1 Additive Manufacturing Magnetic Materials

Manufacturing Hard Magnets (NdFeB) 2025

Prepared by: Xavier Walls, Rene Lam, Mingzhang Yang

Reviewed By: Mohsen Keshavarz

We acknowledge the significant contribution of Fabrice Bernier at NRC as well as the coop students from the MSAM lab.

Supervised by Mihaela Vlasea

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2 Build 3.X Summary

Summary table:

Build #	Objective	Total samples	Failed samples	Samples that survived	Analysis recommendations
5.1	Modify the most successful (highest density) recipe from Build 2 (12) to see if it's possible to get a better bonding recipe and decrease cracks while keeping the same high density.	20	0	20	Analyze 9 of the successful samples by CT Scanning and metallographic analysis. Only 9 is necessary because replicates were printed, the original recipe won't be analyzed as we already have results of that one.
5.2	Print a series of focused beam recipes based on the low-speed low energy recipes from build 2. Point distance was modified from 3.5 microns to 25 microns	24	24 print was stopped due to severe delamination	0	No analysis suggested
5.3	Print a series of focused beam recipes based on the low-speed low energy recipes from build 2. Point distance was modified from 3.5 microns to 25 microns	24	20 samples had to be stopped	4 samples survived, two of those had big cracks	The two successful samples could be analyzed but no analysis is suggested as next prints were printed to improve the parameters used on these samples.
5.4	Print different shapes based on the best results from build 2. Low speed and low energy samples and high-speed high-energy samples. The samples will be sent to NRC to be magnetized if successful. 4 defocused samples were added with the objective of understanding the effect of point distance (15 to 30 microns) using the low speed, low energy parameters. 1 double scanned sample was added with the objective of determining if double scanning would help to melt the material properly.	13 "complex shaped" geometry samples 4 defocuse d samples 1 double scanned sample	All complex shaped samples had cracks or were damaged. Low energy, low speed samples were stopped to prevent any delamination 1 defocused sample failed Double scanned sample	3 defocused samples were successful	Analyze the 3 successful samples, CT scanning and metallographic analysis

			failed and was stopped to prevent any damage to other samples.		
5.5	Defocused samples were added with the objective of understanding the effect of point distance (35 to 45 microns) using the low speed, low energy parameters. Focused samples were added with the objective of understanding the effect of focusing and point distance (15 to 45 microns) using the low speed, low energy parameters. Double scanned sample were added with the objective of determining if double scanning would help to melt the material properly different upskin parameters (power and point distance) were used.	3 defocuse d samples 7 focused samples 9 double scanned samples	2 defocused samples failed 1 focused sample failed 8 double scanned samples failed	1 successful defocused sample 3 successful focused samples 1 successful double scanned sample	Analyze the 5 successful samples, CT scanning and metallographic analysis

3 Build 3.1 CCD around recipe 12 from build 2.X

3.1 Build 3.1 goals

Improve the best recipe (sample with better density and better fixation to the plate) of batch 2.X (recipe 12) by using a CCD varying speed and energy between 5 and 10%.

3.2 Build 3.1 Details

3.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.0 > 2-DOE>Recipes (parameters)> Build #3.X
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 3.1
Purpose of build	Try to improve the bonding recipe changing the parameters in max. 10% (E* and V*)
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 1-CAD & Designs>Build #3.1
Coupon types and quantities	• Cylinder 1-10; CCD for core (1) 6mm diameter x 9 mm tall (20) • Replicates were printed in a randomized order
Supports	None; direct welding to plate
Tests intended	-
Build time	2.3 Hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No
Post-removal observations	Difficult to remove. Samples “break” while they’re removed
Improvements to suggest	Samples have to be analyzed before any improvements are suggested

3.2.2 Build visuals of CAD designs for components

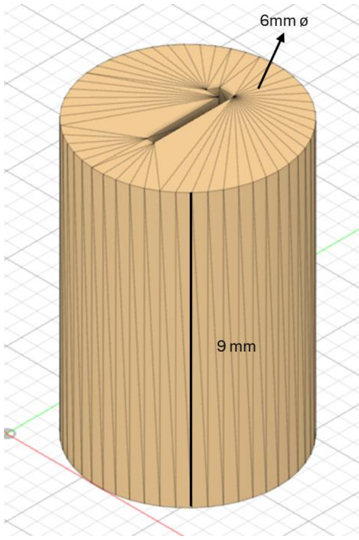


Figure 1. The picture shows the CAD design for the coupons. The picture shows they have a cylindrical shape. The cylinder dimensions are 6mm (diameter) x 10mm (height). The number of each of the cylinders was printed on the top of each to allow easy identification of the sample number.

3.2.3 Build plate visualization, pre-build

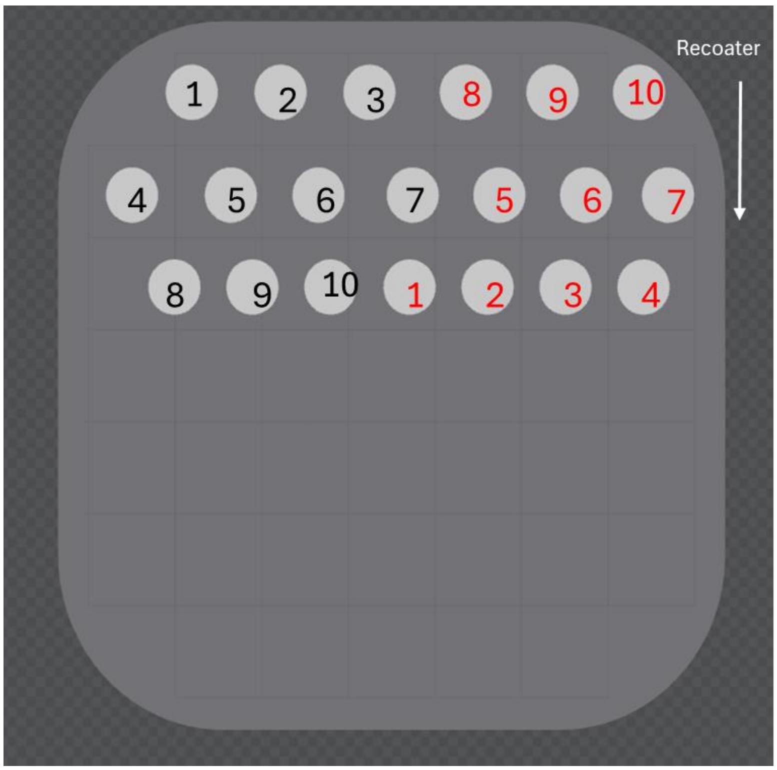


Figure 2. Build plate setup for build 3.1. The order of the coupons on the build plate is shown. Two batches were printed. One is printed in numerical order (black) and the other one is printed in a randomized order (red).

3.2.4 Build plate visualization, post-build

Figure 3. Build 3.1 once printing was finished. The image shows that all printed coupons were successful.

3.3 Part Characterization and Results

In total all 20 samples survived. None of them failed. It was impossible to decide which of the samples had a better fixation to the plate as they all showed practically the same behavior. It was impossible to cut the samples without damaging the part in contact with the saw. A different coloration was observed with respect to the original recipe that was printed previously. After reviewing the parameters provided to the machine it was observed that there may have been an error when transferring the data and the hatch distance changed from 100 to 140. Considering this, these samples will be used by Carleton University for academic purposes and no further characterization is currently planned.

4 Build 3.2 Effect of point distance in focused samples

4.1.1 Build 3.2 goals

Test the point distance effect (3.5, 10, 25 µm) using 4 of the most successful recipes from build 2.X (2-5) using a focused laser and printing replicates.

4.2 Build 3.2 Build Details

4.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 2-DOE>Recipes (parameters)> Build #3.2
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 3.2
Purpose of build	Understand the point distance effect on 4 recipes from build 2.X using a focused laser and printing replicates.
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 1-CAD & Designs>Build #3.2
Coupon types and quantities	• Cylinder 1-10, 6mm diameter x 10 mm tall (24) • Replicates were printed in a randomized order
Supports	No, but bonding recipe was used
Tests intended	-
Build time	1 Hour (stopped)
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	A lot of delamination was observed. The sample was stopped.
Post-removal observations	No removal as no samples survived.
Improvements to suggest	Samples have to be analyzed before any improvements are suggested

4.2.2 Build visuals of CAD designs for components

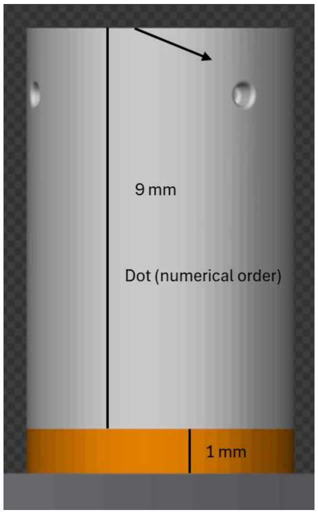


Figure 4. CAD designs for Build 3.2. The image shows the two types of cylinders that were used for this build. The left side shows a cylinder in which dots were placed as identifiers for the sample. The number of dots was used to identify the sample number. For example, one dot for sample 1 or 10 dots for sample 10. The right side shows another type of cylinder which was used for the randomly ordered samples. In this case circles were placed as identifiers and likewise the number of dots was used to identify the sample number. For example, one dot for sample 1 or 10 dots for sample 10.

4.2.3 Build plate visualization, pre-build

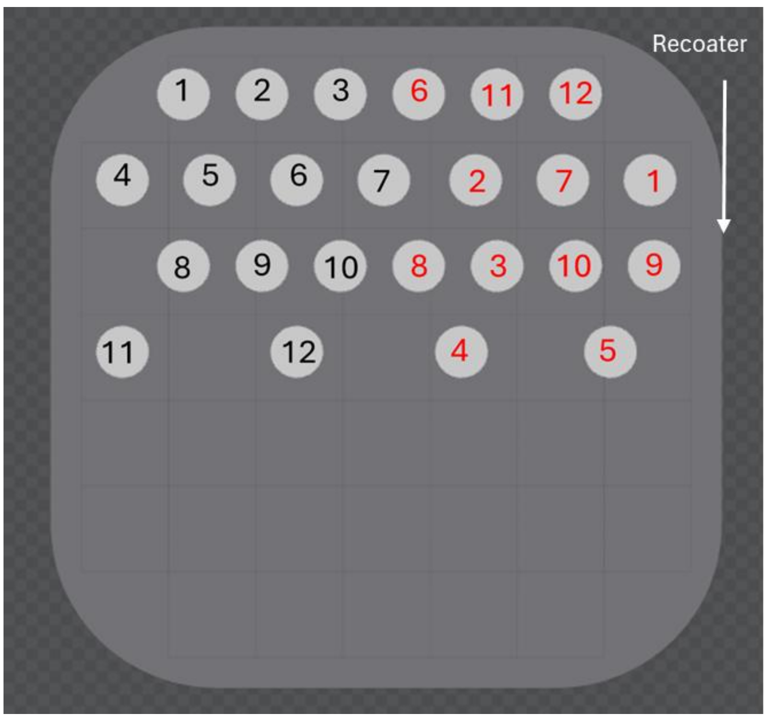


Figure 5. Build plate setup for Build 3.2. The order of the coupons on the build plate is shown. Two batches were printed. One is printed in numerical order (black) and the other one is printed in a randomized order (red).

4.2.4 Build plate visualization, post-build

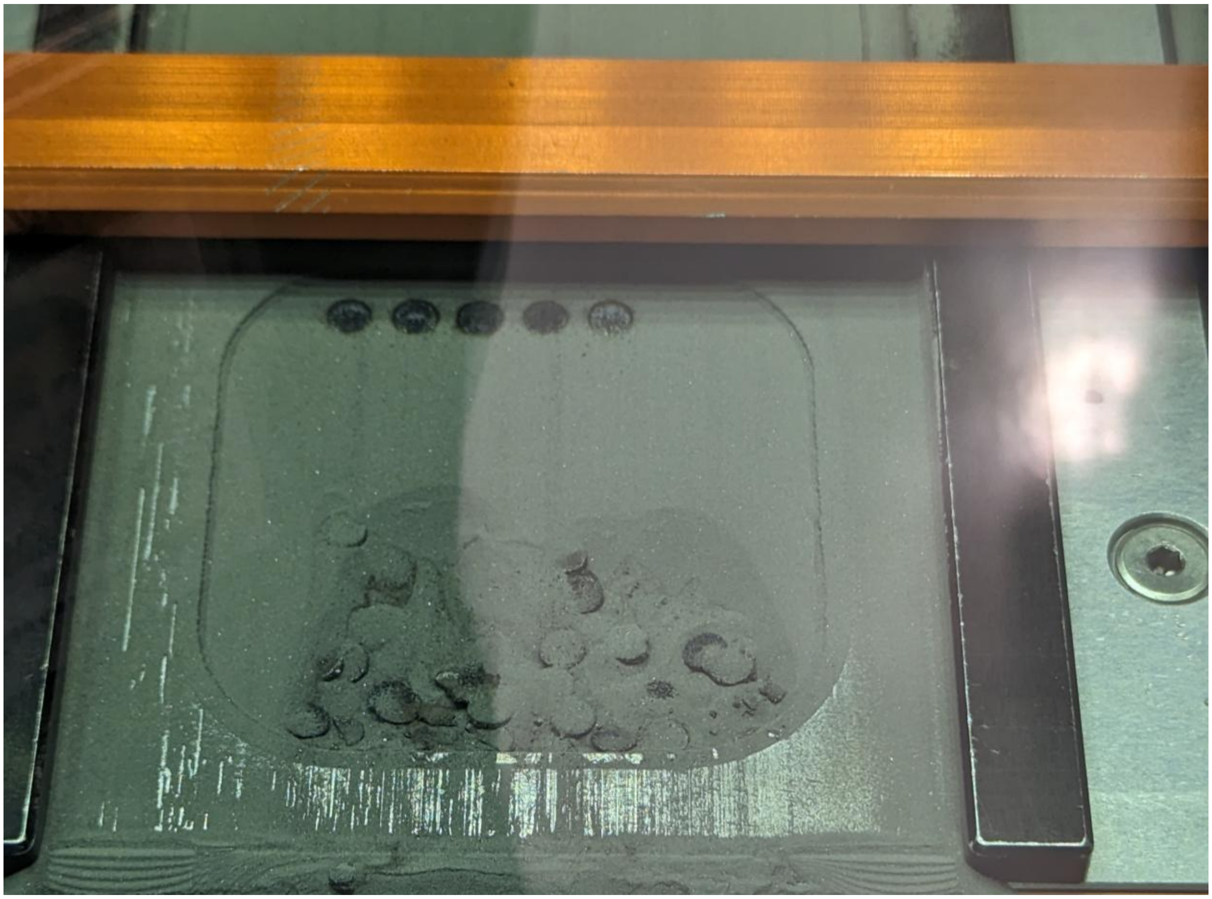


Figure 6. Delamination observed on Build 3.2. The image shows the printing process. It is possible to notice that most of the samples suffered delamination. Therefore, it was decided not to continue with the printing process.

4.3 Part Characterization and Results

The observed heavy delamination in the print indicates that there is an excess of energy supplied to the specimens. To test if it is possible to print with a focused laser, it was suggested to try increasing the point distance.

5 Build 3.3 Effect of point distance in defocused samples

5.1 Build 3.3 goals

Test the point distance effect (3.5, 10, 25 µm) using 4 of the most successful recipes from build 2.X (2-5) using a defocused laser and printing replicates.

5.2 Build 3.3 Build Details

5.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 2-DOE>Recipes (parameters)> Build #3.3
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 3.3
Purpose of build	Understand the point distance effect on 4 recipes from build 2.X using a defocused laser and printing replicates.
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 1-CAD & Designs>Build #3.3
Coupon types and quantities	• Cylinder 1-10, 6mm diameter x 10 mm tall (24) • Replicates were printed in a randomized order
Supports	No, but bonding recipe was used
Tests intended	-
Build time	4 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	A lot of delamination was observed. Several samples were stopped.
Post-removal observations	-
Improvements to suggest	Samples have to be analyzed before any improvements are suggested

5.2.2 Build visuals of CAD designs for components

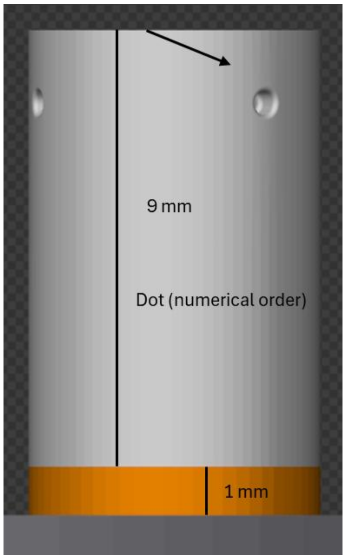


Figure 7. Figure 8. CAD designs for Build 3.3. The image shows the two types of cylinders that were used for this build. The left side shows a cylinder in which dots were placed as identifiers for the sample. The number of dots was used to identify the sample number. For example, one dot for sample 1 or 10 dots for sample 10. The right side shows another type of cylinder which was used for the randomly ordered samples. In this case circles were placed as identifiers and likewise the number of dots was used to identify the sample number. For example, one dot for sample 1 or 10 dots for sample 10.

5.2.3 Build plate visualization, pre-build

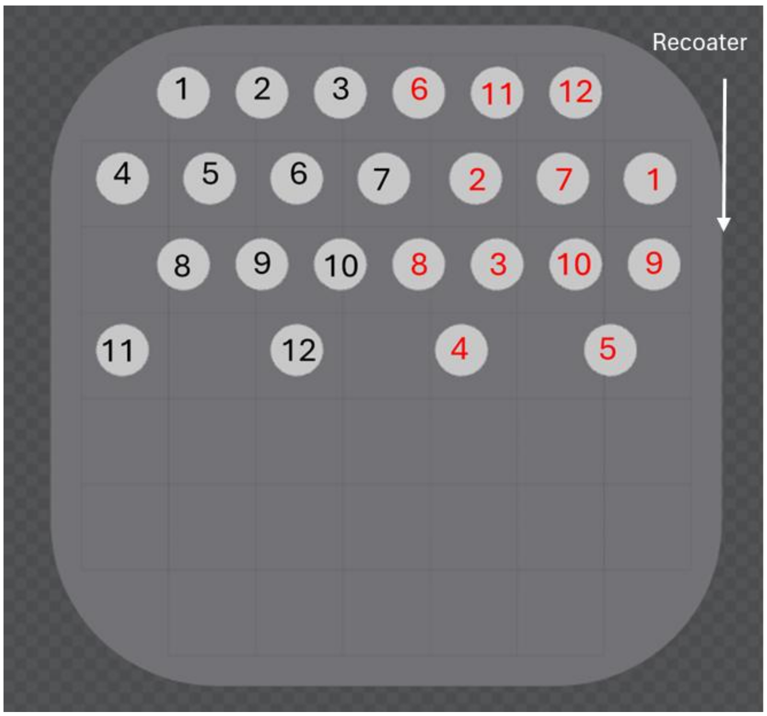


Figure 9. Figure 10. Build plate setup for build 3.3. The order of the coupons on the build plate is shown. Two batches were printed. One is printed in numerical order (black) and the other one is printed in a randomized order (red).

5.2.4 Build plate visualization, post-build

Figure 11. Build 3.3 after the printing process. Only 4 samples completed the printing process. The rest of the samples were stopped as soon as delamination was observed. The samples on the left side present fractures that can be seen when zooming in. The samples located on the upper side did not suffer any damage.

5.3 Part Characterization and Results

As shown in Figure 9, only 4 of 24 samples survived. These corresponded to recipe number 8, recipe number 11 (both samples survived) and recipe number 12. Recipe number 8 had very large fractures in its structure, therefore, even though it survived, it can be considered as a failed sample. Recipes number 9, 10, 11 and 12 had the same point distance (25 microns). Since three of the four surviving samples had the same “large point distance”, it may be assumed that by increasing it, better results can be obtained. Considering the above, it was decided to generate new recipes with larger point distances for builds 3.4 and 3.5.

6 Build 3.4 Samples to be magnetized, effect of point distance in defocused samples, and double exposed samples

6.1 Build 3.4 goals

Print samples that can be magnetized and have their magnetic properties tested. For this purpose, cubic samples were printed out in triplicate and a large arc-shaped sample was printed as well. In addition, 5 cylinders were printed. Four of them were printed using a defocused laser beam to further test the point distance (15, 20, 25, 30 μm) effect and one of them was printed with a double exposure technique to check if it would help to improve melting in the sample.

6.2 Build 3.4 Build Details

6.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 μm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 2-DOE>Recipes (parameters)> Build #3.4
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 3.4
Purpose of build	Magnetize samples and test their magnetic properties. Further test the effect of point distance in defocused samples (15, 20, 25, 30 μm) Test double exposure as a technique too improve melting in the samples.
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 1-CAD & Designs>Build #3.4
Coupon types and quantities	• Cylinder 1-10, 6mm diameter x 10 mm tall (5) • "Cubes" 7 x 6 x 5 mm (12) 4 batches of 3 replicates • Arc Height: 40mm angle 150° internal distance: 30.85mm
Supports	No, but bonding recipe was used
Tests intended	-

Build time	6 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	Several samples were stopped (most cubes) to prevent any delamination from damaging the large part.
Post-removal observations	-
Improvements to suggest	Test the effect of latency time on big parts. When the latency time decreased the samples started burning and the corners of the samples were severely damaged. Also improve printing parameters for samples with pointy corners (a lot of cracks were present on them).

6.2.2 Build visuals of CAD designs for components

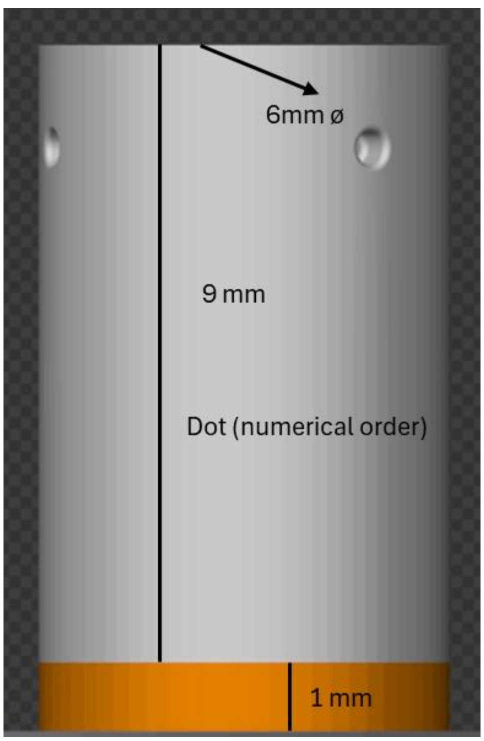


Figure 13. CAD designs for Build 3.4. The image shows the type of cylinder that was used for this build. In this cylinder, dots were placed as identifiers for the sample. The number of dots was used to identify the sample number. For example, one dot for sample 1 or 10 dots for sample 10.

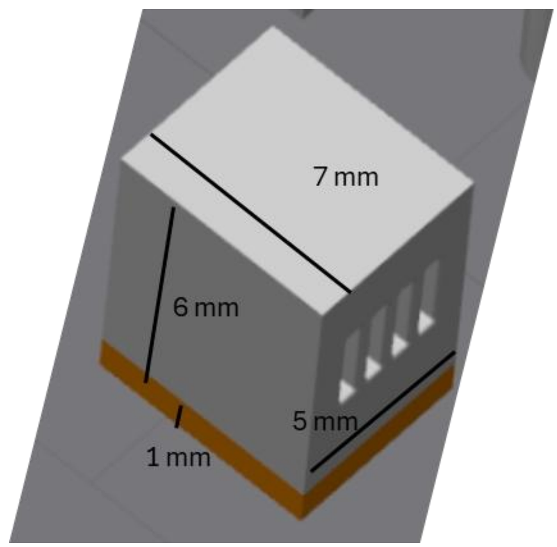


Figure 12. CAD designs for Build 3.4. The image shows the type of "cubes" that were used for this build. The design has different measures in its three dimensions to be able to make anisotropy tests after magnetizing the samples. . The number of lines was used to identify the sample number. For example, one line for sample 1 or 4 dots for sample 4.

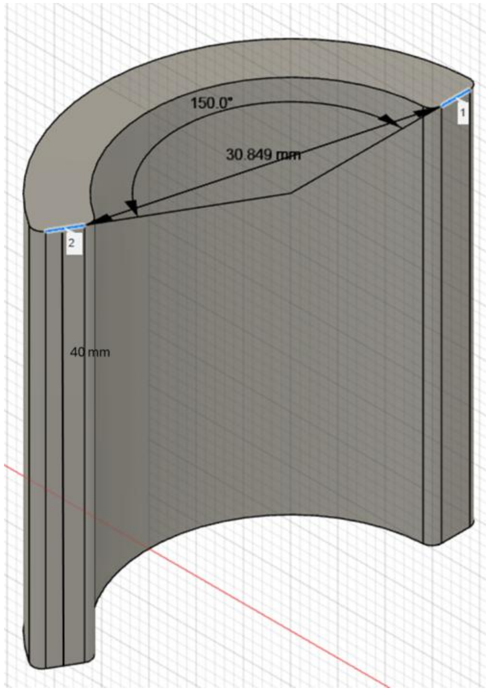


Figure 14. CAD designs for build 3.4. The image shows the design for a large arc magnet. The part has the shape of an arc so it can be tested in an engine.

6.2.3 Build plate visualization, pre-build

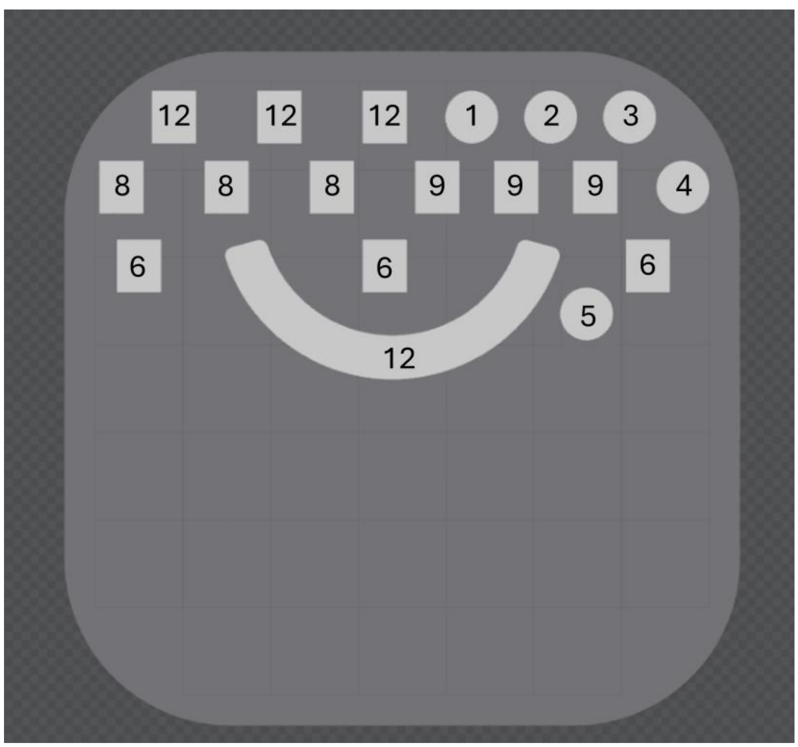


Figure 15. Build plate setup for build 3.4. Three different types of samples are shown: cubes represented by a square, cylinders represented by a circle and an arc representing a large size object that was printed.

6.2.4 Build plate visualization, post-build

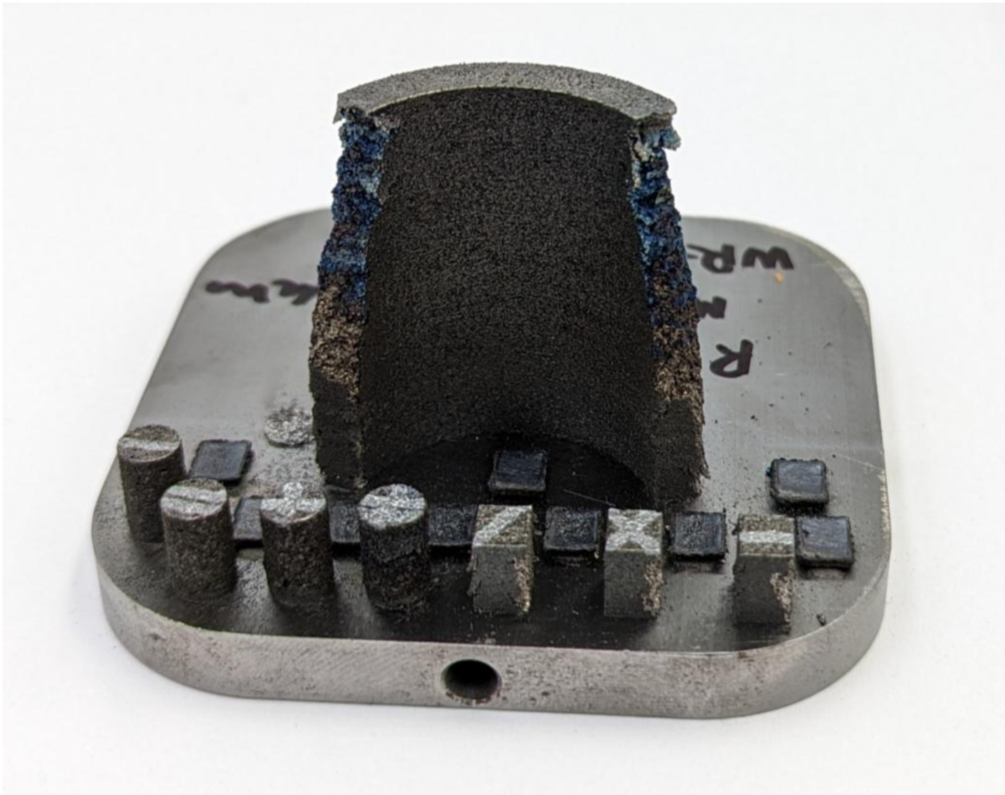


Figure 16. Build 3.4 after printing. From bottom to top it is shown that all samples located at the bottom (those that were closest to the coater during printing) survived. It can also be seen that most of the cubes had to be stopped to avoid delamination affecting the larger piece. The arc-shaped shows gradual damaged throughout the print. The top section shows the gradual damage and signs of burning. Finally, the sample left to of the arch part was unsuccessful as well and corresponds to the double exposed sample.

6.3 Part Characterization and Results

As shown in Figure 14, all the samples located in the central part of the plate were stopped to prevent any delamination, as this could damage the larger piece. It can also be seen that despite this, the larger piece suffered damage on the sides. It can be inferred that this is because the decrease in latency time caused it to overheat. It may be observed that the samples begin to show damage just above the height of the printed cylinders and cubes. This seems to indicate that as soon as the cubes and cylinders stopped printing, and once the large piece was the only one being printed, there was no time for it to cool down before the next laser scan. It can also be seen that the cubes that finished the print show fractures in the corners. This suggests that the selected parameters are not suitable for this type of geometry. We propose to run tests modifying the parameters of the borders to prevent this type of damage to the material. We also suggest printing only with rounded edges until an improvement in the parameters for samples with sharp corners is achieved. Finally, it is shown that 4 out of 5 cylinders survived. The cylinder that did not survive corresponds to the double exposed sample. This sample had to be stopped to avoid delamination as the coater was about to damage it. The four remaining cylinders were printed using a defocused laser with a relatively large point distance (15, 20, 25, 30 μm). From these, the cylinder with a point distance of 15μm can be considered as unsuccessful as fractures and burns were observed on it, this suggests that this is the point distance limit at which the samples can survive even if they have considerable defects.

7 Build 3.5 Effect of point distance in focused and defocused samples and effect of changing power and point distance in double exposed samples

7.1 Build 3.5 goals

Further test the effect of point distance using both a defocused laser beam (35, 40, 45 µm), and a focused laser beam (15, 20, 25, 30, 35, 40, 45 µm). Also, further test double-exposed samples changing the power and point distance of the second exposure.

7.2 Build 3.3 Build Details

7.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 2-DOE>Recipes (parameters)> Build #3.5
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 3.5
Purpose of build	Further test the effect of point distance using both a defocused and a defocused laser beam. Also, test the effect of power and point distance in double-exposed samples.
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #3.X > 1-CAD & Designs>Build #3.5
Coupon types and quantities	• Cylinder 1-10, 6mm diameter x 10 mm tall (19)
Supports	No, but bonding recipe was used
Tests intended	-
Build time	2.5 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	All but one double exposed samples were stopped.

Post-removal observations	-
Improvements to suggest	Samples have to be analyzed before any improvements are suggested

7.2.2 Build visuals of CAD designs for components

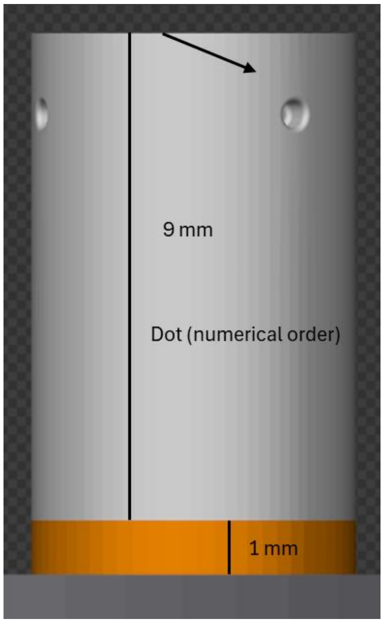


Figure 17. CAD designs for Build 3.5. The image shows the two types of cylinders that were used for this build. The left side shows the cylinders that were used for the double exposure samples. In this cylinder, dots were placed as identifiers for the sample. The number of dots was used to identify the sample number. For example, one dot for sample 1 or 10 dots for sample 10. The right side shows another type of cylinder which was used for the samples where the point distance was modified. In this case circles were placed as identifiers and likewise the number of dots was used to identify the sample number. For example, one dot for sample 1 or 10 dots for sample 10.

7.2.3 Build plate visualization, pre-build

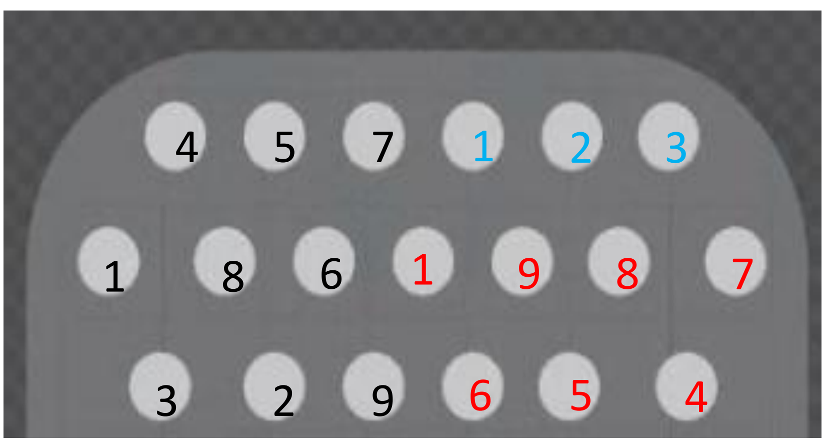


Figure 18. Build plate setup for build 3.5. Three different types of samples can be seen on the image. 9 samples that were printed by double exposure are shown in black. The samples that were printed with a defocused laser are shown in blue and the samples that were printed with a focused laser are shown in red.

7.2.4 Build plate visualization, post-build

Figure 19. Build plate 3.5 after printing. It is shown that most of the left side samples were unsuccessful. Only 1 located in the top center part seems to have been successful. On the other hand, it is shown that except for 3 samples, all the right side ones were successful.

7.3 Part Characterization and Results

This image shows that only one of the samples on the left side was successful (7). It corresponds to the sample exposed to lower energy and higher spot distance in the second exposure. This sample was analyzed by CT Scanning showing a high density (99.8%). It can also be observed that most of the right side samples survived (7 out of 10). The samples that did not survive were samples 2, 3, and 4. Samples 2 and 3 correspond to the largest point distance samples printed using a defocused laser beam. This seems to indicate that the printing range (in terms of point distance) is between 20 and 35 microns. On the other hand, sample number 4 corresponds to the lowest point distance sample using a focused laser. Despite surviving, samples 5, 6, and 7 showed structural damage in the form of cracking. This would indicate that the point distance range for this type of sample would be from 35 to 45 micrometers. This range could be over 45 micrometers, but it would have to be demonstrated in a future print. This corroborates the hypothesis that a relatively long point distance gives good results. It has also been demonstrated that it is necessary to use a larger point distance for samples printed with a focused laser beam due to its higher energy compared to a defocused laser.

8 Build 4.X Summary

Summary table:

Build #	Objective	Total samples	Failed samples	Samples that survived	Analysis recommendations
4.1	Repetition of build 2.3 to confirm its printability and to confirm the effect of the latency time	20	4	16	No analysis to be performed on these samples.
4.2	Test lower layer thickness (40 um layer thickness) Study point distance Study effect of beam focusing	20	7	13	Selected samples analyzed via CT scanning: 3, 4, 5, 6, 14, 15, 16, 17, 18, 19, 20
4.3	Print samples for characterization based on best samples from builds 2.X and 3.X	18	3	15	Selected samples analyzed via CT scanning: 1-5
4.4	Print duplicates of the most successful samples from Build 4.2 for potential heat treatment and microstructure analysis of a potential phase 2	28	1	27	Samples will be stored for future characterization.
4.5	Print complex-shaped parts using the parameters of the two best visually appealing samples from build 4.2.	2	0	2	No further characterization is expected.

9 Build 4.1 Latency Time Study

9.1 Build 4.1 goals

Repetition of build 2.3 to confirm its printability and to confirm the effect of the latency time in this type of material.

9.2 Build 4.1 Details

9.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.0 > 2-DOE>Recipes (parameters)> Build #4.X
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 4.1
Purpose of build	Confirm the effect of the latency time.
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.X > 1-CAD & Designs>Build #4.X
Coupon types and quantities	• Cylinder 1-10; (10 total) 6 mm diameter x 10 mm tall • Quadrangular prisms 1-10 (10 total) 6 mm side x 10 mm tall
Supports	None; direct welding to plate
Tests intended	None
Build time	Around 8 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No
Post-removal observations	Difficult to remove. Samples “break” while they’re removed
Improvements to suggest	No future improvements planned

9.2.2 Build visuals of CAD designs for components

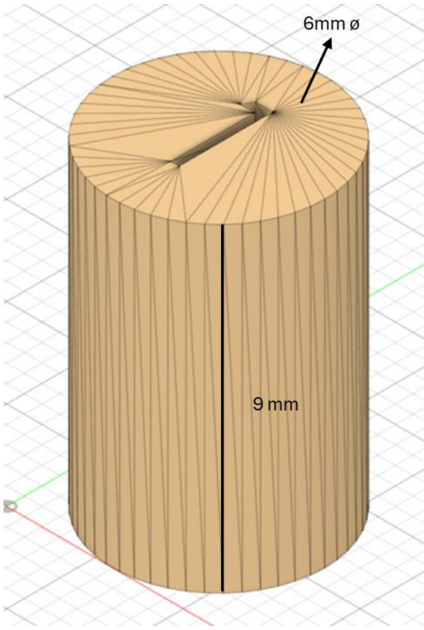


Figure 20. The picture shows the CAD design for the cylindrical coupons. The picture shows they have a cylindrical shape. The cylinder dimensions are 6mm (diameter) x 10mm (height) considering the bonding recipe. The number of each of the cylinders was printed on the top of each to allow easy identification of the sample number.

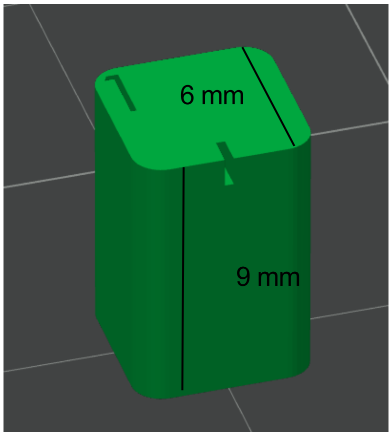


Figure 21. The picture shows the CAD design for the squared coupons. The picture shows they have the shape of a quadrangular prism. The dimensions are 6 mm per side x 10mm (height) considering the bonding recipe. The number of each of the cylinders was printed on the top of each to allow easy identification of the sample number. The small ridge was including to facilitate cutting.

9.2.3 Build plate visualization, pre-build

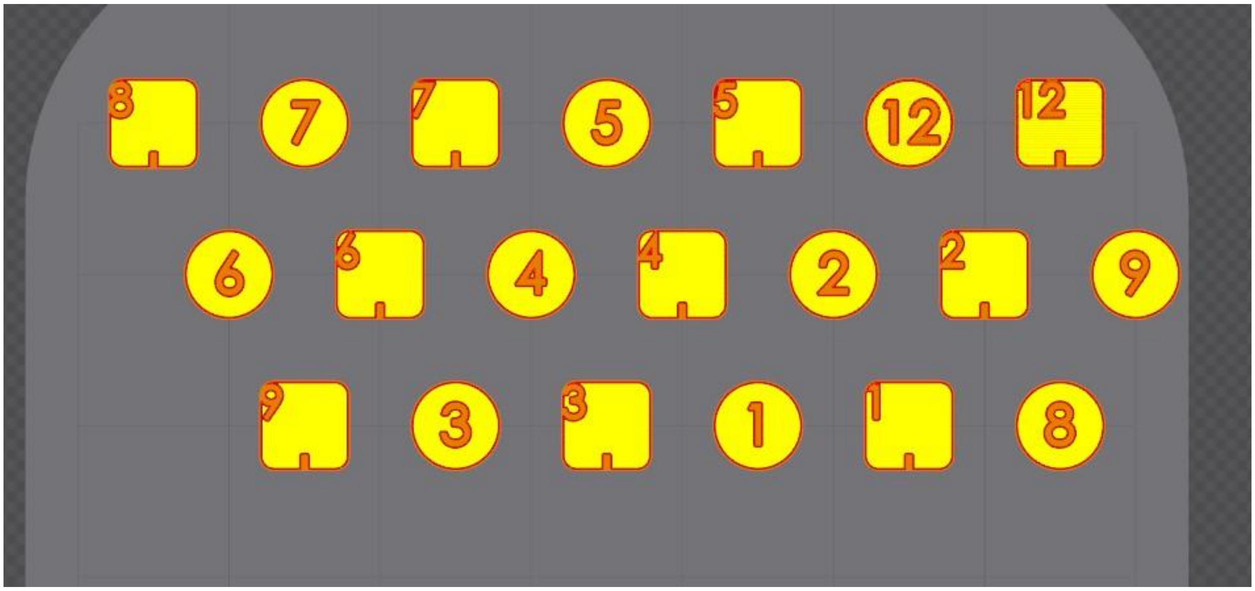


Figure 22. Build plate setup for build 4.1. The order of the coupons on the build plate is shown.

9.2.4 Build plate visualization, post-build

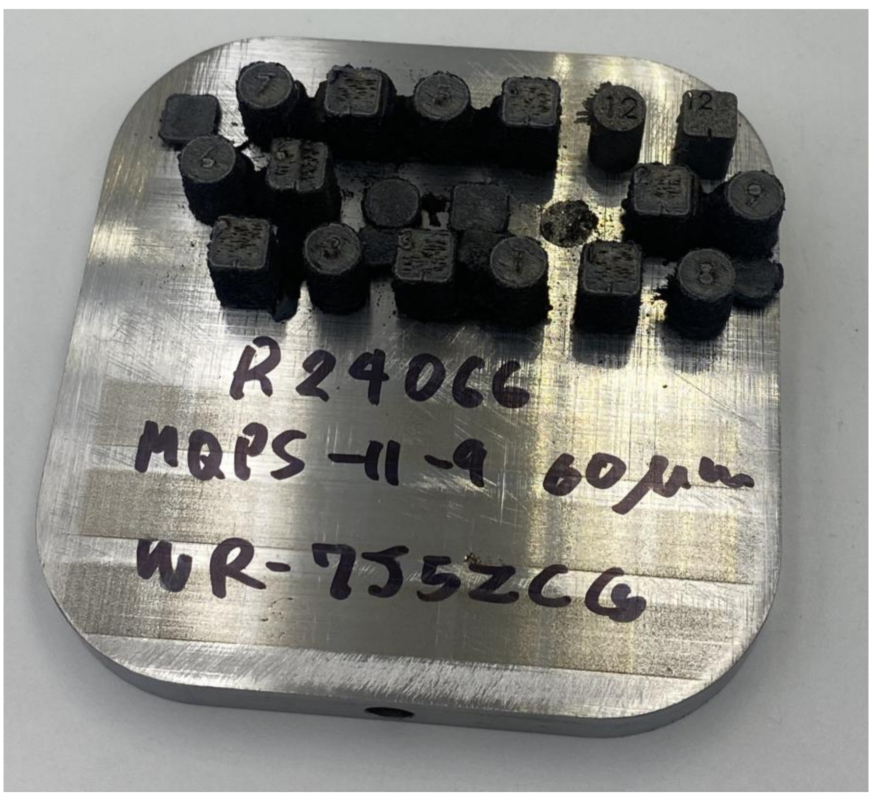


Figure 23. Build 4.1 once printing was finished. The image shows that 4 samples had to be stopped to prevent damage to adjacent samples. It's also shown that overall, the print was successful.

9.3 Part Characterization and Results

Samples were removed from the plate by hand using a hacksaw. No analysis of samples from this build has been completed or is intended.

10 Build 4.2 Decreasing layer thickness to 40 μm

10.1 Build 4.2 goals

- Test the feasibility of printing samples with a lower layer thickness (40 um layer thickness)
- Study effect of point distance (15 – 60 um)
- Study effect of beam focusing (focused beam – 70um and defocused beam – 120 um)

10.2 Build 4.2 Details

10.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.0 > 2-DOE>Recipes (parameters)> Build #4.X
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 4.2
Purpose of build	Evaluate the feasibility of printing with a layer thickness of 40 μm
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.X > 1-CAD & Designs>Build #4.X
Coupon types and quantities	• Cylinders 1-10 printed with defocused beam; 6 mm diameter x 10 mm tall • Cylinders 11-20 printed with focused beam; 6 mm diameter x 10 mm tall
Supports	None; direct welding to plate
Tests intended	None
Build time	Around 4 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No

Post-removal observations	Samples were harder to remove from plate, used handheld Dremmel saw to remove samples from plate.
Improvements to suggest	No future improvements planned

10.2.2 Build visuals of CAD designs for components

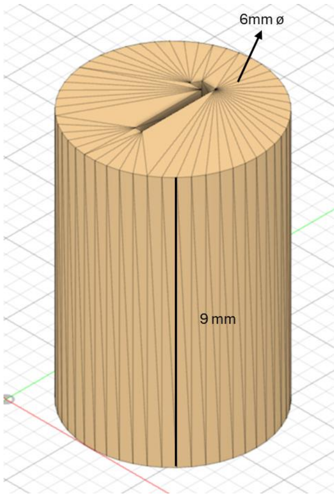


Figure 24. The picture shows the CAD design for the cylindrical coupons. The picture shows they have a cylindrical shape. The cylinder dimensions are 6mm (diameter) x 10mm (height) considering the bonding recipe. The number of each of the cylinders was printed on the top of each to allow easy identification of the sample number.

10.2.3 Build plate visualization, pre-build

Figure 25. Build plate setup for build 4.2. The order of the coupons on the build plate is shown.

10.2.4 Build plate visualization, post-build

Figure 26. Build 4.2 once printing was finished. The image shows that 7 samples had to be stopped to prevent damage to adjacent samples. Some samples also showed cracking and other defects, however it's possible to notice that most samples were able to finish the printing process.

10.2.5 Process Parameter Map

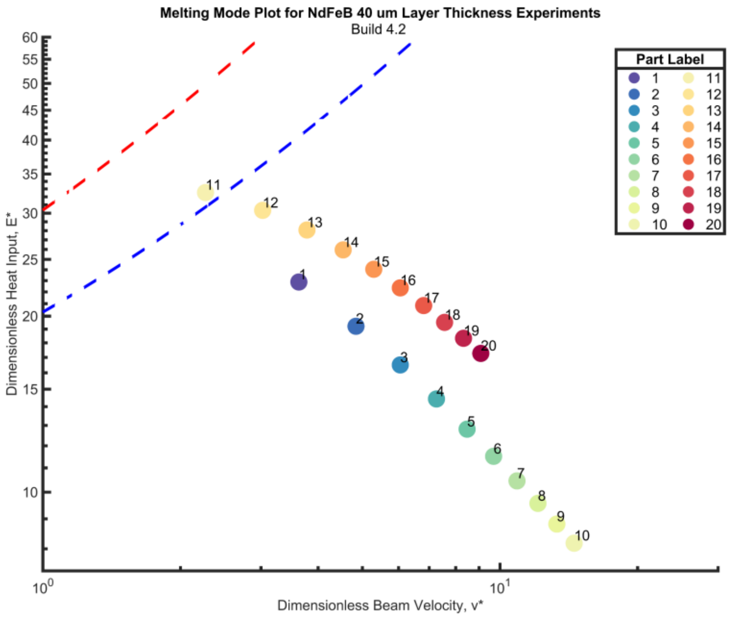


Figure 27. Dimensionless process parameter map of recipes printed in Build 4.2.

10.3 Part Characterization and Results

Majority of the samples were in conduction mode, with one in transition mode.

10.3.1 Print Results

7 recipes failed due to overheating of the parts and the recoater hitting the sample. These samples were cancelled to prevent damage of other parts on the plate

Failed Samples: 1, 2, 9, 10, 11, 12, 13

10.3.2 CT Analysis

Select successful samples were selected for CT scanning for the purpose of density analysis.

Sample 3, 4, 5, 6, 14, 15, 16, 17, 18, 19, 20

Note: Samples 7 and 8 were successful, however not selected for CT scanning since the trend was that with increasing point distance, there was a decrease in density and the target is to increase density.

The following table reports the density of each sample that was analyzed.

CT Density Analysis	
Sample ID	Relative Density (%)
3	99.28
4	98.44
5	97.29
6	96.44
14	97.18
15	96.80
16	97.30
17	93.33
18	94.13
19	88.55
20	89.84

CT Visuals and density calculations can be found in this powerpoint on the MSAM NAS:
https://msamnas01.uwaterloo.ca:5051/d/f/11dSUURALa6fRqmBHlyzBMHj4wFYgWRz

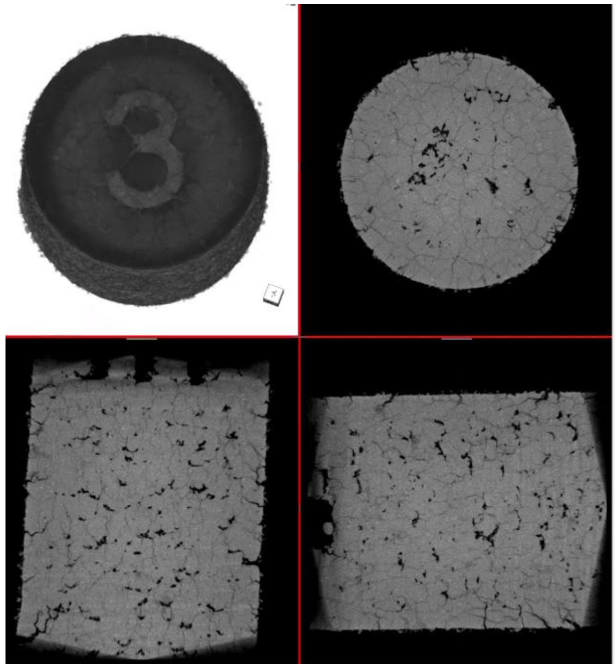


Figure 28. Example of CT scan of Sample 3

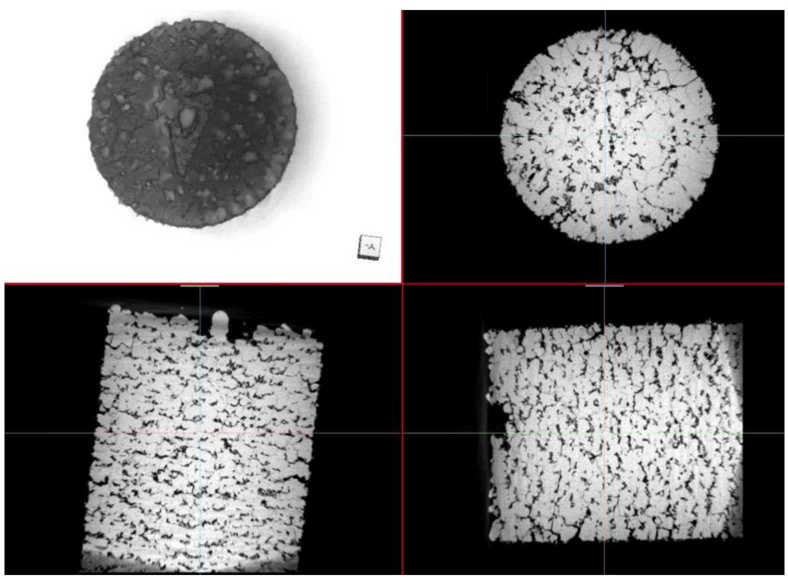


Figure 29. Example of CT scan of Sample 4

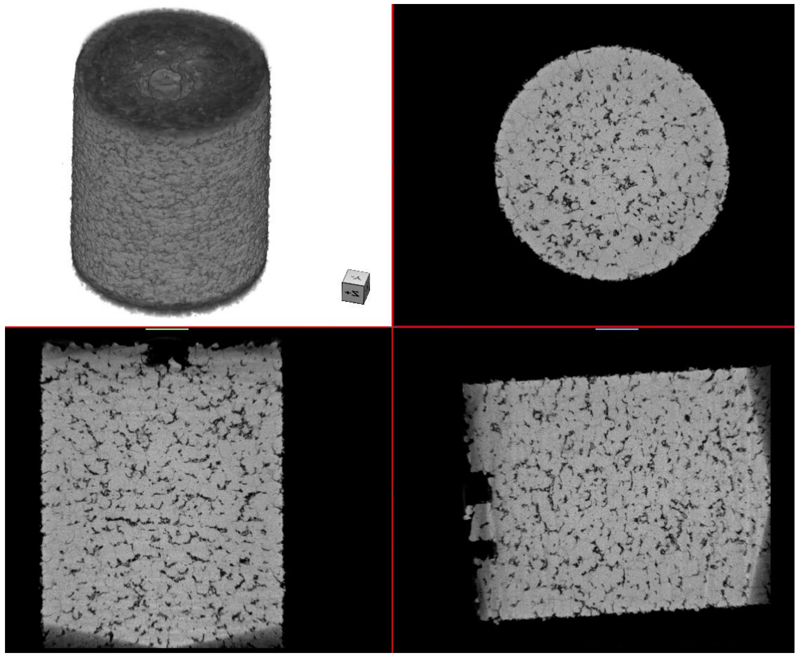


Figure 30. Example of CT scan of Sample 6

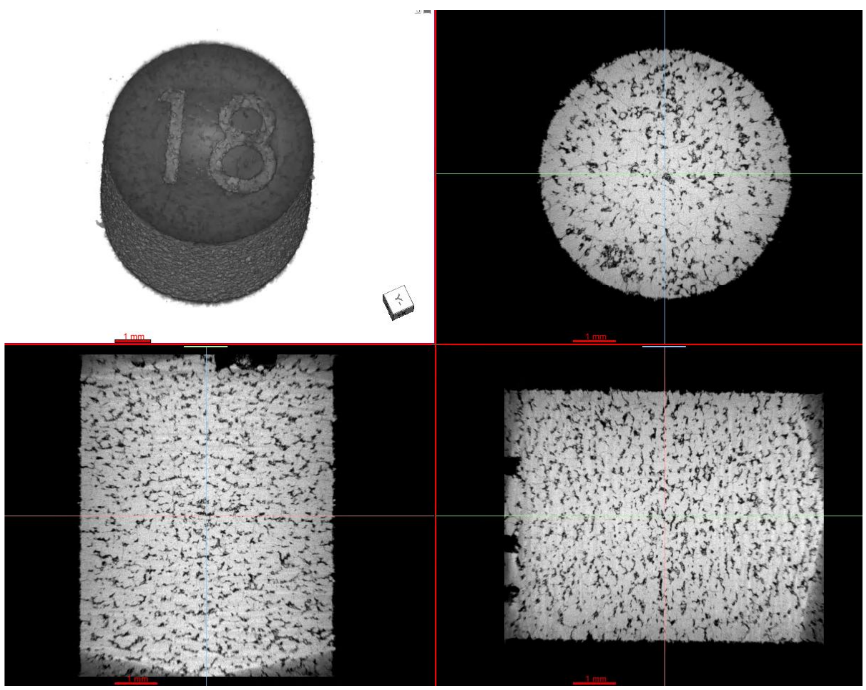


Figure 31. Example of CT scan of Sample 18

10.3.3 Microstructural Analysis

Two of the highest density samples (Sample 3 and 4) and two samples selected to print complex geometries based on physical appearance (Sample 6 and 18) were selected to be further analyzed for microstructure.

These samples were sectioned with an Isomet Precision Saw with the soft blade, then mounted in conductive Polyfast epoxy. They were grinded with SiC papers from 300 – 4000 grit, then polished with 6um polishing pad and suspension with water as lubricant. Then a 1um diamond polishing paste along with the 1um polishing pad was used with lapping oil as the lubricant. Finally, a 50 nm alumina suspension in lapping oil was used along with an OPS polishing pad and lapping oil as the lubricant to complete the polishing.

Figure 32. Optical microscopy after cutting, mounting and grinding of Sample 3 at 20x magnification. The coaxial lighting is used here.

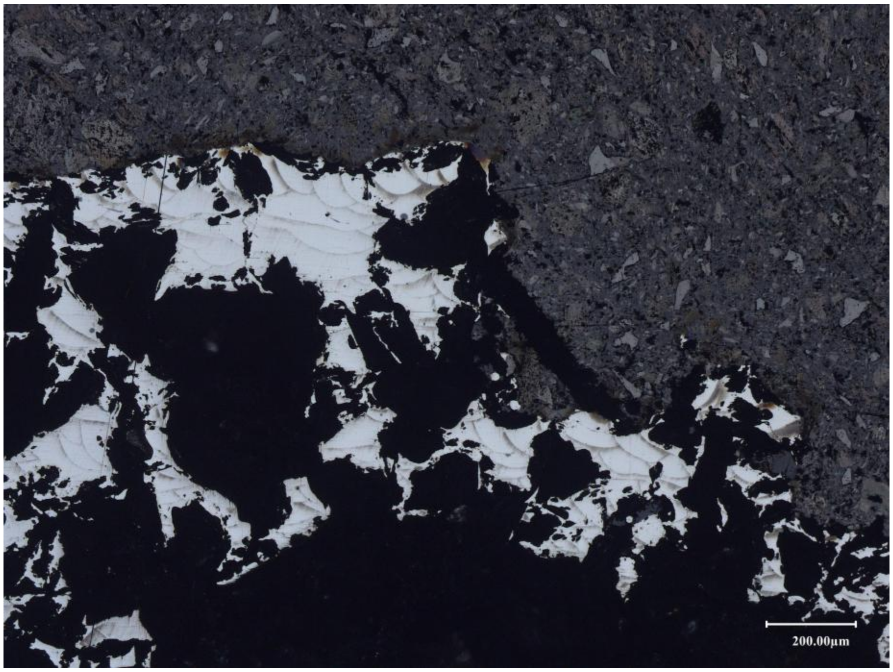


Figure 33. Optical microscopy after cutting, mounting, grinding and polishing of Sample 3 at 150x magnification. Melt pools are visible with grinding at 4000 grit SiC paper. Coaxial lighting is used here.

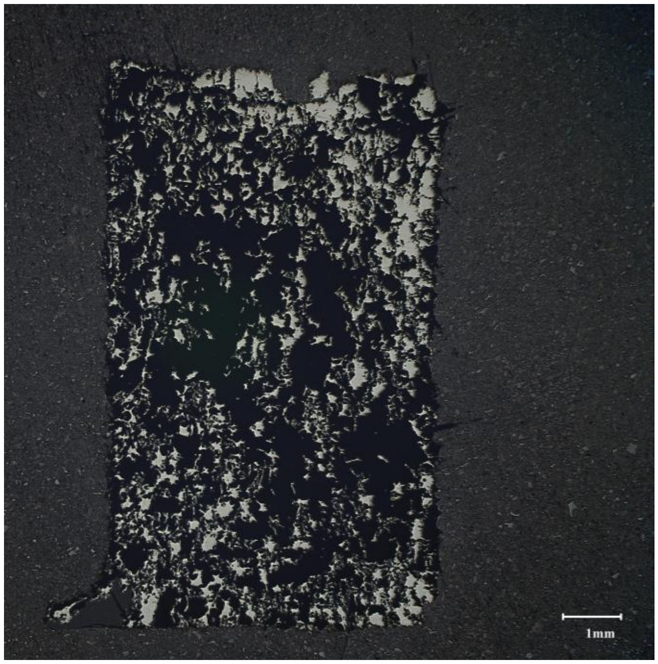


Figure 34. Optical microscopy after cutting, mounting and grinding of Sample 4 at 20x magnification. Coaxial lighting is used here.

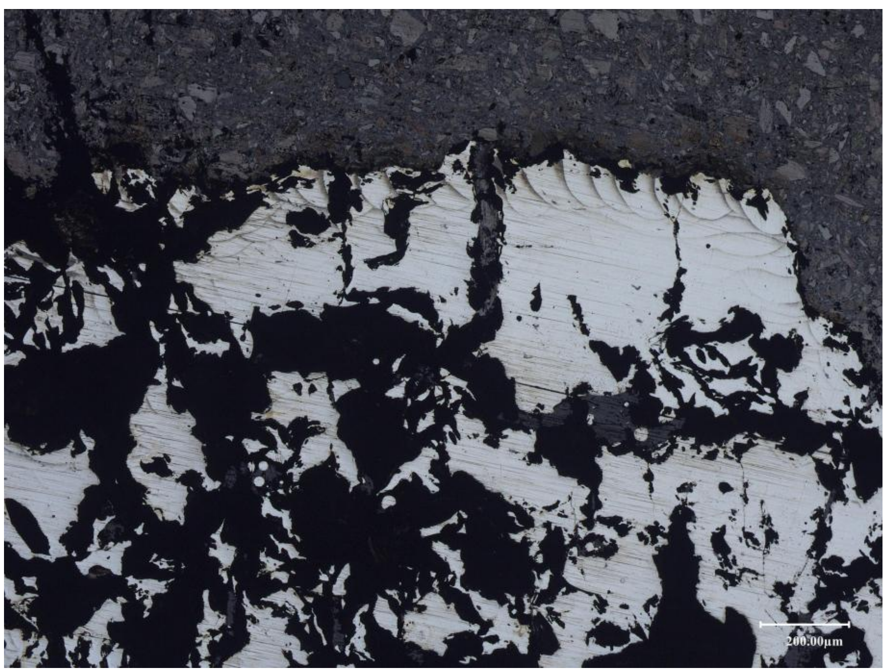


Figure 35. Optical microscopy after cutting, mounting, grinding and polishing of Sample 4 at 150x magnification. Melt pools are visible with 4000 grit SiC paper grinding. Coaxial lighting is used here.

Note* Sample 6 and 18 were not cut before mounting, as a trial since the cutting process did not result in a smooth cross section. (Samples 3 and 4 resulted in small sections of samples with many cracks and pores instead of a smooth cross section). Samples 6 and 18 were mounted, then grinded to find a suitable cross section, however, as demonstrated in the following photos, it made no significant difference in obtaining a better cross section.

Figure 36. Optical microscopy after cutting, mounting, grinding and polishing of Sample 6 at 40x magnification. There are cracks in the sample, likely due to the grinding process. No melt pools were visible due to only small sections at the top of sample. Mixed (coaxial and ring) lighting is used here.

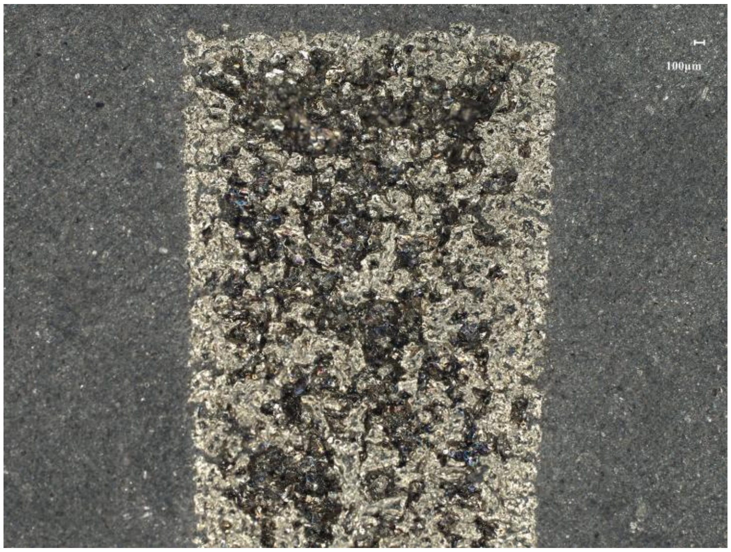


Figure 37. Optical microscopy after cutting, mounting, grinding and polishing of Sample 18 at 40x magnification. There are cracks in the sample, likely due to the grinding process. No melt pools were visible due to only small sections at the top of sample. Mixed (coaxial and ring) lighting is used here.

10.3.4 Magnetization Results

2 samples (3, 4, 6, 18) were sent to be magnetized at NRC. The magnetization plots are shown below:

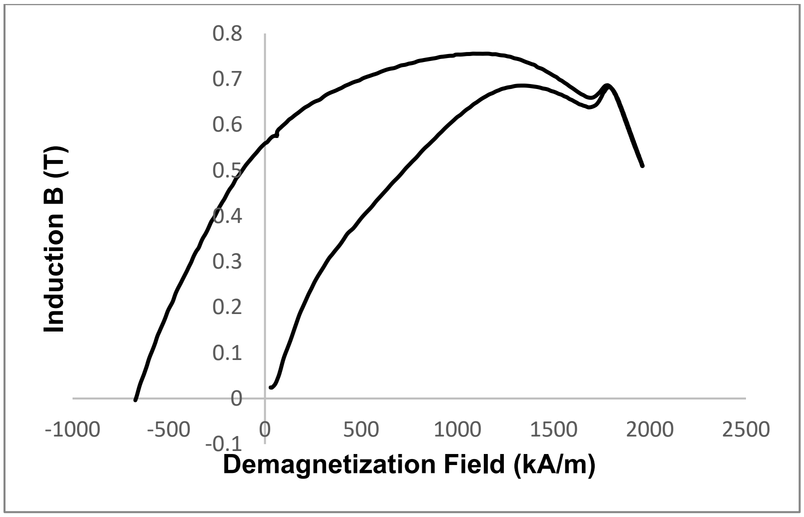


Figure 38. Magnetic curve showing the magnetic properties of Sample 3.

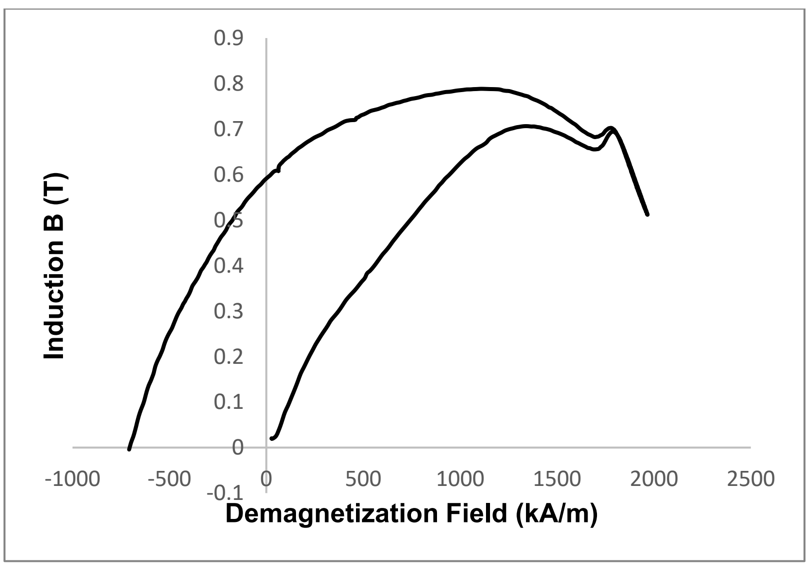


Figure 39. Magnetic curve showing the magnetic properties of Sample 4.

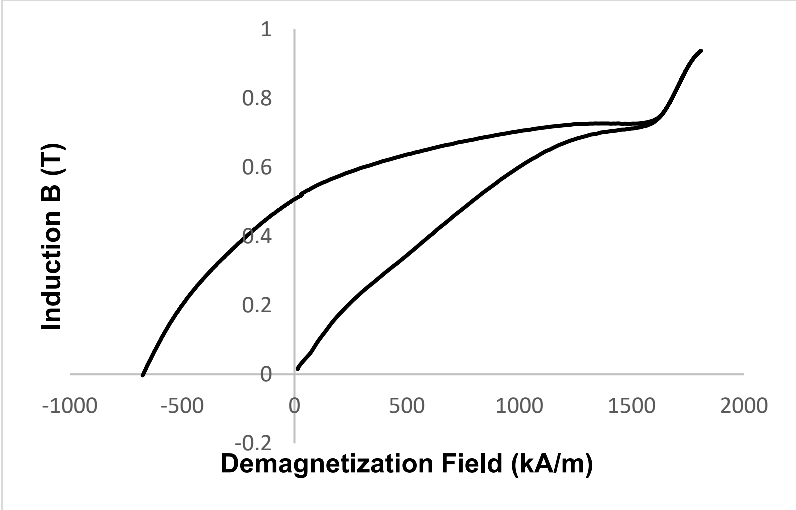


Figure 40. Magnetic curve showing the magnetic properties of Sample 6.

Results from sample 18 yet to be sent by NRC. An updated version of report will be provided when data available.

11 Build 4.3 Samples for magnetization

11.1 Build 4.3 goals

Print samples for magnetization and analysis based on best samples from builds 2.X and 3.X

11.2 Build 4.3 Details

11.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.0 > 2-DOE>Recipes (parameters)> Build #4.X
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 4.3
Purpose of build	Evaluate the feasibility of printing with a layer thickness of 40 µm
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.X > 1-CAD & Designs>Build #4.X
Coupon types and quantities	• Cylinders 1-6; 6 mm diameter x 10 mm tall • 2 irregular cuboids with rounded corners per cylinder (total of twelve), labeled as no label, X, ⏪, ⏮, ⛊, and ⏭; (5 mm x 6 mm x 7mm)
Supports	None; direct welding to plate
Tests intended	None
Build time	Around 4 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No
Post-removal observations	Difficult to remove. Samples “break” while they’re removed
Improvements to suggest	No future improvements planned

11.2.2 Build visuals of CAD designs for components

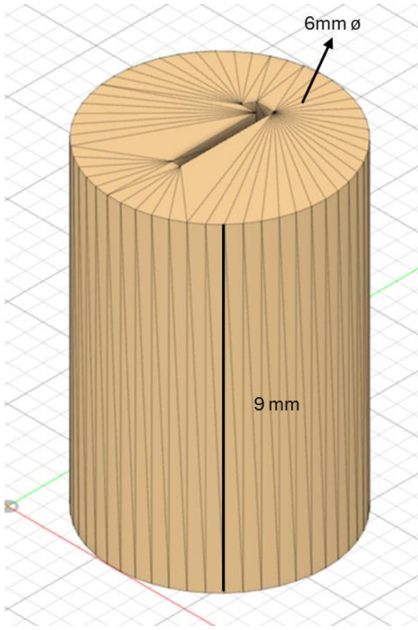


Figure 41. The picture shows the CAD design for the cylindrical coupons. The picture shows they have a cylindrical shape. The cylinder dimensions are 6mm (diameter) x 10mm (height) considering the bonding recipe. The number of each of the cylinders was printed on the top of each to allow easy identification of the sample number.

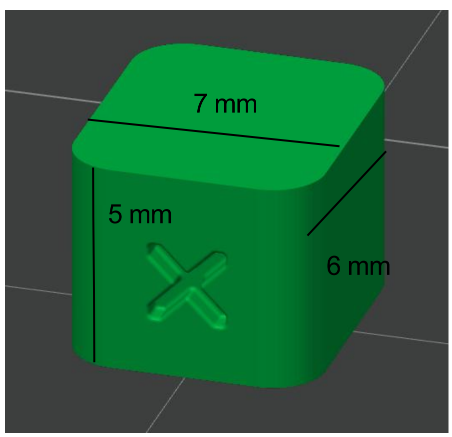


Figure 42. The picture shows the CAD design for the cuboids used for magnetization. The dimensions are different on each side to be able to measure anisotropy,

11.2.3 Build plate visualization, pre-build

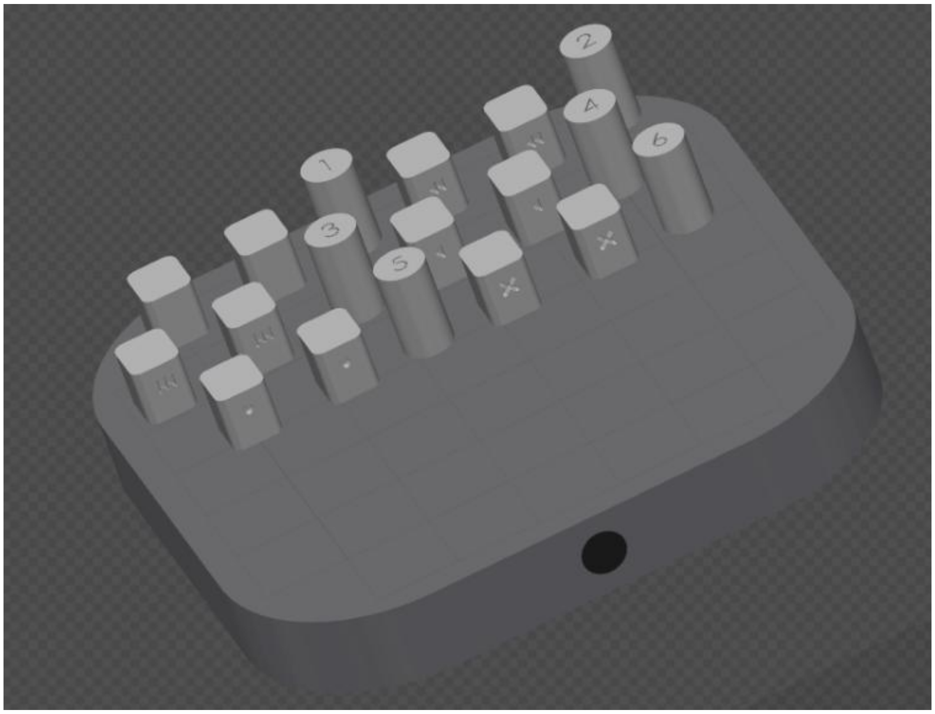


Figure 43. Build plate setup for build 4.3. The order of the coupons on the build plate is shown.

11.2.4 Build plate visualization, post-build

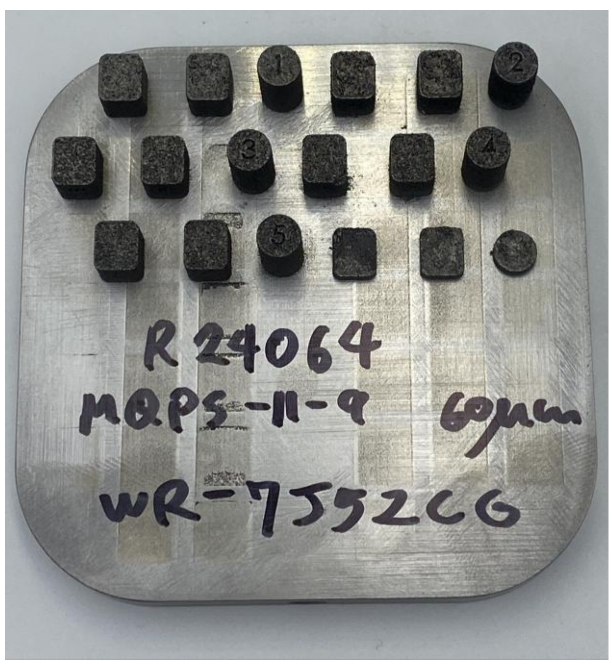


Figure 44. Build 4.3 after the printing process. The image shows that 15 samples were successful and that 3 samples based on recipe 6 had to be stopped due to overheating.

11.3 Part Characterization and Results

11.3.1 Print Results

1 recipe (3 replicates) had to be cancelled due to overheating. This was recipe 6.

11.3.2 CT Analysis

The successful cylinders from this build (1 - 5) were used for CT scanning for the purpose of density analysis.

The following table reports the density of each sample that was analyzed.

CT Density Analysis	
Sample ID	Relative Density (%)
1	98.08
2	96.41
3	94.02
4	92.31
5	89.68

CT Visuals and density calculations can be found in this powerpoint on the MSAM NAS:
https://msamnas01.uwaterloo.ca:5051/d/f/11dSUURALa6fRqmBHlyzBMHj4wFYgWRz

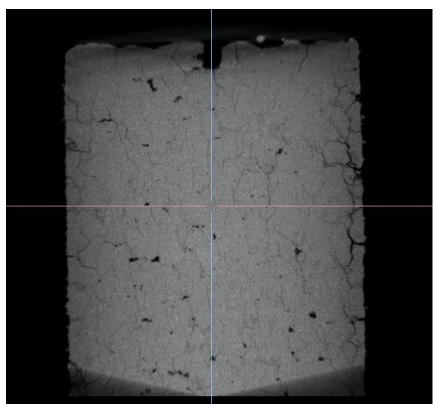


Figure 45. Example of CT scan of Sample 1

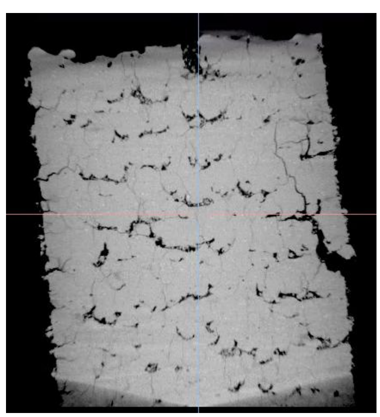


Figure 46. Example of CT scan of Sample 2

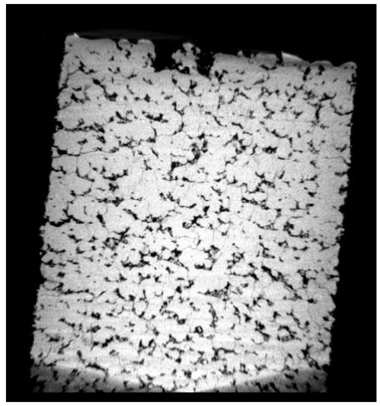


Figure 47. Example of CT scan of Sample 3

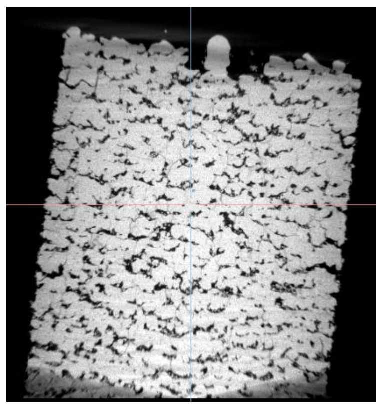


Figure 48. Example of CT scan of Sample 4

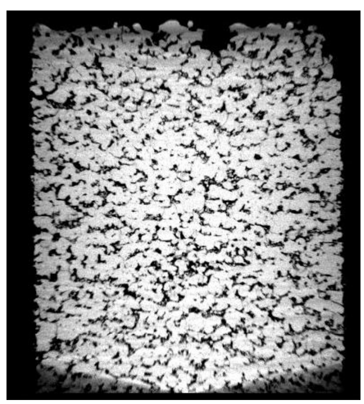


Figure 49. Example of CT scan of Sample 2

11.3.3 Microstructural Analysis

These samples were not subject to microstructural analysis

11.3.4 Magnetization Results

1 cubic coupon from each recipe was analyzed for magnetic properties. The plots are shown below:

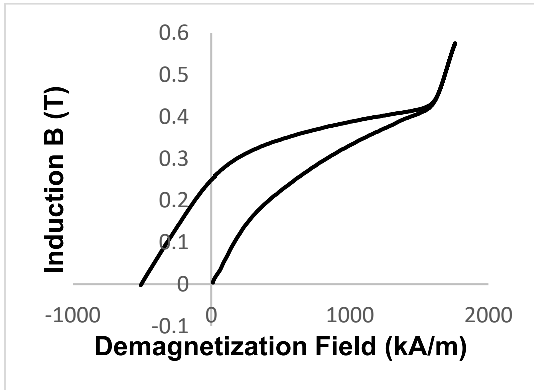


Figure 50. Magnetic curve showing the magnetic properties of Sample 1.

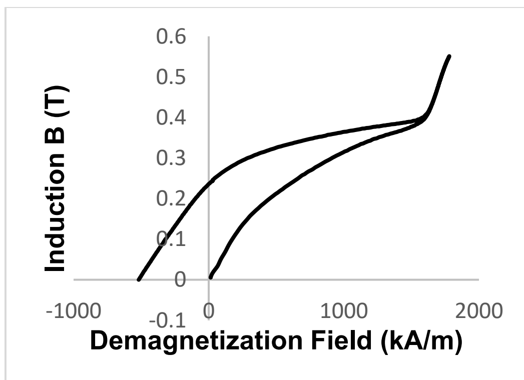


Figure 51. Magnetic curve showing the magnetic properties of Sample 2.

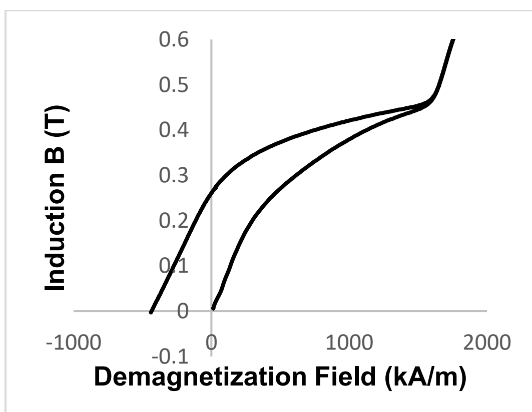


Figure 52. Magnetic curve showing the magnetic properties of Sample 3.

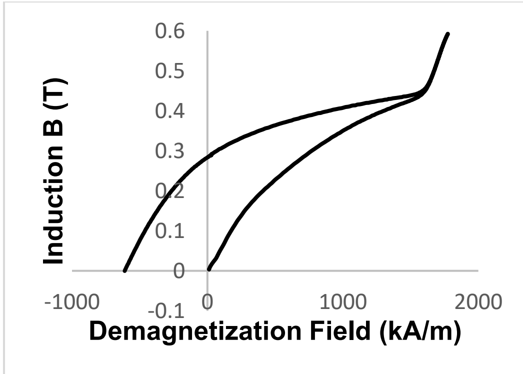


Figure 53. Magnetic curve showing the magnetic properties of Sample 4.

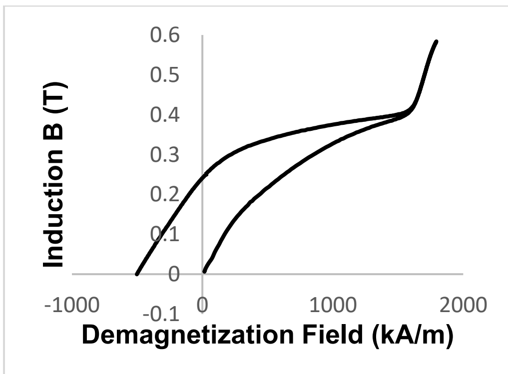


Figure 54. Magnetic curve showing the magnetic properties of Sample 5.

12 Build 4.4 Samples for heat treatments

12.1 Build 4.4 goals

7 most successful recipes from Build 4.2 were selected (by physical examination) to be repeated to have extra samples for further characterization ie. Heat treatments and microstructural analysis.

Recipes 5, 6, 16, 17, 18, 19, 20 from Build 4.2 were repeated (4 replicates)

The samples were also randomly oriented to see if there was any effect associated to the location of the samples on the build plate.

12.2 Build 4.4 Details

12.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.0 > 2-DOE>Recipes (parameters)> Build #4.X
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 4.4
Purpose of build	Print samples for heat treatments
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.X > 1-CAD & Designs>Build #4.X
Coupon types and quantities	• 28 cylinders labeled based on old recipes (5, 6, 16-20). 6 mm diameter x 10 mm tall
Supports	None; direct welding to plate
Tests intended	None
Build time	Around 6 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No

Print special observations	No
Post-removal observations	Difficult to removed, they were removed with a handheld Dremmel saw
Improvements to suggest	No future improvements planned

12.2.2 Build visuals of CAD designs for components

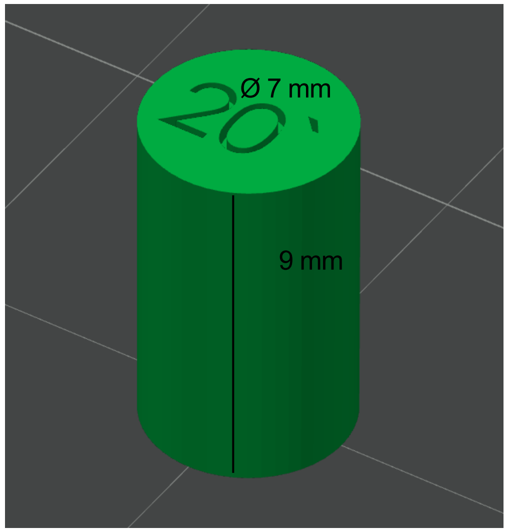


Figure 31. The picture shows the CAD design for the cylindrical coupons. The picture shows they have a cylindrical shape. The cylinder dimensions are 6mm (diameter) x 10mm (height) considering the bonding recipe. The number of each of the cylinders was printed on the top of each to allow easy identification of the sample number each replicate had a different label: ‘, -, and !.

12.2.3 Build plate visualization, post-build

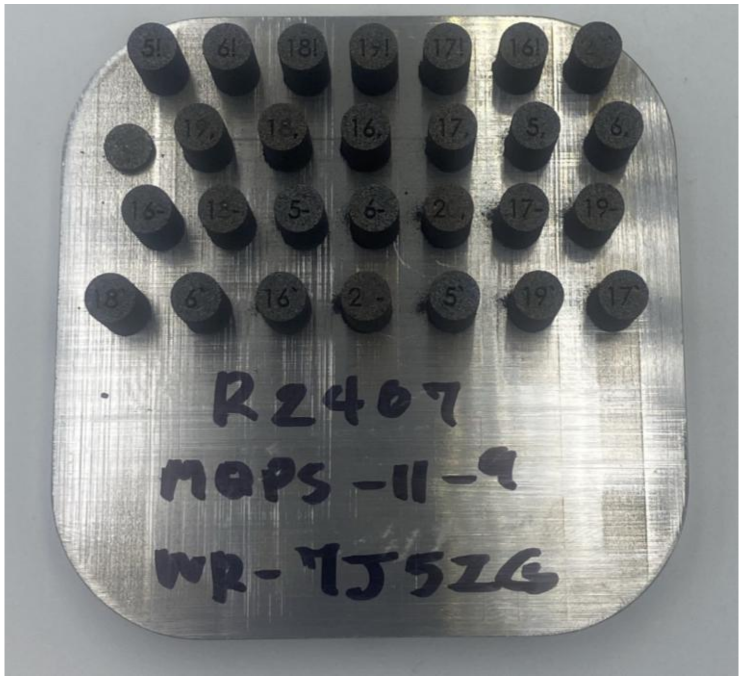


Figure 55. Build 4.4 after the printing process. The image shows that 27 samples were successful and that only one sample had to be stopped.

12.3 Part Characterization and Results

12.3.1 Print Results

All but 1 samples survived.

12.3.2 CT Analysis

These samples were not subjected to CT analysis

12.3.3 Microstructural Analysis

These samples were not subjected to microstructural analysis

12.3.4 Magnetization Results

These samples were not subjected to magnetization

12.3.5 Heat Treatments

These samples were printed in the case that heat treatments are to be explored. However, currently this is not in scope for phase 1.

13 Build 4.5 Complex-shaped parts

13.1 Build 4.5 goals

Print complex-shaped parts using the parameters of the two best visually appealing samples from build 4.2.

13.2 Build 4.5 Details

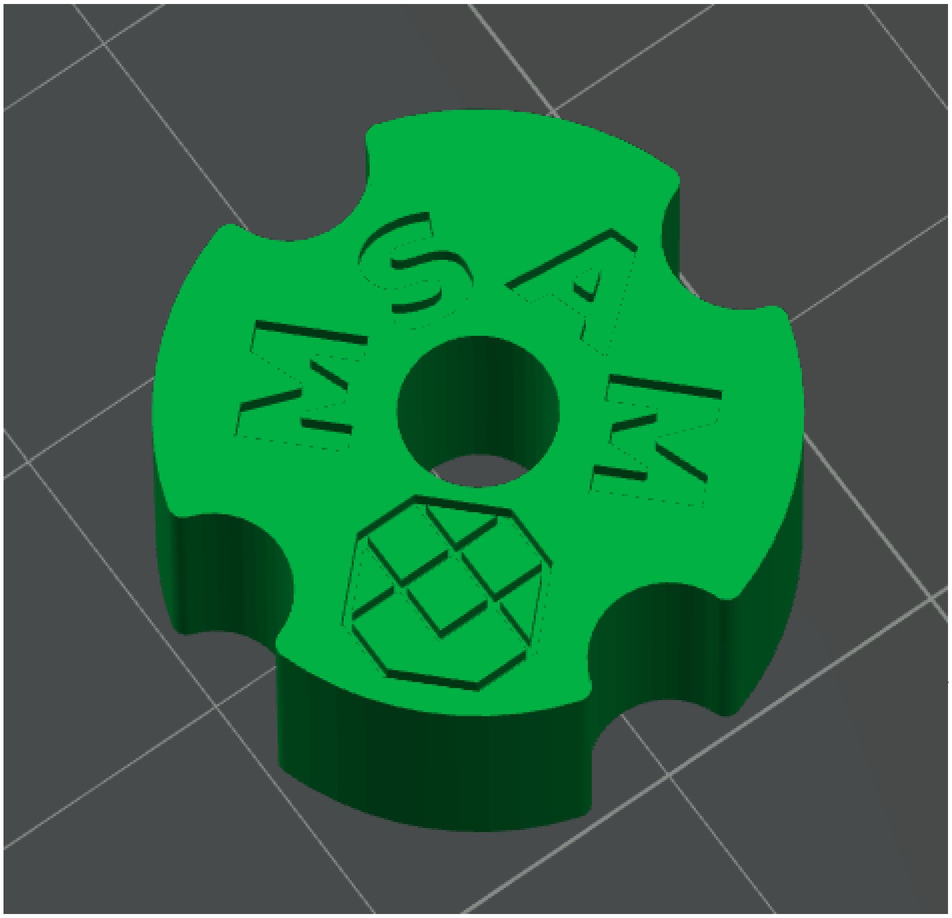
13.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.0 > 2-DOE>Recipes (parameters)> Build #4.X
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 4.5
Purpose of build	Print complex-shaped parts
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #4.X > 1-CAD & Designs>Build #4.X
Coupon types and quantities	• 2 complex-shaped parts with MSAM logo (10 mm tall, external diameter 20mm, internal diameter 5 mm)
Supports	None; direct welding to plate
Tests intended	None
Build time	Around 10 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No
Post-removal observations	Difficult to remove. Samples “break” while they’re removed
Improvements to suggest	No future improvements planned

13.2.2 Build visuals of CAD designs for components



13.2.3 Build plate visualization, post-build

Figure 57. Build 4.5 after the printing process. The image shows that the two samples were successful.

13.3 Part Characterization and Results

13.3.1 Print Results

Both samples printed with success. Recipes 6 and 18 were used to print these coupons from Build 4.2 with a 40um layer thickness. Samples remained on the plate after printing.

13.3.2 CT analysis

These samples were not subjected to CT analysis

13.3.3 Microstructural analysis

These samples were not subjected to microstructural analysis

13.3.4 Magnetization Results

These samples were not subjected to magnetization

14 Build 5.X Summary

Summary table:

Build #	Objective	Total samples	Failed samples	Samples that survived	Analysis recommendations
5.1	Recipe translation from bonding recipe in 60 um to 40 um	20	8 (Recipes 1, 4, 6, 8)	12 (Recipes 2, 3, 5, 7, 9, 12)	CT Density analysis, microstructural and magnetization analysis
5.2	Demonstrator Parts	16	Cylinders 5, 6, 7, 8	3 V shape magnets 1 Complex Magnet 8 cylinders	Magnetization
5.3	N/A	N/A	N/A	N/A	N/A
5.4	Out of Scope for this project (Carleton University Print)				
5.5	Out of Scope for this project (Carleton University Print)				

15 Build 5.1

15.1 Build 5.1 goals

Explore a recipe translation from the best recipe at 60 um from DOE 2.3 (Sample 12) at 40 um. Used dimensionless process mapping and thermophysical models to translate the same recipe but at a lower layer thickness.

With translated point as the center point, a central composite design was used around it to explore this general region. Also, the non-translated point (Same power and velocity etc. but only changing the layer thickness) was printed.

15.2 Build 5.1 Details

15.2.1 Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 5.1
Purpose of build	Try to improve the bonding recipe changing the parameters in max. 10% (E* and V*)
CAD software	Autodesk Fusion 360
Coupon types and quantities	20 samples total (10 cylinders and 10 cubes)
Supports	None; direct welding to plate
Tests intended	-
Build time	Around 8 Hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No
Post-removal observations	Difficult to remove. Samples were removed by hand with hacksaw
Improvements to suggest	Samples have to be analyzed before any improvements are suggested

15.2.2 Build visuals of CAD designs for components

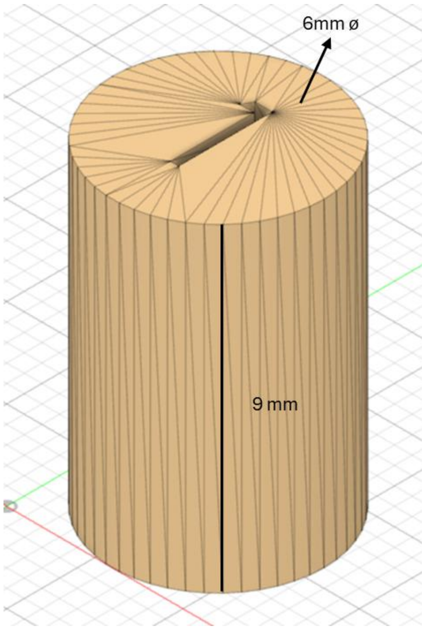


Figure 58. The picture shows the CAD design for the coupons. The picture shows they have a cylindrical shape. The cylinder dimensions are 6mm (diameter) x 10mm (height). The number of each of the cylinders was printed on the top of each to allow easy identification of the sample number.

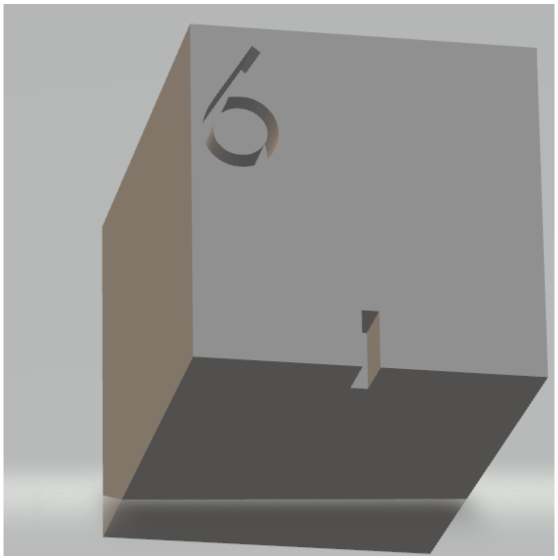


Figure 59. The picture shows the CAD design for the cubes that were printed.

15.2.3 Build plate visualization, pre-build

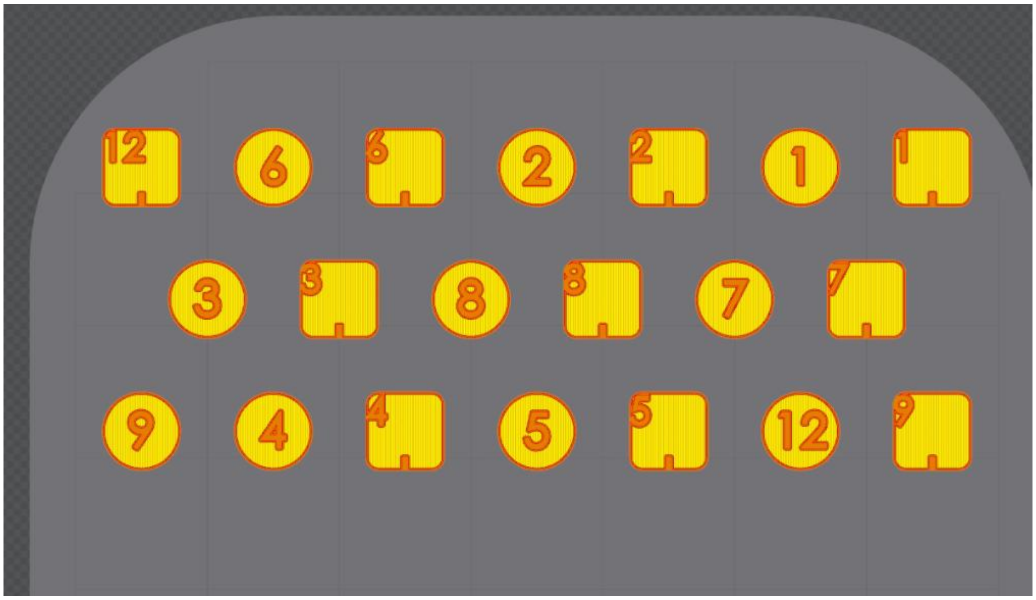


Figure 60. Build plate setup for build 5.1.The order of the coupons on the build plate is shown. Two batches were printed. One is printed in numerical order (black) and the other one is printed in a randomized order (red).

15.2.4 Build plate visualization, post-build

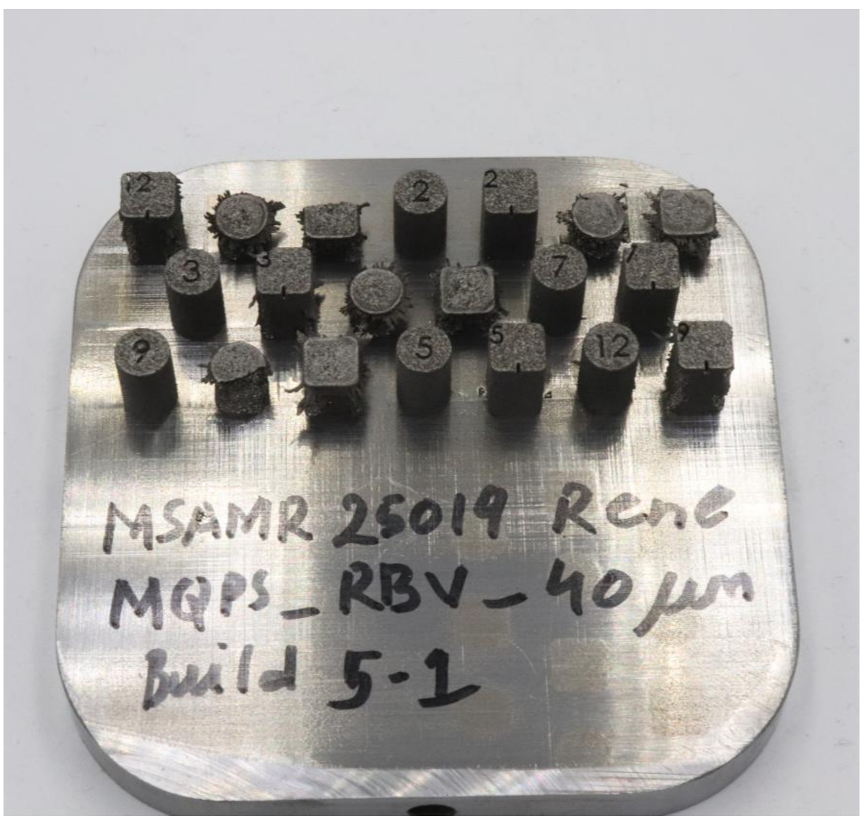
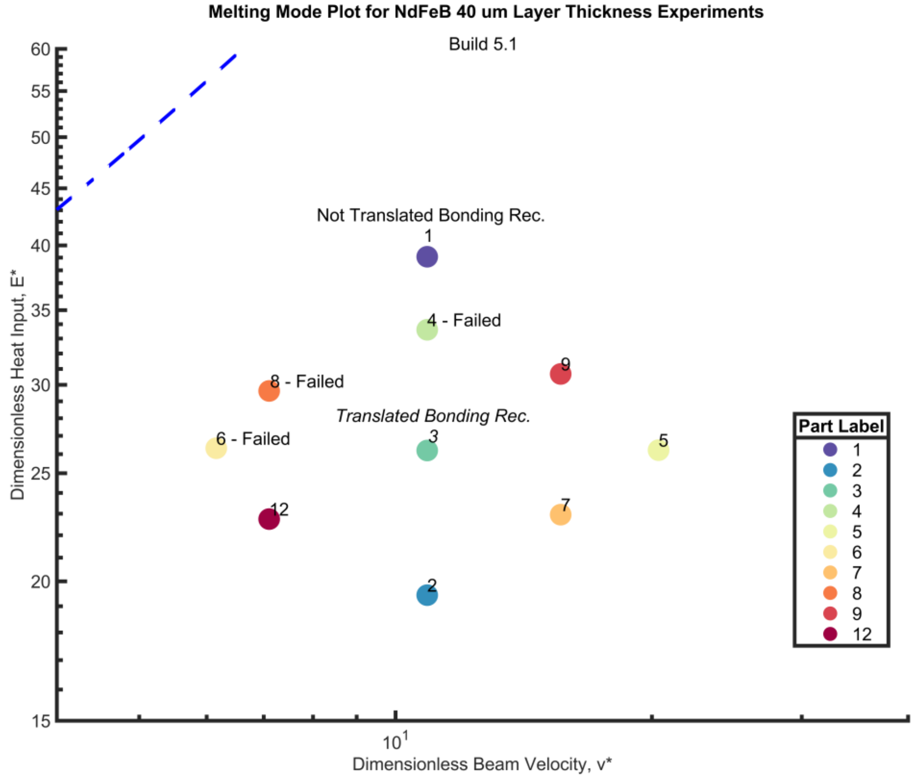


Figure 61. Build 5.1 once printing was finished.

15.2.5 Process Map



15.3 Part Characterization and Results

15.3.1 Print Results

The non-translated recipe (Recipe 1) and other samples failed due to over heating (Recipe 4, 6, 8). Samples 2, 5 and 7 had good surface finishes and corners on the rectangle so were selected for further analysis initially and further printing in 5.2

15.3.2 CT Analysis

Samples 2, 5 and 7 were prioritized for CT analysis due to the good surface finish. Later Recipes 3, 9 and 12 were also CT scanned.

The following is a table with the densities of each sample.

CT Density Analysis	
Sample ID	Relative Density (%)
2	96.39
3	98.31
5	93.38
7	89.95
9	97.27
12	98.00

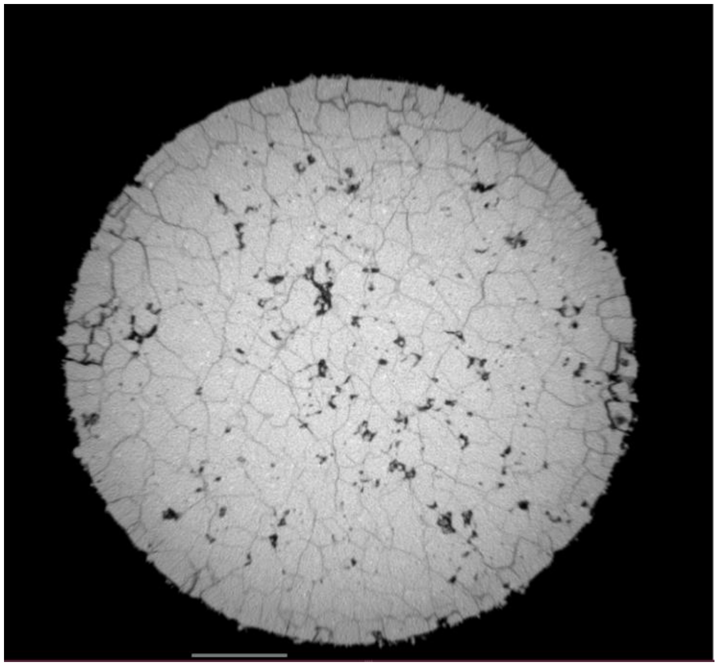


Figure 62. XY view of CT cross-section of Sample 3 (translated recipe) with density of 98.31%.

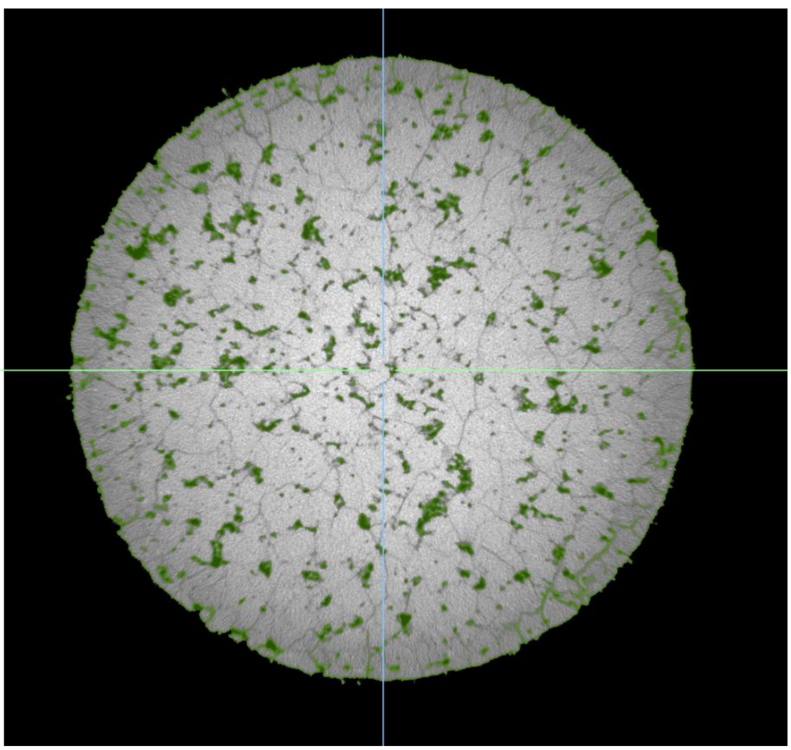


Figure 63. XY view of CT cross-section of Sample 7 with density of 89.95%.

15.3.3 Microstructural analysis

Sample 3 has been selected for microstructural analysis since it is the translated point of the best performing sample from DOE 2.3.

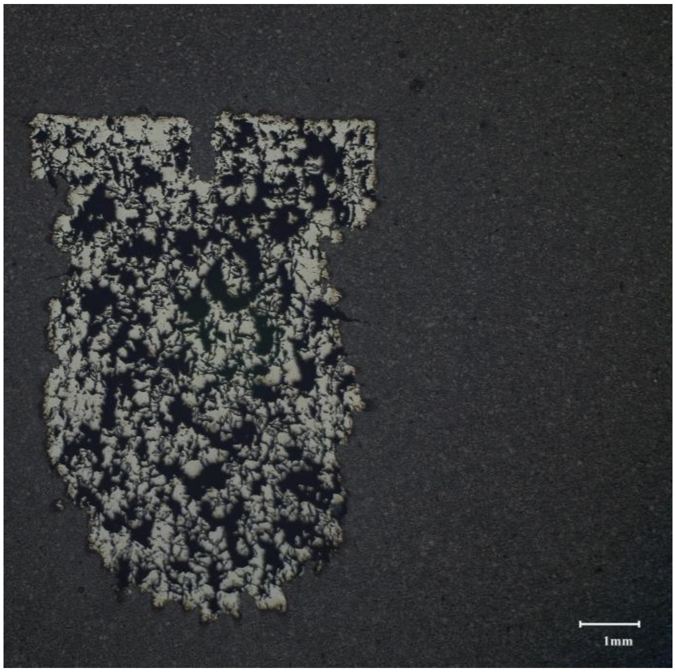


Figure 64. This sample was not cut, but directly mounted to avoid any cracking issues due to the brittle nature of the material. This optical microscopy image shows the sample after the grinding process at 20x with coaxial lighting. This is Sample 3 from Build 5.1.

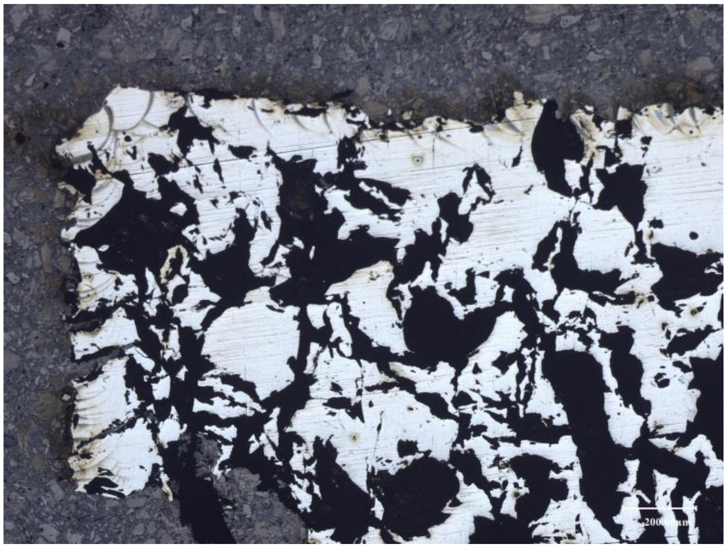


Figure 65. A higher magnification (150x) of the Sample 3 from Build 5.1, showing the visible melt pools in the top layer after 4000 grit SiC paper grinding.

15.3.4 Magnetization Results

Sample 3 was sent to NRC to be magnetized, the results are presented below.

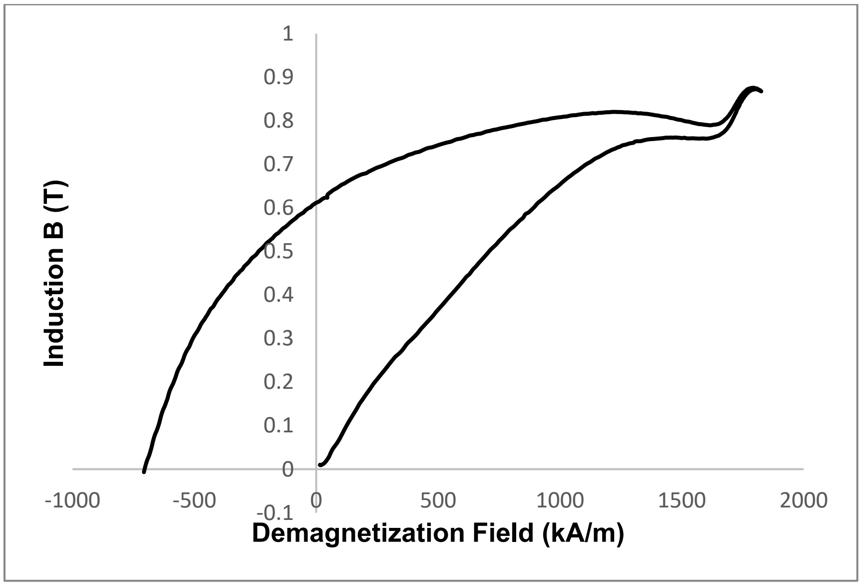


Figure 66. Magnetic curve showing the magnetic properties of Sample 3.

16 Build 5.2

16.1 Build 5.2 Goals

Print demonstrator V shape magnets as proof of concept for printing complex parts. 3 different recipes were explored for the V shape magnet from DOE 4.2 and DOE 5.1. Previous complex shape magnet from Build 4.5 was also printed. 4 replicates of each of the 3 recipes were printed in cylinders with the same height as the large parts for further characterization.

16.2 Build 5.2 Details

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 5.2
Purpose of build	Try to improve the bonding recipe changing the parameters in max. 10% (E* and V*)
CAD software	Autodesk Fusion 360
CAD	
Coupon types and quantities	•
Supports	None; direct welding to plate
Tests intended	-
Build time	2.3 Hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No
Post-removal observations	Difficult to remove. Samples were removed by hand with hacksaw
Improvements to suggest	Samples have to be analyzed before any improvements are suggested

16.3 Part Characterization and Results

16.3.1 Build plate visualization, post-build

Figure 67. Build 5.1 once printing was finished.

16.3.2 Print Results

All the complex geometry magnets survived. The V shape magnet with the best surface finish and structural integrity is the one with no label which used the Recipe 4 from DOE 4.2.

Figure 68. Example of the different surface finishes with the sample second to the left having the best surface finish.

16.3.3 CT Analysis

These samples were not subjected to CT analysis

16.3.4 Microstructural analysis

These samples were not subjected to microstructural analysis

16.3.5 Magnetization

The V shape magnets were magnetized as per request of GreenAge without the epoxy coating. The V-shaped part was successfully magnetized but cracked in the process, leading to further testing of samples printed in build 6. It was not possible to directly characterize the V-shaped parts for the magnetic properties due to their large size relative to the characterization equipment.

17 Build 6.X Summary

Summary table:

Build #	Objective	Total samples	Failed samples	Samples that survived	Analysis recommendations
6.1	Repeat of Build 5.2 with GreenAge Logo	16	0	All Samples	Magnetization
6.2	Shell and Core Strategies	20	7	13	Preliminary trials, out of scope for analysis for this project

18 Build 6.1

18.1 Build 6.1 goals

Print complex-shaped demonstrators with GreenAge logo with Build 4.2 recipe for best surface finish (Recipe 4). Repeat of the same build layout as Build 5.2. Cylinders of best density recipes from Build 4.2 were printed for further and future characterization (Recipes 3, 4, 6 and 18)

18.2 Build 6.1 Details

18.2.1Build summary.

Material	
Name	NdFeB (MQP-S-11-9)
Chemical Composition	Neodymium 17.2% Praseodymium 1.9% Boron 1.7% Cobalt 2.8% Copper 0.1% Titanium 2.1% Zirconium 4.3% Carbon 0.1% Iron 69.8%
Supplier	Neo Magnequench
Progeny	Virgin powder; Part No. 200 0 1 070
Shape / Production Process	Spherical
Size range	35 - 55 µm

AM technology	
Technology class	Magnet Fabrication
Machine	Renishaw AM400
Parameters	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #6.0 > 2-DOE>Recipes (parameters)> Build #6.X
Build setup software	QuantAM

Build summary	
DOE # or Name	Build 6.1
Purpose of build	Print complex-shaped parts for GreenAge
CAD software	Autodesk Fusion 360
CAD	NAS > File Station > PROJECT – NRC GREENAGE >2-Manufacturing & Characterization Data > Build #6.X > 1-CAD & Designs>Build #6.1
Coupon types and quantities	• 3 V-shaped parts with GreenAge logo • 1 complex-shaped toroidal demonstrator with GreenAge logo • 12 long cylinders using different recipes for analysis
Supports	None; direct welding to plate
Tests intended	Microscopy, magnetization, possibly CT and heat treatments
Build time	Around 10 hours
Process gas	Argon
GoPro	No
Meltpool Monitoring	No
Post-processing	No
Print special observations	No
Post-removal observations	Difficult to remove. Samples “break” while they’re removed

Improvements to suggest	No improvements suggested.

18.2.2Build visuals of CAD designs for components

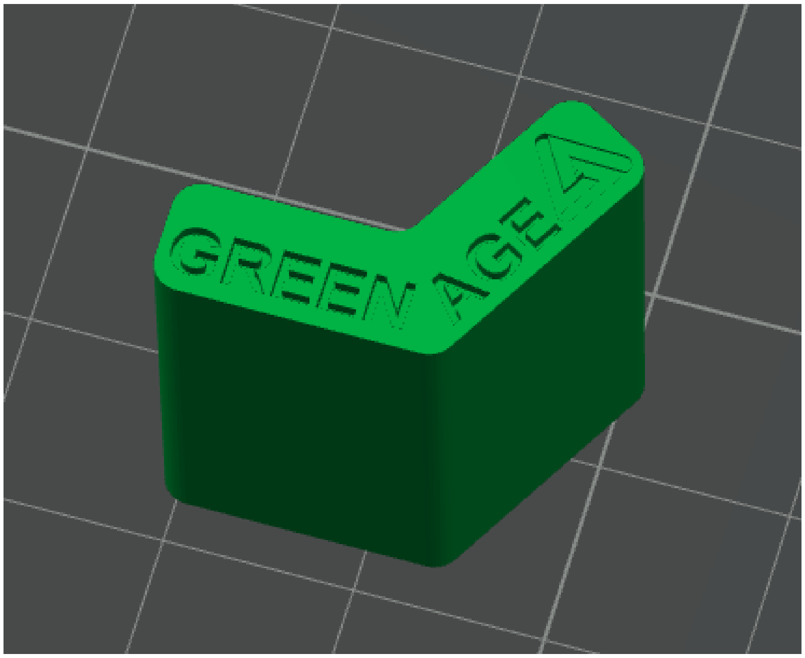


Figure 69. The picture shows the V-shaped parts with GreenAge logo. The image shows the shape with the letters and the logo.

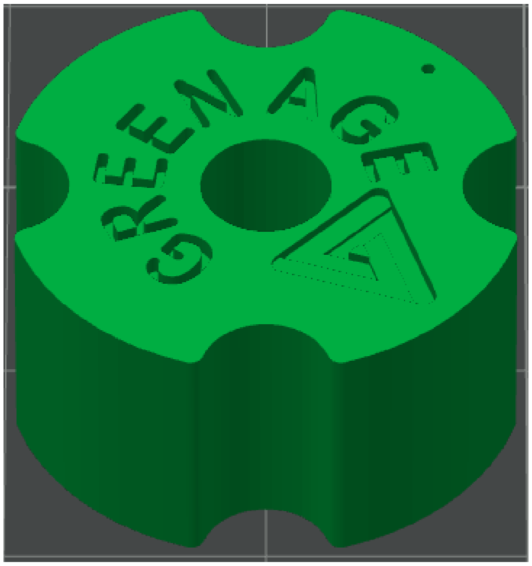


Figure 70. The picture shows the toroidal complex-shaped part with the GreenAge logo.

18.2.3 Build plate visualization, pre-build

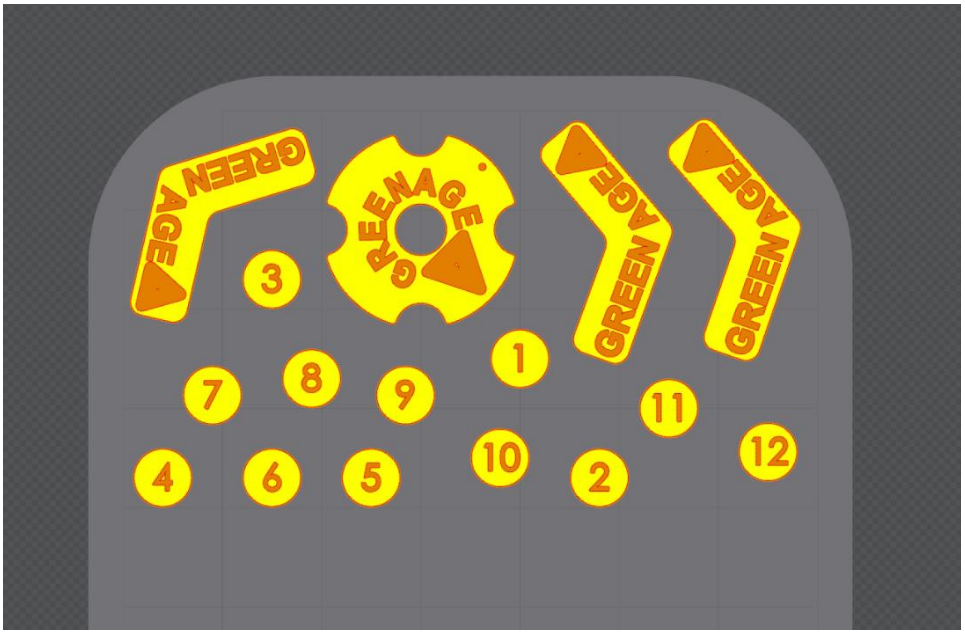


Figure 71. Build plate setup for build 6.1. The order of the coupons on the build plate is shown. Different types of samples were printed: 3 V-shaped parts, one complex shaped toroidal part and 12 long cylinders.

18.2.4 Build plate visualization, post-build

Figure 72. Build 6.1 after the printing process. The image shows that all printed coupons were successful.

18.3 Part Characterization and Results

18.3.1 Print results

All parts were successful, one of the cylinders fell off the plate during cleaning but it was successful during the print and can still undergo characterization.

18.3.2 CT Analysis

These samples were not subjected to CT analysis

Microstructural Analysis

These samples are not currently subjected to microstructural analysis

18.3.3 Magnetization results

All three V-shaped parts as well as the toroidal specimen were successfully magnetized with no epoxy coating, showing the surface finish and the logo. It was not possible to directly characterize the V-shaped parts for the magnetic properties due to their large size relative to the characterization equipment.

The long cylinders will be used for any analysis in the future if required i.e. microstructure, CT scanning, heat treatments, etc.

19 Annex 1. Overview of Phase 0 (Confidential and previous IP)

19.1 Overview

Initial feasibility study for printing neodymium iron boron magnets carried out from January 2021 to June 2021. Second feasibility study carried out from May 2023 – May 2024.

19.1.1 Build 1 Summary

Selected data from literature was plotted in a dimensionless process map with a CCD around the densest points. Experiments were carried out using both focused and defocused laser beams.

19.1.2 Dimensionless Process Map Build 1

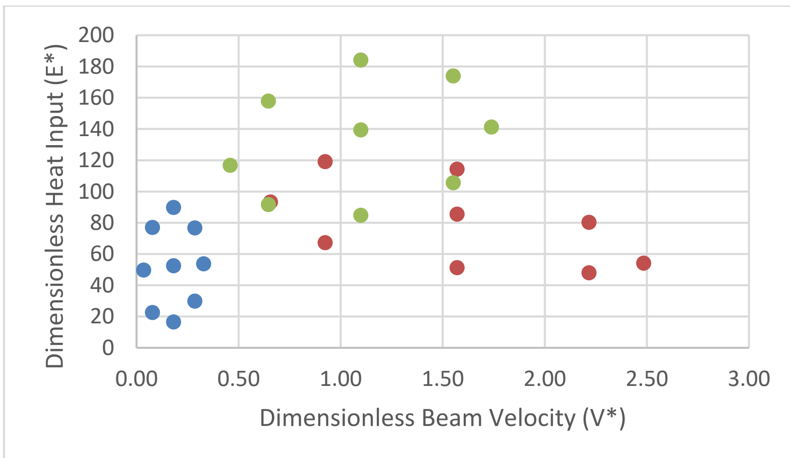


Figure 73. The dimensionless process map used for the feasibility study in build 1 is shown.

19.1.3 Results overview Build 1

In total 27 different process parameters were tested, 7 samples failed, and 20 samples survived with densities ranging from 67 – 99%.

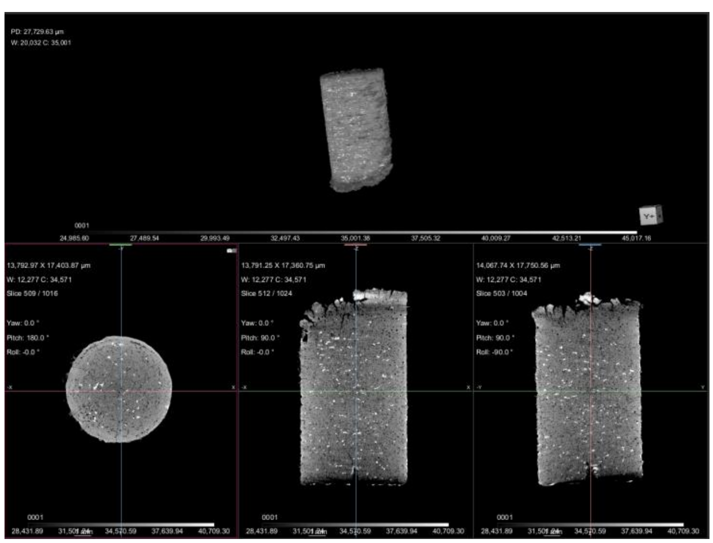


Figure 74. Shows the CT results for one of the most successful samples produced in Build 1.

19.1.4 Build 2 Summary

A CCD was calculated around the 3 most successful parameters from build 1. Experiments were carried out using both focused and defocused laser beams.

19.1.5 Dimensionless Process Map Build 2

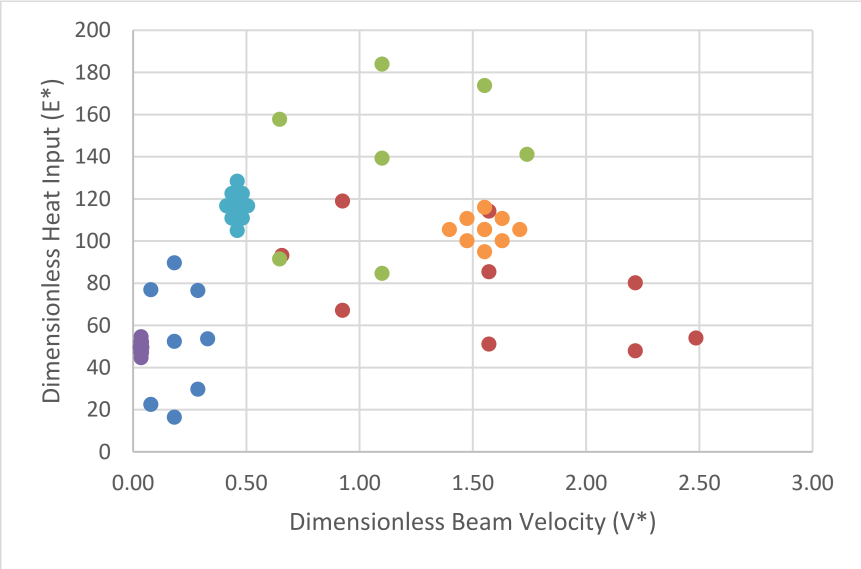


Figure 75. The dimensionless process map used for the feasibility study in build 2 is shown.

19.1.6 Results overview Build 2

In total 27 different process parameters were tested, 13 samples failed, and 14 samples survived with densities ranging from 73 – 99%.

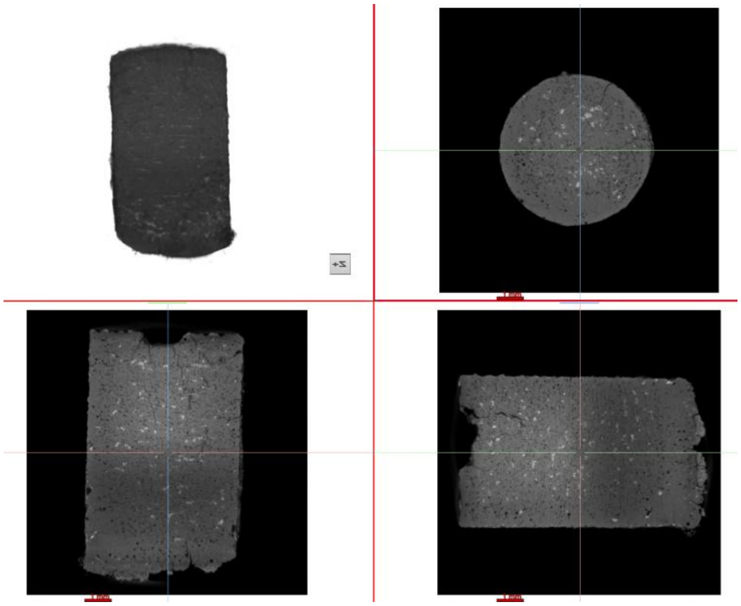


Figure 76. Shows the CT results for one of the most successful samples produced in Build 2.

20 Annex 2. Process Map summary of all experiments from Phases 0 and 1 (Confidential and previous IP)

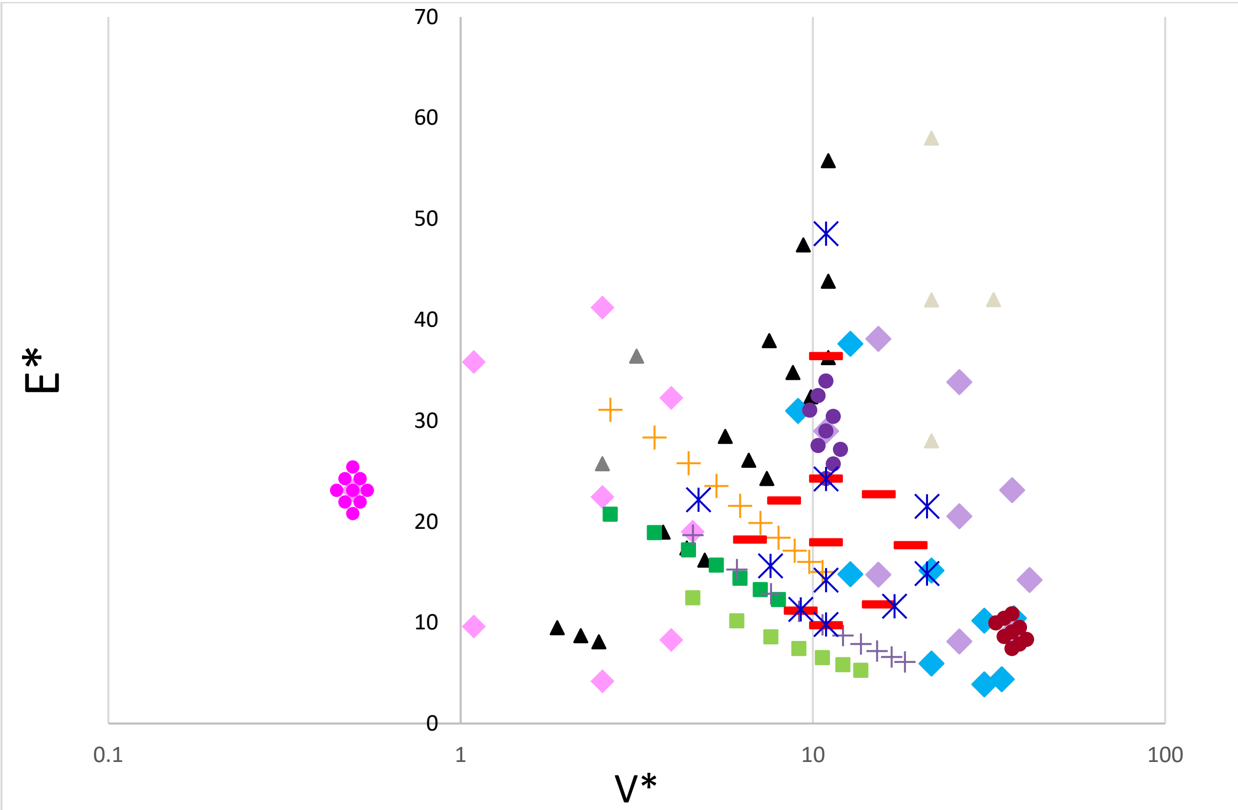


Figure 77. Shows the dimensionless process map summary of all the experiments carried out in phases 0 and 1.