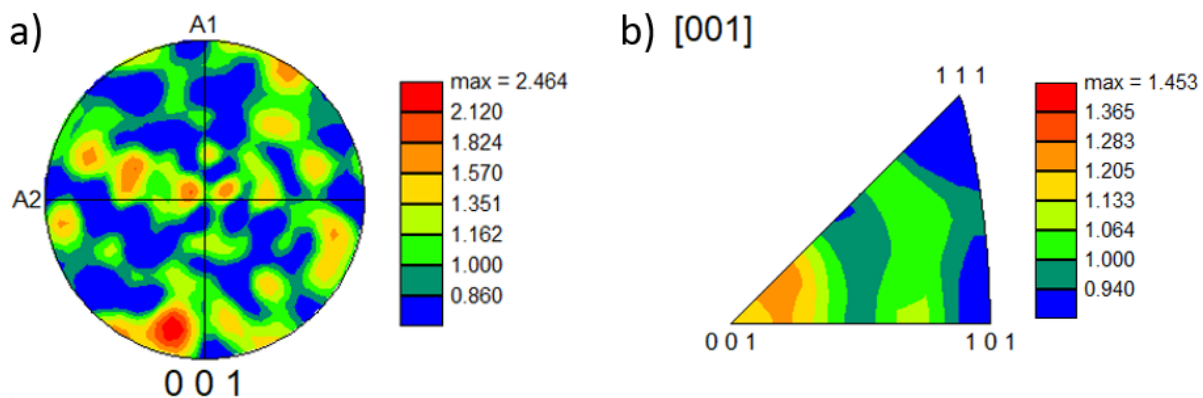


Figure 4-20: Sample 3 A, area 5: a) pole figure; b) inverse pole figure ND

The results of area 5 are more significant because of the larger amount of examined crystal orientations. The intensity of the [001] direction is too low to call this a textured material. Although, the difference between the [001] direction and the [111] direction is noticeable. This could be the result of a depletion zone where the crystals were rotated away from to the [001] direction.

A last measurement is done by combining area 2, 3, and 4 together, which is only possible for a common step size of the measurements. This result will combine the data points for a large dataset so the statistical results can be the final conclusion if crystal alignment is achieved in this extruded sample 3 A. Figure 4-21 shows the pole figure and the inverse pole figure for the combined areas.

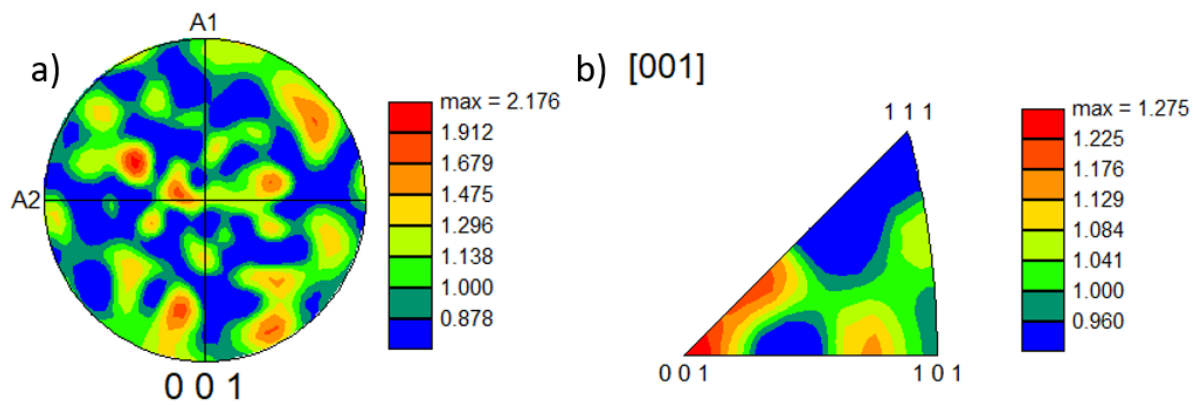


Figure 4-21: Sample 3 A, Combined area 2, 3, and 4: a) pole figure; b) inverse pole figure ND

This result shows similar behaviour as the results from area 5. The intensity of the [001] direction is too low to call this a textured material. Although, the difference between the [001] direction and the [111] direction is noticeable. This could be the result of a depletion zone where the crystals were rotated away from to the [001] direction, what is also visible in Figure 4-20.

4.4.2 Summary sample 3 A

Separate locations are tested on the cross-section to see the possible effect of the printing paste being spread out differently in different layers of the sample. When the influence of new deposited layers would manipulate and deform the previous deposited material to much, the crystal alignment would be disturbed.

The EBSD measurements are executed with a large step size ranging from 2 μm to 6 μm . To ensure good results the step size should be lower than 60% of the smallest grains that are expected in the sample, so each grain is measured by 6-7 points. Out of the PSD of the Fe_{6.5}Si powder the d₁₀ is 7.8 μm . The step size is in some situations too large for an accurate result, but this is a trade-off between the larger area that is covered with a lower resolution.

The Area 1 and 3 show no significant higher intensity in the crystal [001] direction based on the ND, the extrusion direction, of the sample. Area 2, 4, 5' and 5'' show some alignment to the crystal [001] direction, but the intensity is very low to speak of a real texture. What is more interesting is that they all show some sort of depletion zones around [111]. This could be due to the magnetic moment that has the highest magnitude in this region because of the angle of application. The angle between the [001] and the magnetic field is 0°, this means that aligning the crystals perfectly with this direction requires a very high field because the angle of application is significantly smaller.

The larger combined areas have a significant sample size for statistical results. It is visible that a low intensity of crystal alignment with the [001] direction is present. Both results have a low intensity around the [111] direction.

4.5 Conclusion

A first look at the crystallographic orientation of the sintered sample shows that the used powder is single crystal. This can confirm that the sintering step does not affect this condition significantly. The results of fibre sample 1 nor 4V show crystal alignment in the [001] direction. The low intensity of the pole figure and the inverse pole figure suggest that the samples have a randomized crystallographic orientation, which indicates that the magnetic field had no effect on these tested conditions. When the particles are aligned to the external field these images should show crystal orientation in the [001] direction or show a higher intensity for the [001] direction of the A2 - ED direction.

The analysis of the cross-section of spiralled sample 3 A, extruded in 230 mT, covers more area to see the difference in the extruded layers of the sample. All EBSD measurement use a step size ranging from 2 μm to 6 μm to reduce the time to cover large areas but reduce the accuracy of the grain boundaries. Area 3 is the first, and lowest, layer of the sample that in theory exhibits the most influence of the other deposited material. This EBSD measurement shows a randomized and low texture result.

The larger combined areas have a significant sample size for statistical results. A small intensity is visible around the preferred [001] direction, but it is insufficient to classify the material as textured. What is more interesting is that they all show some sort of depletion zones around [111]. This could be due to the magnetic moment that has a high magnitude in this region because of the angle of application of the magnetic moment. The largest angle of application is between [001] and [111] so it is possible that this region shows signs of rotated crystals away from this direction. The angle between the [001] and the magnetic field is 0° , this means that aligning the crystals perfectly with this direction requires a very high field because the angle of application is significantly smaller.

It is difficult to exclude that the pre-magnetization of the powder to 1.6 T has a better result than the 1.2 T for the manual extruded fibres because the shear thinning effect of the conical nozzle with a smaller diameter of 580 μm is more likely to have influence on the crystal alignment, and because in both situations remanence is present.

5 Conclusions and future work

5.1 Conclusions

The design and creation of two different magnetic circuits have been completed. The first toroidal design had an insufficient cross-sectional area and poor magnetic properties, which lead to low magnetic saturation levels. The next rectangular design achieved higher flux densities by using a large cross-sectional area and additional coils that are positioned close to the air gap to reduce the leakage flux. Flux concentration with a taper angle of $\beta = 55^\circ$ helps to boost the flux density inside the air gap and powder capsule. With a total of 282 windings, a current of 55 A, and a gap thickness of 6 mm, it is possible to magnetize the Fe_{6.5}Si powder to 1.6 T.

For the magnetic field-influenced extrusion of the paste, two different extrusion tests are conducted, one manual extrusion and one using a state-of-the-art 3D printer setup. Manual extrusion is done to see if fundamental crystal alignment is possible. The test with the 3D printer at VITO enables for better control of the flow rate of the material. The tests used an electromagnet with low magnetic field strengths to limit the increase in apparent viscosity of the paste material, so extrusion remains possible. After extrusion of the samples, a debinding and sintering step creates a high-density solid sample that is possible to analyse via EBSD.

The EBSD measurements of the fibre samples showed no significant crystal alignment to the preferred direction. The results for sample 3 A are showing possible signs of crystal alignment. A small intensity is visible around the preferred [001] direction, but it is insufficient to classify the material as textured. The results of the areas uniformly show a depletion zone for the intensity of the [111] direction. This is the direction with the largest angle of application of the magnetic moment. It could be possible that this is the result of crystal rotation in this zone. Perfect alignment of the [001] crystal direction with the magnetic field direction remains difficult because of the small angle of application. This suggests that crystal rotation is possible during the 3D micro-extrusion process, which would confirm the prove of concept. The rotation is possibly partially prevented by the high viscosity of the paste material.

5.2 Future work

A future outlook for the next steps in the development of crystal alignment during 3D micro-extrusion is done. More information is needed about the magneto-rheological behaviour of the paste when under the presence of a magnetic field. The increase of the apparent viscosity for increasing field strengths make the extrusion process difficult. A possible solution would be the use of ultrasonic vibrations on the nozzle to increase the shear rate inside the material, and thus lower the apparent viscosity.

Aligning the particles perfectly with the external field direction is difficult because of the small angle of application for the magnetic moment. To achieve further rotation of the crystals, additional energy is needed to overcome the interaction forces with the other particles and the binder material. Adding additional energy could be in the form of ultrasonic vibrations but more investigations are needed to find an optimum without having an impact on the 3D-extrusion process.

Because EBSD is a time-consuming process, the number of analysed results is limited. Finding an additional method for measuring the presence of crystal alignment in extruded samples could prove useful.

Durability study

This paper describes the design and creation of a magnetic circuit, which was made with refurbished materials that were available at the lab. The low carbon rod and the electrical steel laminates were left over parts of different objects.

When designing the rectangular design, more focus went into the reconfiguration possibilities of the object without mounting the parts in an irreversible way so modifications could be made on the same object. This was less the case with the toroidal core design that could only be tested in one configuration.

3D printing of objects for electrical machines has the advantage of adding material instead of subtracting it. Conventional technique's today often use large presses to stamp 2D shaped laminates out of larger steel coils. This process results in a high amount of unusable material when inner holes of a stator are punched for the electrical steel stack. This increases the waste and transportation costs and necessitates re-transporting the scrap metal pieces for recycled. This increases the inefficiency of the technique, depending on the amount of usable material based on the weight of the blank steel coil.

Micro-extrusion is a relatively inexpensive technology with less energy consumption when compared to LPBF. This could result in large differences in scalability of the production process. The energy needed for the laser system in LPBF is quite large and the build chamber must be shielded with an inert gas to avoid oxidation of the powder inside the build chamber. Both processes, micro-extrusion and LPBF require some extend of post-processing. The only advantage of LPBF is that no debinding step is needed for burning out the polymer matrix that is present in the paste-based material. The densification step of the parts will be similar, so energy wise this is comparable.

Throughout this paper, the powder and the extruded samples travelled large distances from preparation to analysis. If it were possible to extrude the samples on an in-house micro-extrusion setup, the transportation would be reduced.

The importance of this work in terms of energy efficiency for electrical motors is discussed in more detail in chapter 1.

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Appendix A

Beckman Coulter LS 13 320

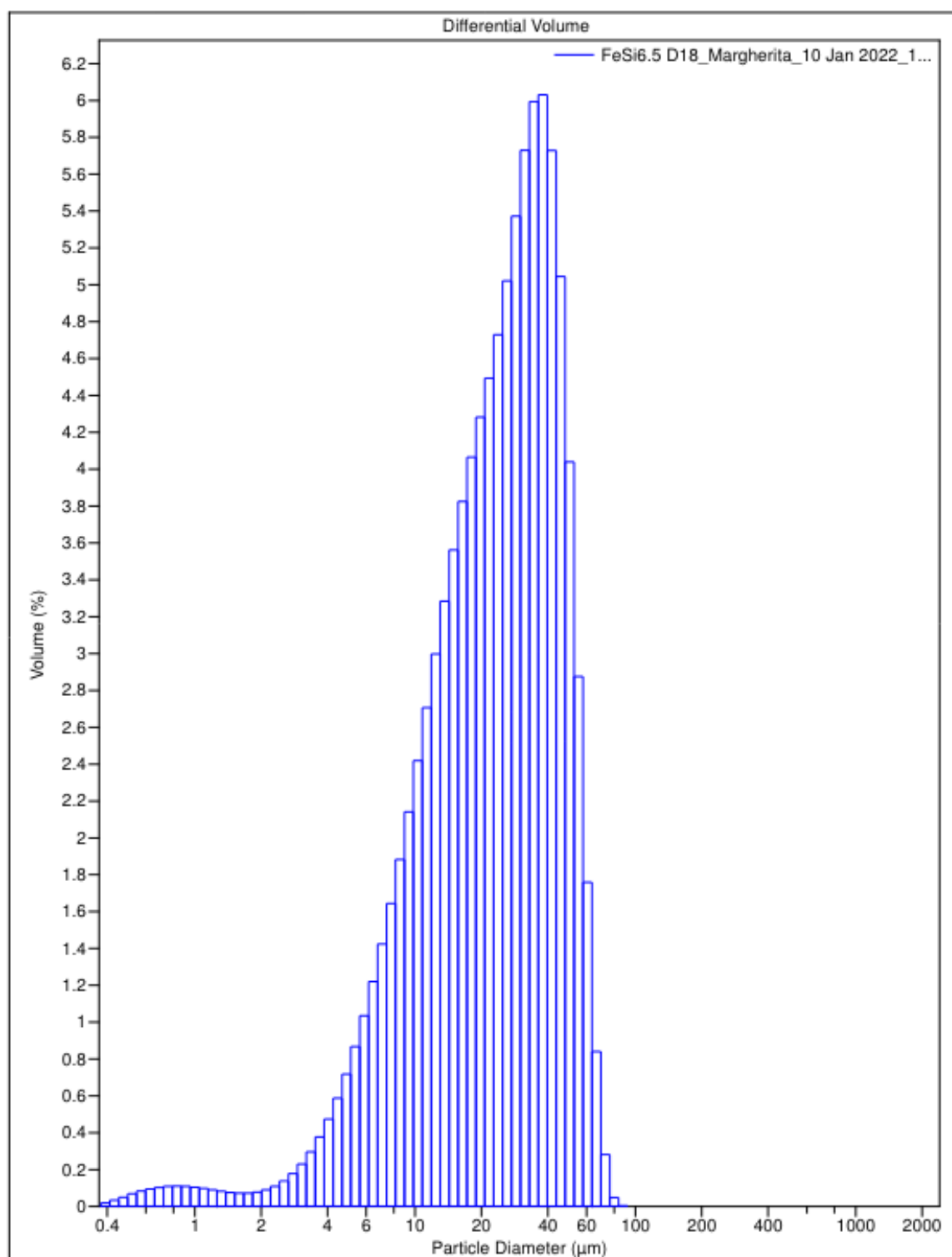


Figure 5-1: PSD of the Fe_{6.5}Si powder

Appendix B

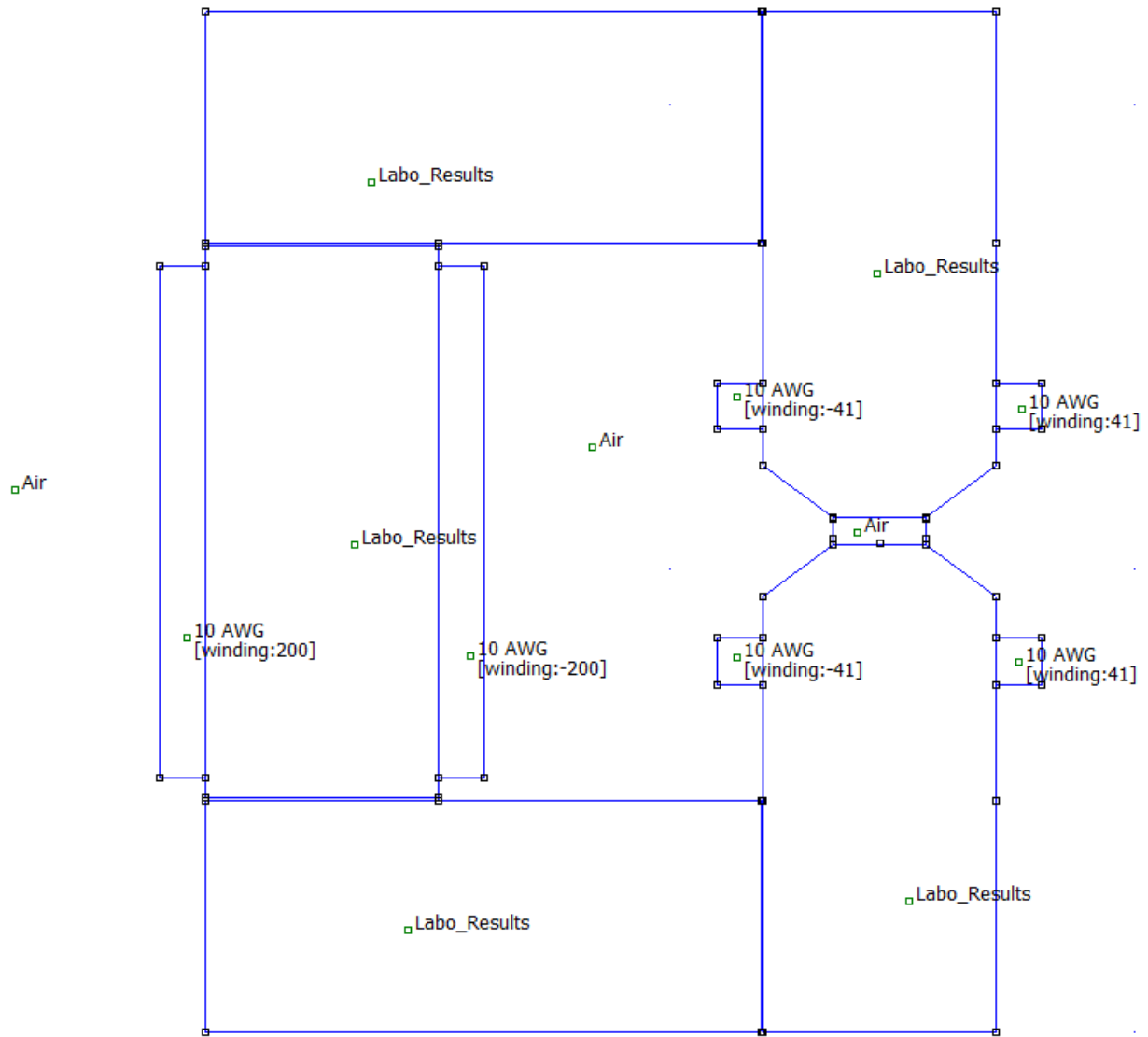


Figure 5-2: Final FEMM simulation of the rectangular design

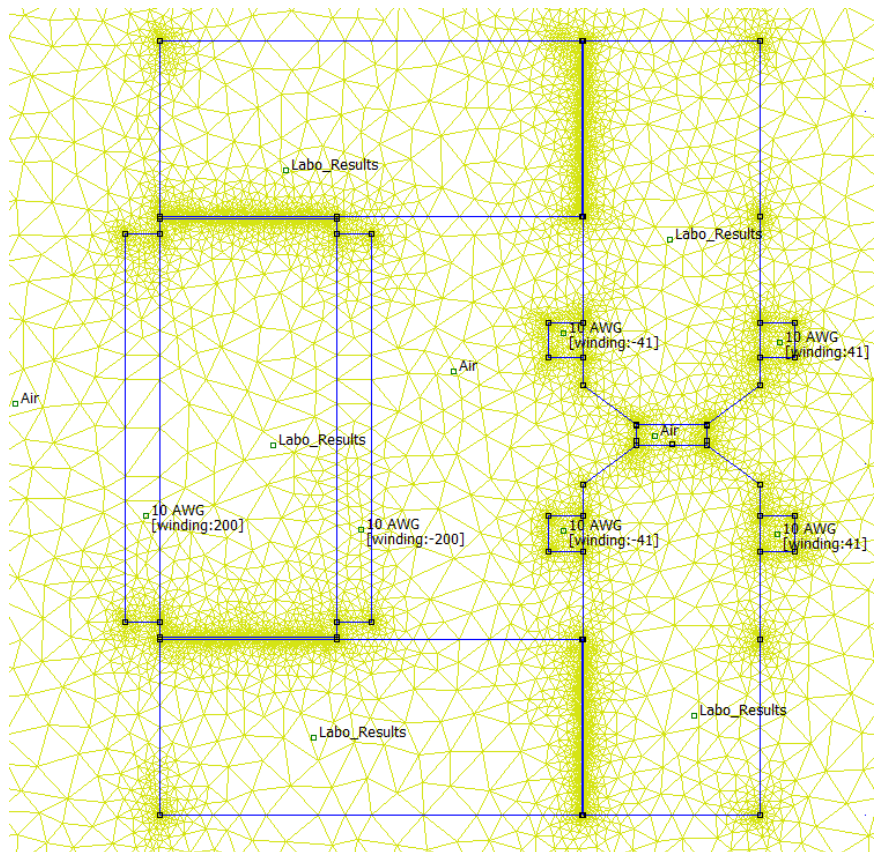


Figure 5-3: Meshed rectangular design of the FEMM simulation

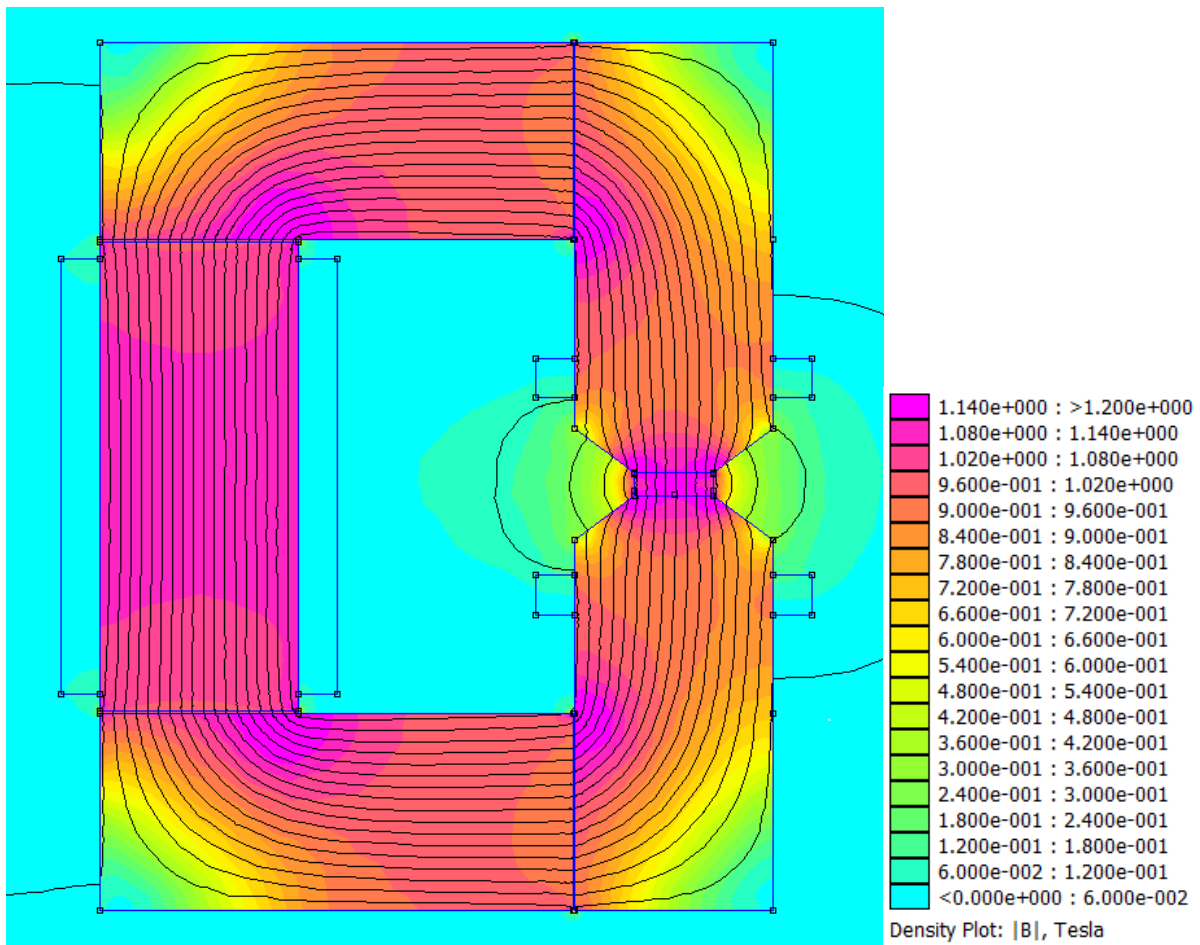


Figure 5-4: Results of the final FEMM design for 25 A

Appendix C

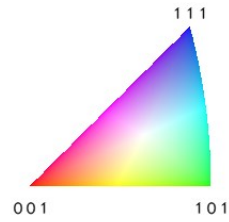


Figure 5-5: Colour coded legend for the inverse pole figures

- **Area 1** (in the .osc files Area 2)

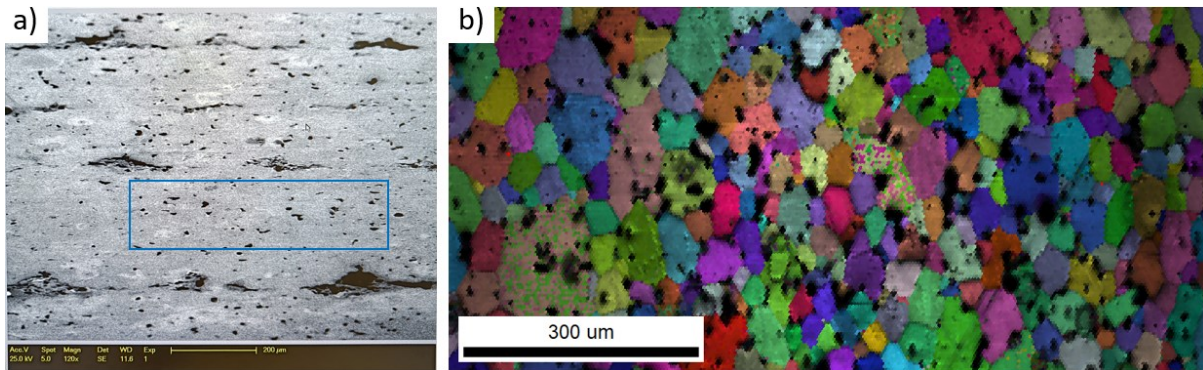


Figure 5-6: Sample 3 A, area 1, magnification 120x: a) SEM; b) inverse pole figure of ND, step size 2 μm

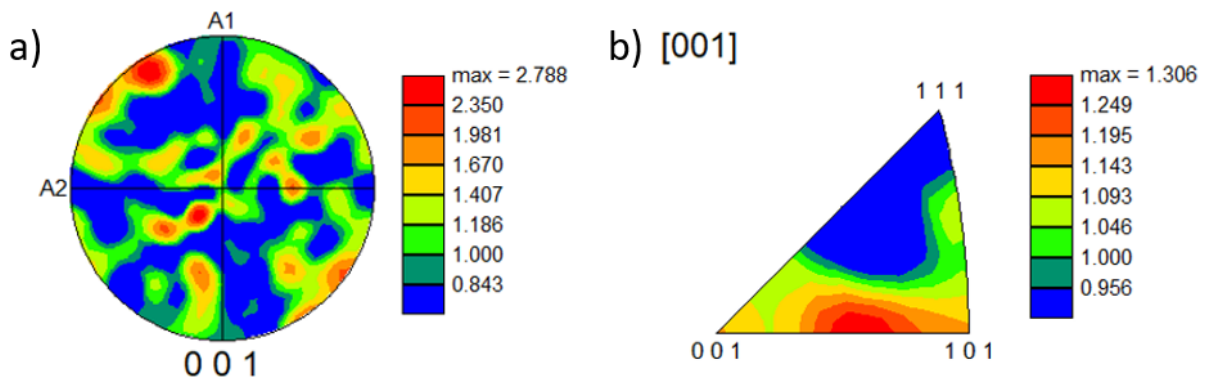


Figure 5-7: Sample 3 A, area 1: a) pole figure; b) inverse pole figure ND

- **Area 2** (in the .osc files Area 3)

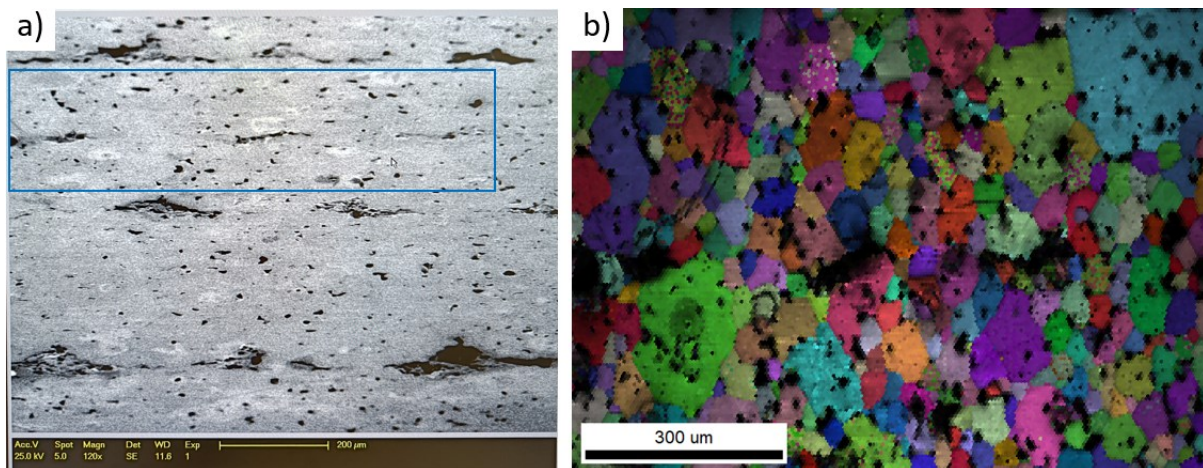


Figure 5-8: Sample 3 A, area 2, magnification 120x: a) SEM; b) inverse pole figure of ND, step size 2 μm

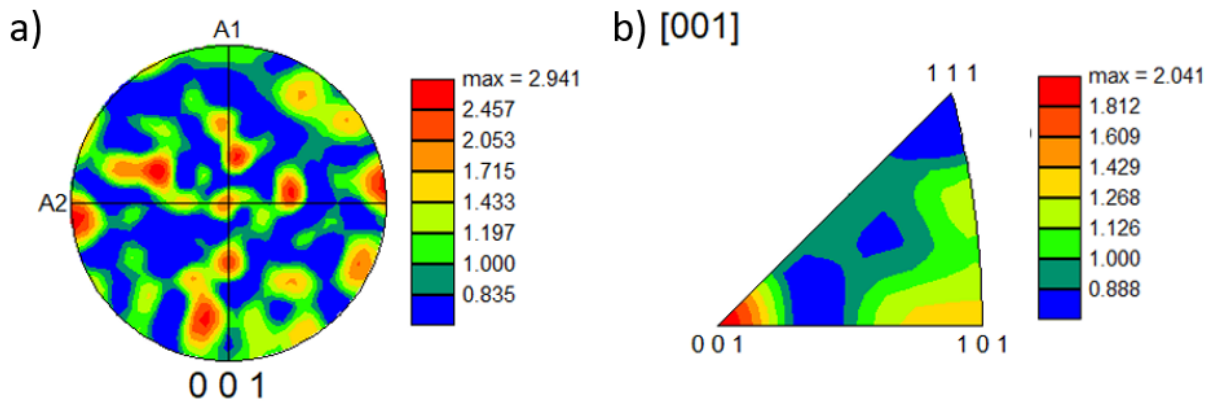


Figure 5-9: Sample 3 A, area 2: a) pole figure; b) inverse pole figure ND

- **Area 3** (in the .osc files Area 4)

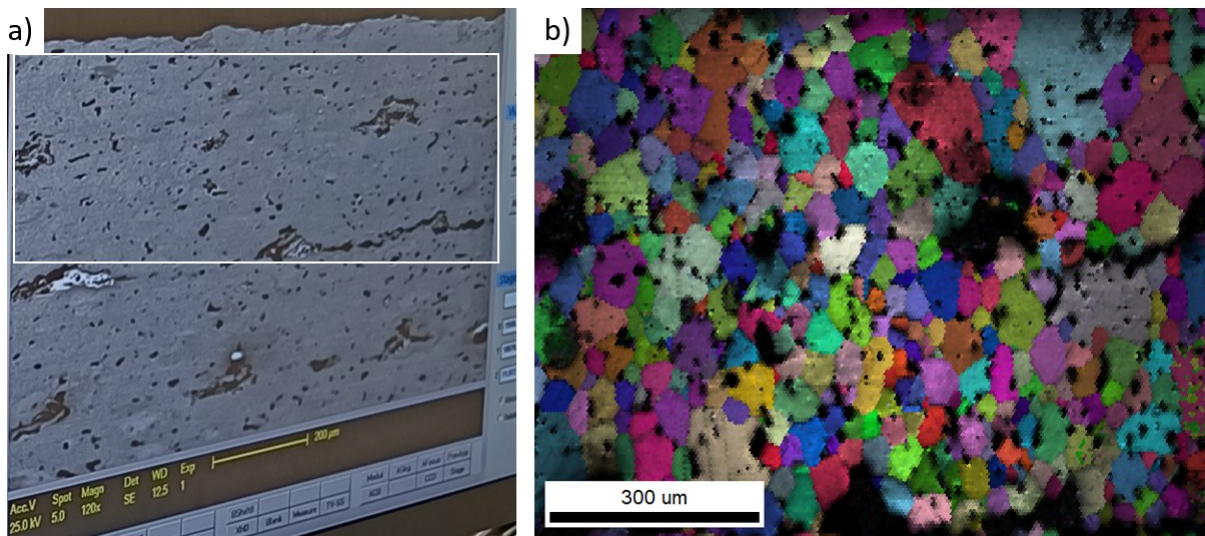


Figure 5-10: Sample 3 A, area 3, magnification 120x: a) SEM; b) inverse pole figure of ND, step size 2 μm

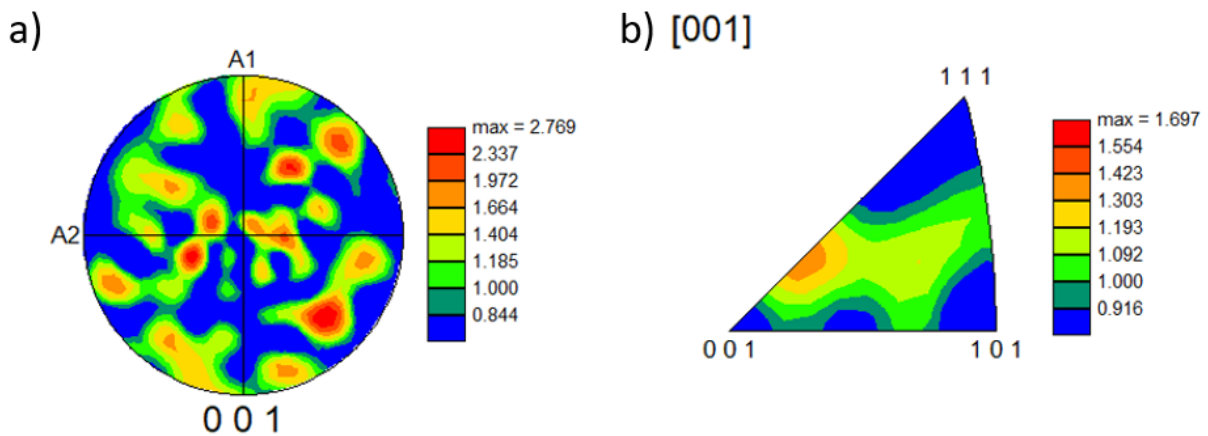


Figure 5-11: Sample 3 A, area 3: a) pole figure; b) inverse pole figure ND

- **Area 4** (in the .osc files Area 5)

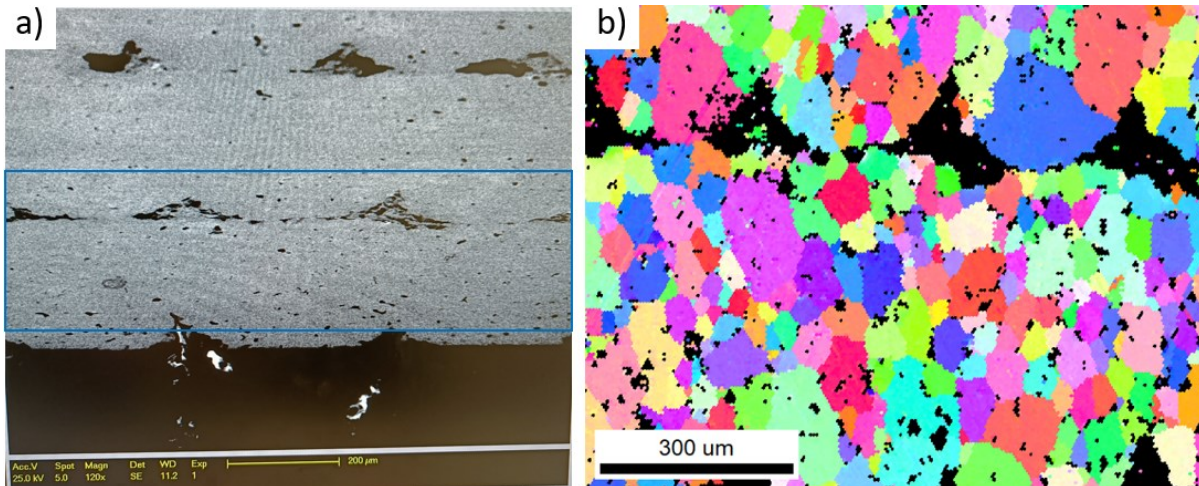


Figure 5-12: Sample 3 A, area 4, magnification 120x: a) SEM; b) inverse pole figure of ND, step size 5 μm

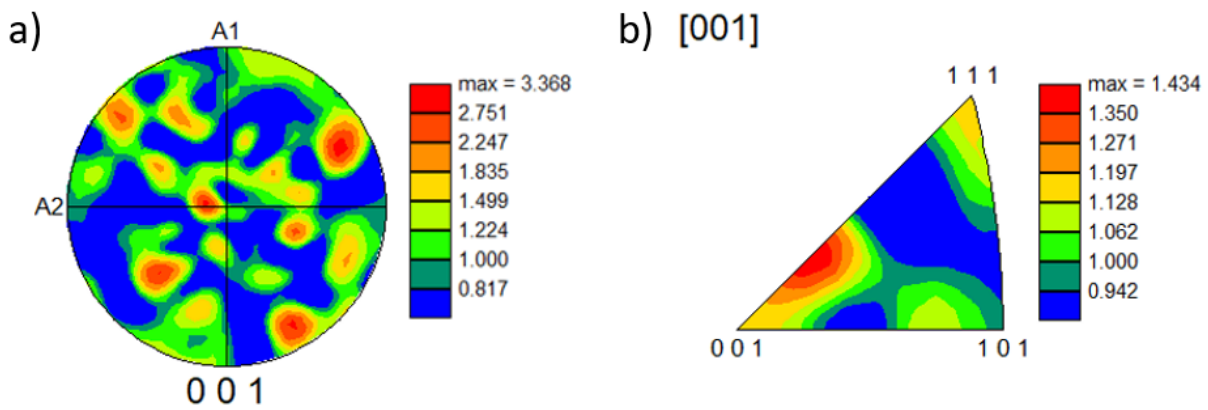


Figure 5-13: Sample 3 A, area 4: a) pole figure; b) inverse pole figure ND

- **Area 5'** (in the .osc files Area 15)

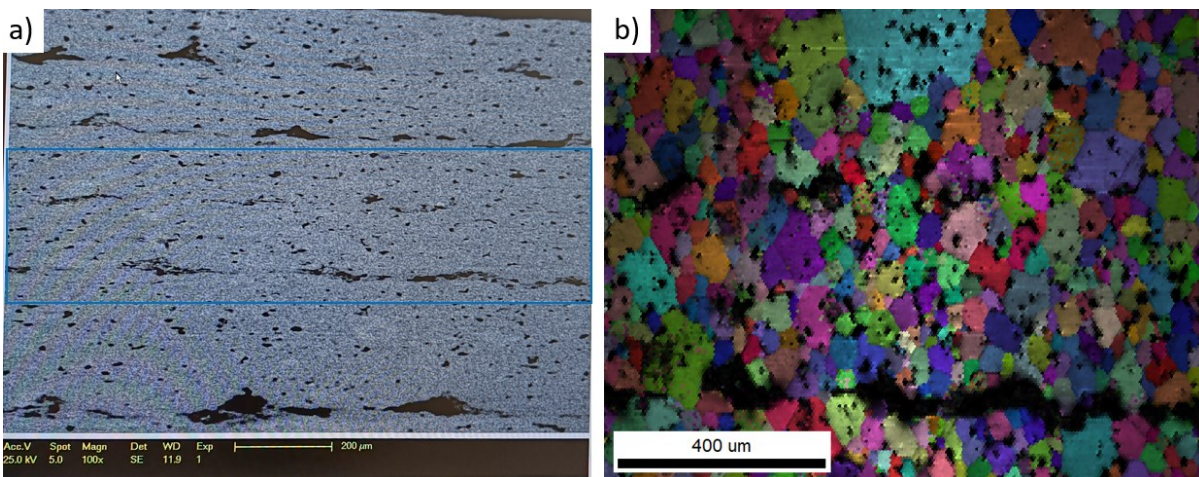


Figure 5-14: Sample 3 A, area 5', magnification 100x: a) SEM; b) inverse pole figure of ND, step size 6 μm

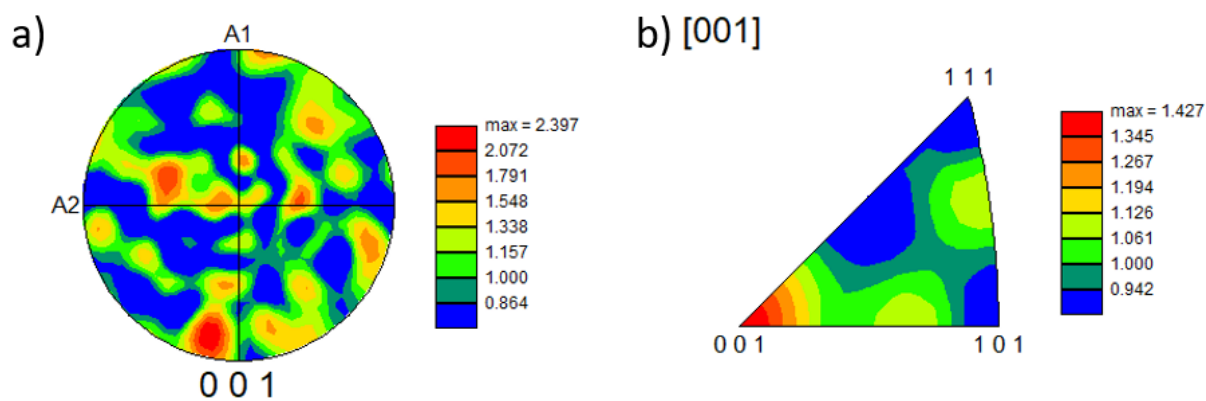


Figure 5-15: Sample 3 A, area 5': a) pole figure; b) inverse pole figure ND

- **Area 5''** (in the .osc files Area 12)

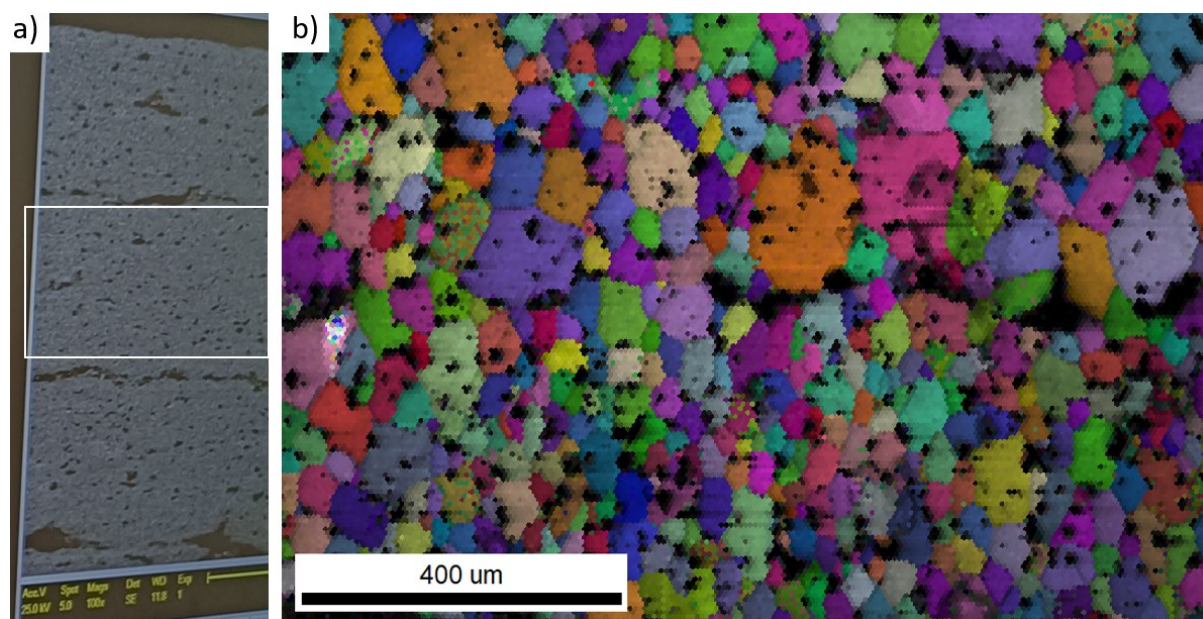


Figure 5-16: Sample 3 A, area 5'', magnification 100x: a) incomplete SEM of the examined area; b) inverse pole figure of ND, step size 6 μm

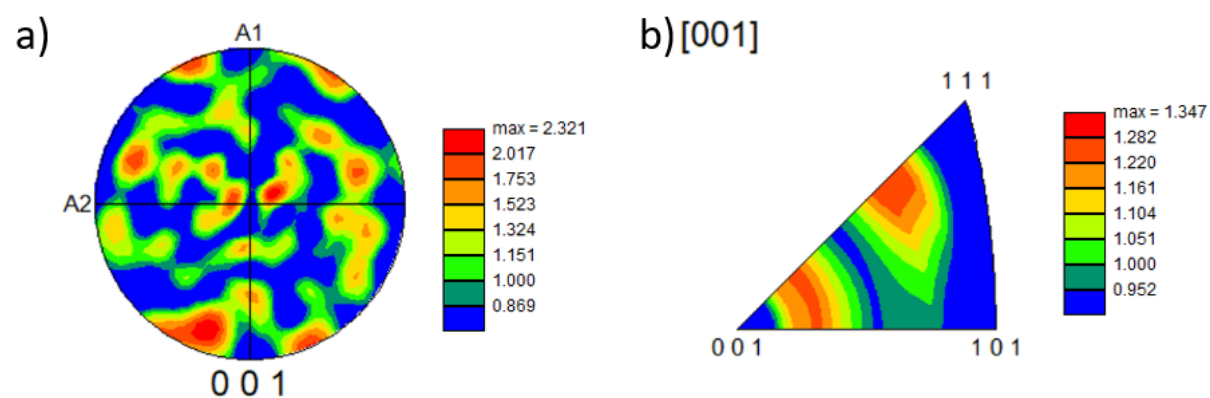


Figure 5-17: Sample 3 A, area 5'': a) pole figure; b) inverse pole figure ND