POWDER RHEOLOGY WITHIN AM PRODUCTION:

EVALUATING COMPRESSIBILITY, PERMEABILITY, & AERATION FOR 316L POWDERS WITHIN SLM PROCESSES

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Abstract

Additive manufacturing with the use of metals have been a steadily increasing field, being able to create products with a higher degree of complexity than traditional processing techniques. SLM is a popular AM process that uses metal powder as feedstock, and one of the key components of this process is the powder rheology. In recent years the use of a powder rheometer has been shown to be a good way of evaluating powder rheology of metal powders used within AM processes, but there is a clear lack of standardised tests and methods. In this study the Compressibility, Permeability, and Aeration test for 316L powders used within SLM processes was evaluated with a FT4 powder rheometer. 15 powders that had undergone printing in SLM processes were studied. This showed that the compressibility test had the best results in differentiating the bad preforming powders, thereafter the Aeration test. The Permeability test wasn't able to differentiate the bad preforming powders with the settings used. This study demonstrates that some tests with a powder rheometer can evaluate the powder performance in SLM processes, but further research to evaluate the tests and standardise the settings are needed for clearer test results.

Purpose

The purpose of this study was to evaluate the Compressibility, Permeability, and Aeration tests with a FT4 Powder Rheometer from Freeman Technology. The tests were evaluated for 15 316L stainless steel powders used in SLM processes.

Sammanfattning

Additiv tillverkning med metall är ett område som stadigt ökat i intresse, främst på grund av möjligheten att producera produkter med en mycket högre grad av komplexitet i jämförelse med traditionella processmetoder. SLM är en populär AM process som använder metallpulver som råmaterial, och en av huvudkomponenterna för processen är pulvrets reologi. Under senare år har användningen av en pulver-reometer visat sig ett bra sätt att utvärdera pulver-reologi för metallpulver som används inom AM, men det finns en klar avsaknad av standardiserade test och metoder. I denna studie utvärderas Kompressabilitet, Permeabilitet, och Aerabilitet testen för 316L pulver producerade för SLM processer med en FT4 pulver-reometer. 15 pulver som genomgått SLM printing studerades. Studien visar att kompressabilitets testets utfall bäst överensstämde med det som setts under SLM processen, och bäst urskilde pulvren som fungerat dåligt att printa med, därefter Aerations testet. Permeabilitets testet kunde inte urskilja de sämre pulvren med de inställningarna som användes. Studien demonstrerar att vissa test och index samlade med ett pulver reometer är mer tillförlitliga än andra när det gäller för att utvärdera pulvrets prestanda inom SLM processer, men vidare forskning och studier krävs för att utvärdera testen och standardisera inställningar baserat på pulvret som testas.

Syfte

Syftet med studien var att utvärdera testerna Kompressibilitet, Permeabilitet, och Aeration med en FT4 pulver reometer från Freeman Technology. Testen utvärderades för 15 pulver i 316L rostfritt stål producerade för användning inom SLM processer.

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1. INTRODUCTION

Table 1 Overview of abbreviations and their meaning.

Nomenclature			
AE	Aeration energy (mJ)	CI	Compressibility index (%)
AM	Additive manufacturing	EBM	Electron beam melting
AMS	Additive manufacturing suitability	PBF	Powder bed fusion
AR	Aeration ratio	PD	Pressure drop (mbar)
BFE	Basic flow energy (mJ)	SLM	Selective laser melting
c	Cohesion coefficient (kPa)	SE	Specific flow energy (mJ)
CAD	Computer-aided design	UYS	Unconfined yield strength (kPa)
CBD (ρ_c)	Conditioned bulk density (g/ml)	WFA	Wall friction angle (°)
CFE	Consolidated flow energy (J)		

Table 2 Overview of settings and the data gathered for each test.

Test	Settings	Data gathered
Compressibility test	1-15 kPa	CBD (g/ml) CI (%)
Permeability test	1-15 kPa 2 mm/s	CBD (g/ml) PD (mbar)
Aeration test	0-30 mm/s	BFE (mJ) AE (mJ) AR

1.1 Research questions

- Can the FT4 by Freeman technology be used to evaluate 316L stainless steel powders used in SLM processes?

- Are the Compressibility, Permeability, and Aeration tests well suited to measure flowability for 316L stainless steel SLM powders?

- What settings are best suited for the Compressibility, Permeability, and Aeration tests for 316L stainless steel SLM powders?

1.2 Additive manufacturing

Additive manufacturing (AM) also known as 3D printing, is based on an incremental layer-by layer manufacturing method opposed to conventional manufacturing methods where material is removed (1, 2). Additive manufacturing has steadily increased in popularity over the years, due to the increasing demand for complex geometrical designs, and the design possibilities that AM provides. AM processes have been implemented in most fields including aerospace, automotive, and medical industries just to name a few. There are several AM processes where metals are used, some of the most common are binder jetting, powder bed fusion, metal extrusion, sheet lamination, and direct energy deposition. Of these only binder jetting and powder bed fusion uses metal powders as raw material (1, 2).

1.2.1 Powder bed fusion

Powder bed fusion (PBF) is one of the most commonly used AM processes for metals (1). The layer-by-layer process for PBF uses metal powder, where a thin layer of powder is spread, melted, and fused before the process is repeated (1, 2).

PBF is divided into two methods Selective Laser Melting (SLM), and Electron Beam Melting (EBM) (2). The general process of SLM and EBM is the same, a thin layer of powder is spread (20 µm–100 µm for SLM, and 50 µm–200 for EBM), melted, and fused (1).

But there are distinct differences, such that the SLM process uses a laser to melt the powder in an inert gas atmosphere such as N2 or Ar, whereas the EBM process uses an electron beam for melting in a vacuum. The SLM process has a significantly higher cooling rate than EBM and therefore a much faster build time. The advantage of EBM is that it can be used with much more brittle materials as the high cooling rate of the SLM process can lead to cracks with some materials (2).

For the PBF process to produce products accurate to its CAD model a lot of factors must come together. But of all the factors one key component is the powder and its flowability (3).

The majority of the powders used in BPF are produced through well-established methods, such as water, gas or plasma atomization (1). The powders particle distribution differs between SLM and EBM processes, where SLM powders have a much smaller particle distribution between 10-60µm compered to EBM where the powder distribution usually is 50-150µm, making the SLM powder generally more cohesive (3). The powders used SLM are Al-based alloys Ti-based alloys Fe-based alloys Ni-based alloys Co-based alloys, whereas EBM is more limited with the material choices due to it being a more complex process, the powders used for EBM are usually Ti grade 2, Ti6Al4V, Inconel 718, CoCrMo (2).

1.3 Powder rheology

Powder rheology, or the aspect of flowability in powders is essential to study in the context of AM methods using powders as feedstock. The precision needed for a successful AM process is high, and if the feedstock isn't behaving as expected it will have detrimental effects on the process as a whole (3). The flowability of powders have been an interest for a long time, most notably within the pharmaceutical industry (4). It is important to note that flowability is not one comprehensive bulk property of a powder, but instead a term describing the complex behaviour of powder when it is mobilized of affected by stress (3). With that in mind, the term of flowability of a powder can only be connected to the equipment used to measure the flowability aspect of the powder, and for the measured flowability to be applicable and relevant to the application the equipment must be performed in such a manner and conditions as close to the application as possible (3).

There are several types of equipment used to measure flowability in powders. The most used standardized equipment being Hall flowmeter funnel, and Carney funnel, as these are inexpensive and easy to use (3). However, these methods have been criticized by authors regarding the application of AM, as these methods heavily favours superiorly flowing powders with larger particle distribution. But fail for more cohesive powders and/or with smaller particle distribution that still work fine in the AM process (3).

Because of the inaccuracy of basic equipment to measure flowability of AM powders, the use of a powder rheometer has steadily increased in popularity, with promising results (3, 5-12).

1.3.1 FT4 Powder Rheometer

The FT4 Powder Rheometer from Freeman Technology have been used a lot within studies of flowability for metal powders for AM with promising results (3, 5-12). The FT4 uses glass vessels of differing inside diameter and volume according to table 3, where different vessel size requires different size accessory tools. The 25mm inner diameter vessels was found to be the most commonly used within the AM literature (3, 5-12).

The accessory tools for the FT4 are, a Blade/Impeller, Vented piston, Shear cell, Standard base, and aeration base (4).

The FT4 divide its measurements in 4 categories of methodologies, Bulk, Dynamic Flow, Shear, and Process (13), as seen in figure 1.

Basic flow energy, specific energy, and bulk density were the most common methods of using the FT4 and had good correlation with AM performance (3, 5-12).

Table 3 Vessel size and volume options for the FT4 Powder Rheometer from Freeman Technology

Vessel size	**Split options** mm = Inside diameter of vessel ml = Volume of sample after split	**Solid Vessels** mm = Inside diameter of vessel ml = Volume of vessel
25mm	25mm x 10ml 25mm x 25ml	25mm x 35ml
50mm	50mm x 85ml 50mm x 160ml	50mm x 260ml
62mm	62mm x 240ml	62mm x 400ml

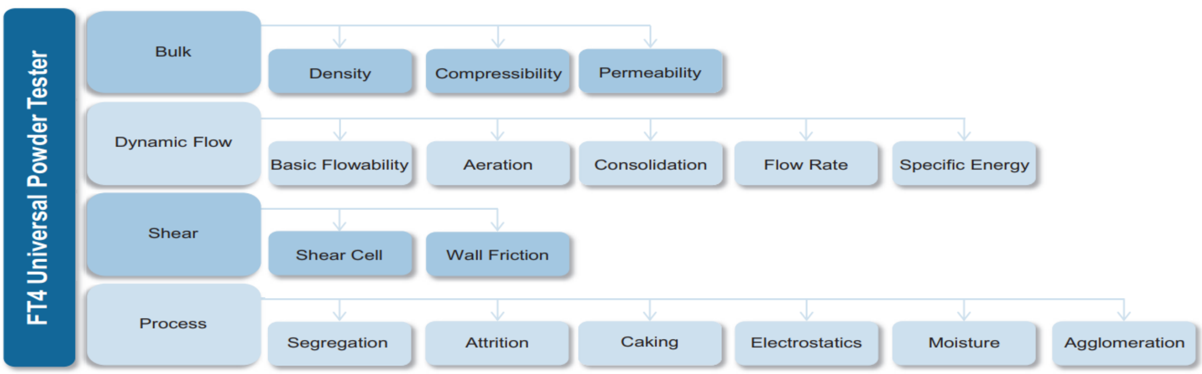

Figure 1 FT4 Categories of Methodologies as seen in reference (13)

1.3.1.1 Conditioning

Conditioning is a process where the FT4 standard blade applies uniform stress and slightly aerates the whole powder sample. This gently displaces the sample removing air pockets and negates effects from handling. This step is crucial as factors like the density of the powder can change during handling, transportation, processing, and other activities. This factors if not normalised through conditioning can have a major impact on the powder behaviour and subsequent test results may not be accurate (4).

1.3.1.2 Compressibility test

The Compressibility test measures how the conditioned bulk density of the powder changes when subjected to normal stress. This bulk property is influenced by a myriad of factors, such as particle size distribution, cohesivity, particle stiffness, particle shape and texture to name a few. Although this bulk property isn't a direct measurement of flowability, it can be used to determine how the powder will perform in environments such as hoppers/feeders, and spreading of the powder, which is important knowledge within the AM process.
The standard test uses the vented piston to compress the powder sample with increasing normal stress. Before compression, the powder sample is conditioned with the standard FT4 blade and split. The blade is then exchanged for the vented piston before the compression test is resumed (14).

Compressibility is shown to be a good indicator of the microstructure powder (5, 6, 10-12). It also has a clear impact on the AM process, where too high of a change in volume is correlative to worse results in other flowability tests and printed parts. However, the results from the compressibility test have to be used in conjunction with other tests, as flow energy and bulk density for a clearer picture (5, 6, 10-12).

1.3.1.3 Permeability test

The Permeability test measures how easily air can pass through the bulk of the powder sample. This bulk property is influenced by factors similar to the compressibility test. Them being, particle size distribution, cohesivity, particle stiffness, shape, surface texture, and bulk density. To measure the permeability air is forced through the permeable bottom, through the powder sample and the subsequent drop in pressure between the bottom and the vented piston is measured. In the standard program the air velocity is kept constant, and the vented piston applies increasingly higher normal stress as the test progresses, measuring the difference in permeability when the powder is effected by additional normal stress. As in the compressibility test the powder sample is first conditioned with the standard FT4 blade and split before the blade is exchanged for the vented piston, and the airflow and normal stress is applied (14).

Permeability was not used as much in the literature as the other two tests. The test shows contradicting data, Clayton saw a clear correlation between permeability and specific energy, where the bad preforming powders had both low permeability and low specific energy (7). But Brika found the inverse correlation. With the powder with the highest permeability having the highest specific energy, preforming better than the powders with lower permeability (10).

1.3.1.4 Aeration test

The Aeration test measures the cohesivity of the powder sample as well as how it is affected by increasing air velocity. The properties if powders are all affected by air to some extent due to the fact that the space between particles if filled with air. The amount of air present influences how the particles interact with each other, and this interaction between particles impacts directly on the flow properties of the powder. When a sufficient amount of air surrounds each particle, they act as a fluid. How much air that is needed generally depends on the cohesivity of the powder, as the airflow have to be enough to overcome the cohesive forces of the particles to separate them.

To measure the Aeration the powder sample is first conditioned with the standard FT4 blade and split, the powder sample is then transferred over to a solid vessel (so no air escapes through the sides during the test) and placed on the permeable bottom. The powder is then conditioned again, and the flow energy is measured with the use of the standard FT4 blade without any air output. The flow energy is then measured repeatedly with increasing air velocity through the permeable bottom to quantify how these changes the flow properties of the powder by the reduction of flow energy.

How much the flow energy can be reduced is dependent of several factors, the main factor being cohesion between particles, but also particle shape, texture, and density.

Aeration was not used as much as other flowability tests but was shown to be a good indicator of powder with high fluidity (5, 10, 15). It also seems to be a clearer indicator than basic flow energy (10).

1.3.2 AM Suitability Factor

In order to express the overall performance of the powders by the use of the data collected with the FT4 Brika et. al (10) proposed an additive manufacturing (AM) suitability factor. The AM suitability factor uses each FT4-generated index gathered, CI, CBD, BFE and so forth. These indices are then normalised between all the powders according to the maximum value obtained. All indices are then summarised for each powder and then minimised, where the powder with the highest AMS factor had the overall worst performance across the indices measured.
The equation used by Brika et. al (10) can be seen in equation 1. Where ρ_c is Conditioned Bulk Density; CI, the Compressibility Index; PD, the Pressure Drop; SE the Specific Energy; AE, the Aeration Energy; BFE, the Basic Flow Energy, and c the Cohesion coefficient.
The reason for the CBD to be inverted in the equation is due to the CBD showing better performance with higher CBD compered to the other indices where a higher value is related to worse performance in SLM processes. The calculated AMS factor was comparable to the powder performance in the SLM process and printed part (10).

The AM Suitability factor proposed by Brika et. Al (10) was also used by Kneips et. al (12) though modified to the indices measured in this study. The calculated AMS factor was comparative to the powder performance and printed parts in this study as well. The equation used by Kneips et. Al (12) can be seen in equation 2. Where CFE is the Consolidated Flow Energy; UYS, the Unconfined Yield Strength, and WFA the Wall Friction Angle (12).

$$AMS^B = \left(\frac{1}{\rho_c} + CI + PD + SE + AE + BFE + c\right)/7 \quad (1)$$

$$AMS^K = \left(\frac{1}{\rho_c} + CI + SE + CFE + UYS + WFA\right)/6 \quad (2)$$

2. METHODS

15 powders of 316L stainless steel used for SLM processes was tested by the use of Compression, Permeability, and Aeration with the use of a FT4 powder rheometer by freeman Technology. The powders were tumbled with a Turbula Type T2 C Shaker Mixer by Willy A. Bachofen AG for 30 minutes, and then spread out in a plastic tray for moisture equalisation. The powder was equalised for 60 minutes for the Aeration test, and 30 minutes for the compressibility and permeability test due to time constraints. All powders have been used in SLM processes by operators at Research Institutes of Sweden (RISE) in Mölndal. The powders and have either been able to print well or not, and the powder performance will be a point of interest in the data analysis.

2.1 Compression test

The compression test was performed with the 25mm x 10ml split vessels with the standard bottom, and corresponding vented piston, and FT4 blade. The program used follows the procedure listed in figure 2, where C is condition cycles. The program has 8 steps starts at 1kPa and increase up to 15kPa. The test was performed twice for each powder as variation in test results was found during initial trails and the average of both tests will be used in the data analysis, the Compressibility Index (CI) and Conditioned Bulk Density (CBD) will both be factors of study with the use of this test.

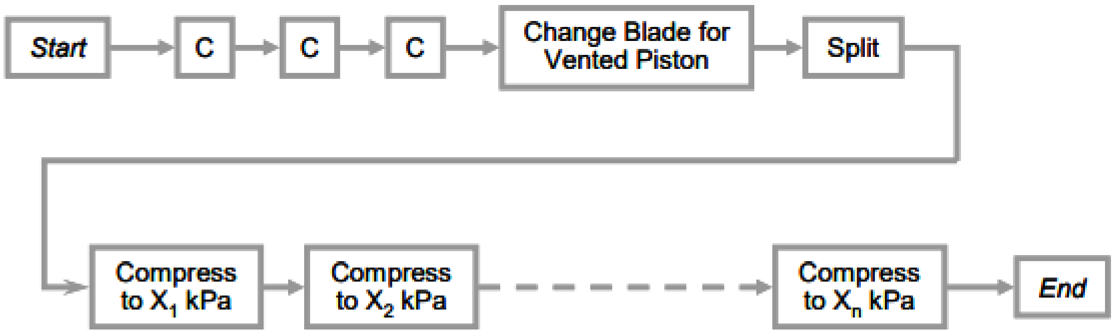

Figure 2 Compressibility Program Cycle as seen in reference (14)

2.2 Permeability test

The compression test was performed with the 25mm x 10ml split vessels with the permeable bottom, and corresponding vented piston, and FT4 blade. The program used follows the procedure listed in figure 3, where C is condition cycles. The program uses the constant air velocity of 2mm/s and have 8 steps where the applied normal stress starts at 1kPa and ends at 15kPa. The test will be performed once, as initial trails showed good stability in between tests. The Pressure Drop (PD) and Conditioned Bulk Density (CBD) will both be factors of study with the use of this test.

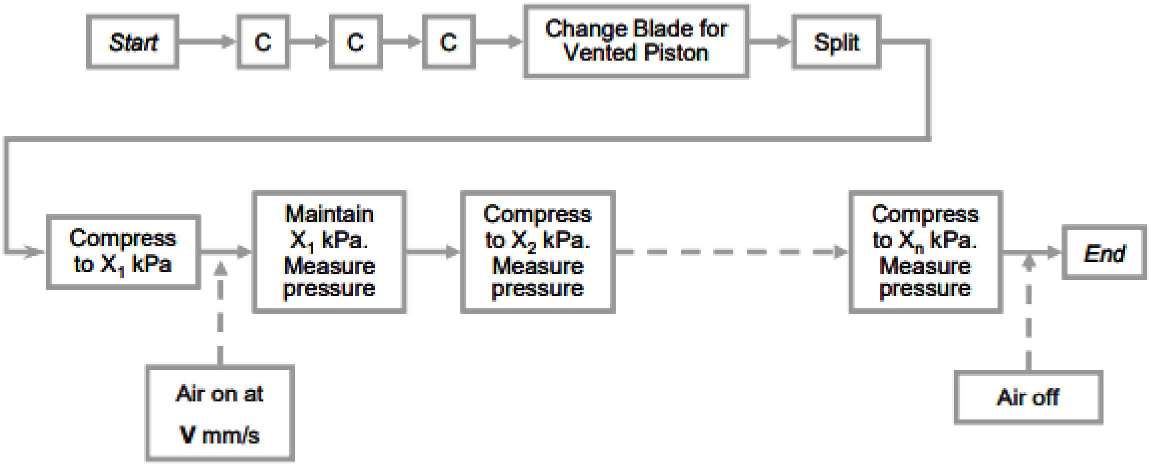

Figure 3 Permeability Program Cycle as seen in reference (14)

2.3 Aeration test

The Aeration test was performed by the use of the 25mm x 35ml solid vessel with the permeable bottom, and corresponding FT4 blade. The powder sample was conditioned and split using the 25mm x 25ml split vessel with a standard bottom and FT4 blade. The split powder was then transferred to the 25mm x 35ml solid vessel and run through the Aeration program. The standard program follows the procedure is listed in figure 4, where C is condition cycle, and T is testing, and goes from 0 – 10mm/s. The modified test used have 7 test cycles, meaning one additional increase in air velocity, condition, and test cycle, and goes from 0 – 30mm/s. This was used as initial testing showed that the standard air velocity showed extremely low aeration of the powder, was found to be too low to find differences in the powders.

The first flow energy test is made without any air output, air is then introduced during the Subsequent conditioning cycles and multiplied after each test cycle. The test will be performed twice for each powder as variation in test results was found during initial trails and the average of both tests will be used in the data analysis, Basic flow energy, the Aerated flow energy at 30mm/s and Aeration ratio will be factors of study from this test.

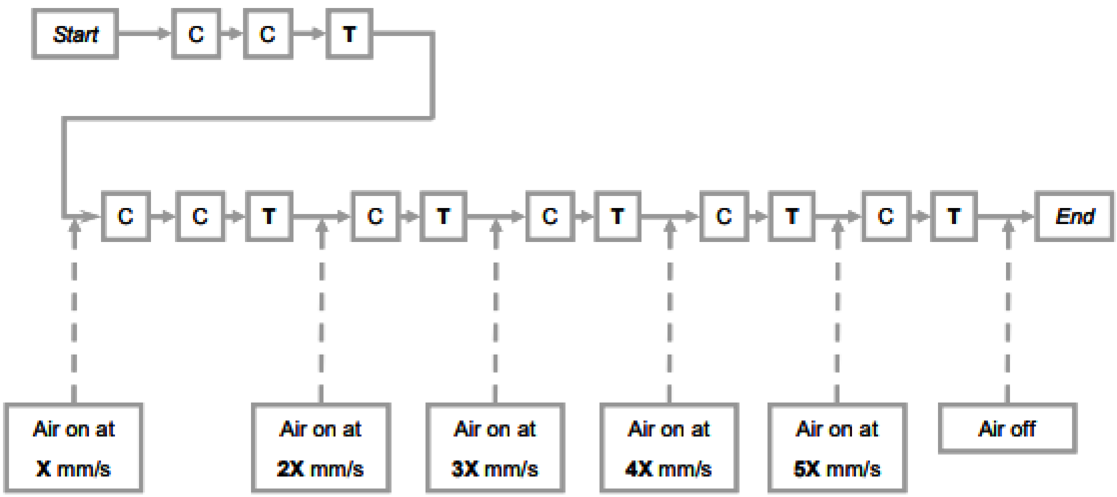

Figure 4 Aeration Program Cycle as seen in reference (14)

2.4 Data analysis

The gathered data from each test was compiled and studied separately and then together to find correlations between the tests and powder properties. The only exception being the conditioned bulk density that was collected from both the compressibility and permeability test, the CBD was averaged and used in all data analysis where the CBD was used. The AM suitability factors (AMS) seen in the literature (10, 12), was also used to quantify each powder.

3. RESULTS

3.1 Powder performance in SLM processes

All powders except M035, M035_mod, M042, M053, & M061 have performed well in SLM processes. The mentioned powders have had problems with spreading even coatings during the process and deemed inappropriate in SLM production by the operators at RISE, all powders except M035 was able to print, and M035 was the only powder that was unable to print at all.
M035_mod is a modified version of the M035 where it was changed to enhance known factors of flowability.

3.2 Compression test

An overview of the collected data from the Compressibility test as well as the CBD from the Permeability test can be seen in table 4. Graphs of the CBD and CI can be seen in figure 5 & 6. A graph plotting the CBD and CI of each powder can be seen in figure 7, as well as the trendline in figure 8. From the gathered data we can see that the powders with the lowest CBD and highest CI are three of the worse preforming powders, namely M035, M042 & M061, which is in line with the literature (5, 6, 10-12). This can clearly be seen in figure 7 where M035, M042, and M061 show a clear deviation from the other powders. M053 and M035_mod powders that had been preforming worse in the SLM process however does not show any deviating behaviour in the compressibility test and is in fact both one of the best preforming powders in the test. Other powders that are of note is M036 and M085 that are in the outer rim of the cluster but still performed well in AM processes suggesting that there might be a limit for well preforming powder with a CBD lower than 4,5 g/ml and a CI above 4,5%.

Table 4 Overview of Data from Compressibility Test. Bad performing powder in SLM processes are highlighted in red. CBD – Conditioned Bulk Density, CI – Compressibility Index, STD – Standard Deviation

	CBD C, g/ml	No of Replicates C	CBD P, g/ml	No of Replicates P	Avg CBD, g/ml	STD Avg CBD, g/ml	CI, % @ 15.0kPa	STD CI
M004	4,56	2	4,56	1	4,56	0,01	3,35	0,03
M009	4,72	2	4,71	1	4,72	0,00	3,07	0,65
M016	4,69	3	4,78	1	4,73	0,06	3,32	0,15
M027	4,68	2	4,76	1	4,72	0,05	3,40	0,45
M028_bis	4,63	2	4,59	1	4,61	0,04	3,84	0,32
M033	4,52	2	4,64	1	4,58	0,07	3,51	0,25
M035	4,37	2	4,53	1	4,45	0,09	5,23	0,12
M035_mod	4,79	2	4,79	1	4,79	0,00	3,09	0,12
M036	4,47	2	4,47	1	4,47	0,01	3,68	0,52
M041	4,53	2	4,53	1	4,53	0,02	3,53	0,53
M042	4,34	2	4,31	1	4,33	0,02	5,16	0,05
M053	4,67	2	4,67	1	4,67	0,01	3,08	0,07
M059	4,70	2	4,70	1	4,70	0,02	2,58	0,34
M061	4,39	2	4,42	1	4,40	0,02	5,00	0,24
M085	4,58	2	4,59	1	4,59	0,03	4,14	0,40

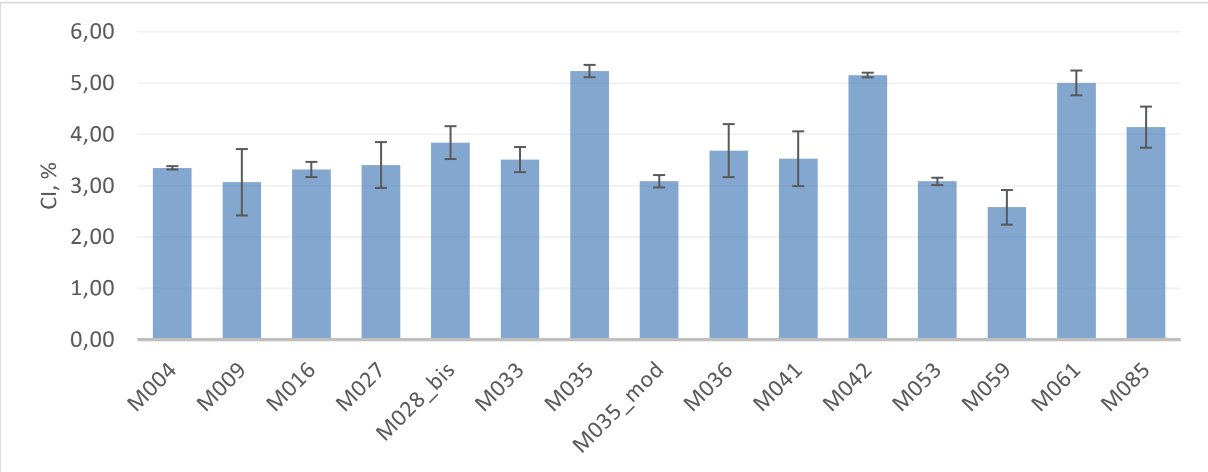

Figure 5 Overview of the Compressibility at 15kPa for all powders, with indicators of the standard deviation of each powder.

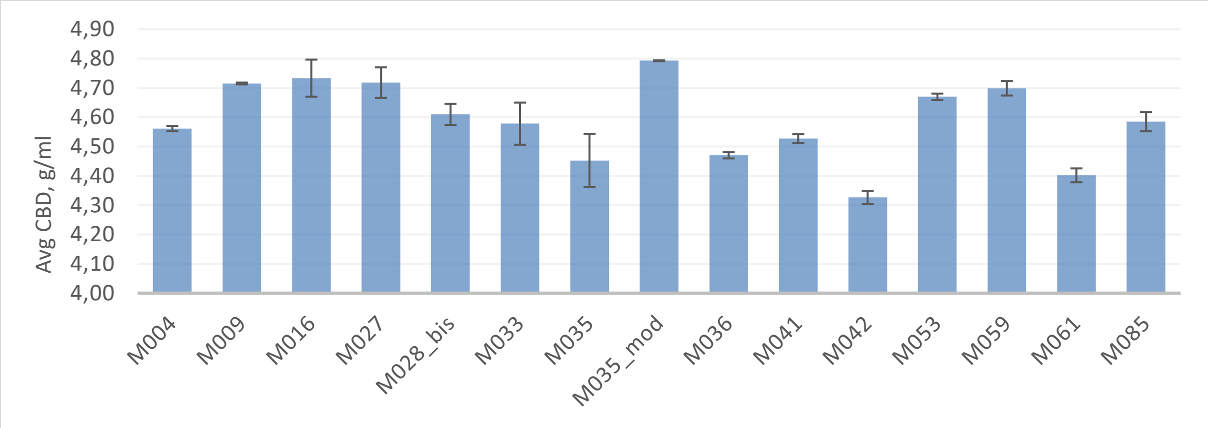

Figure 6 Overview of the Conditioned Bulk Density for all powders, with indicators of the standard deviation of each powder.

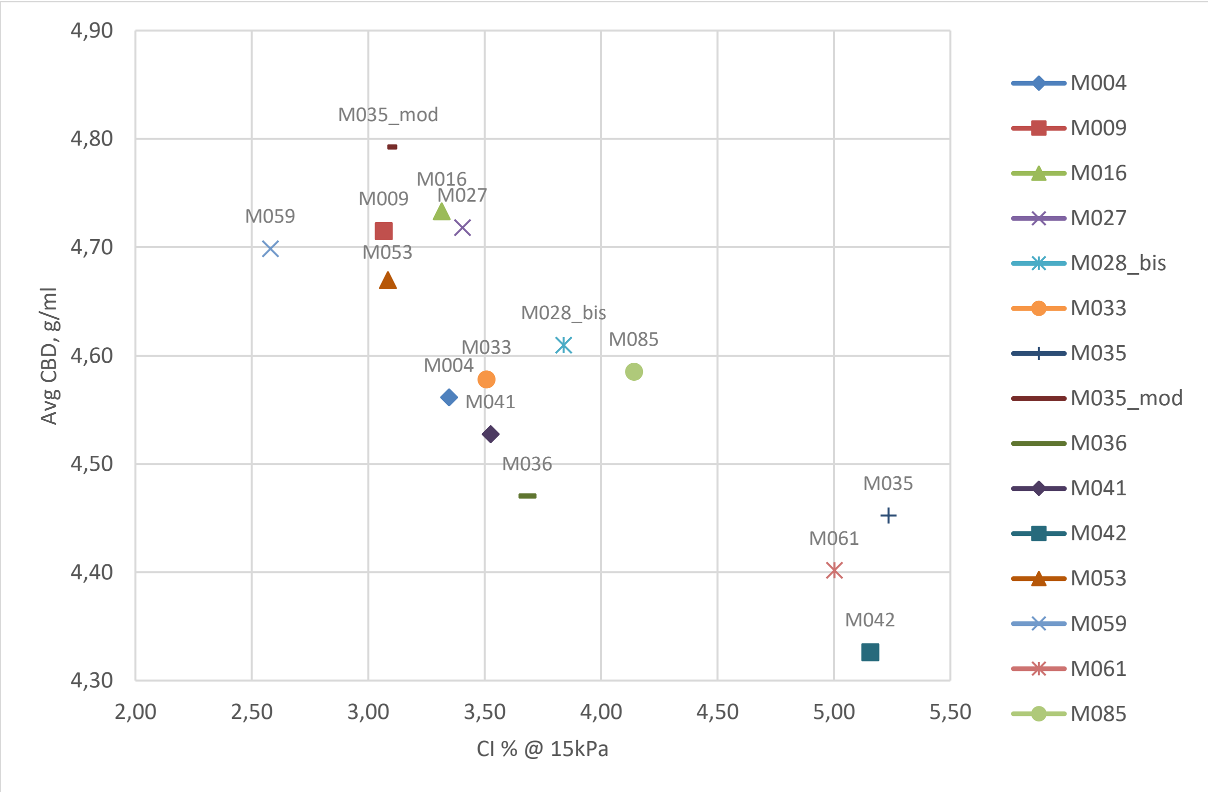

Figure 7 Overview of the compressibility test, plotting Avg CBD and CI at 15kPa.

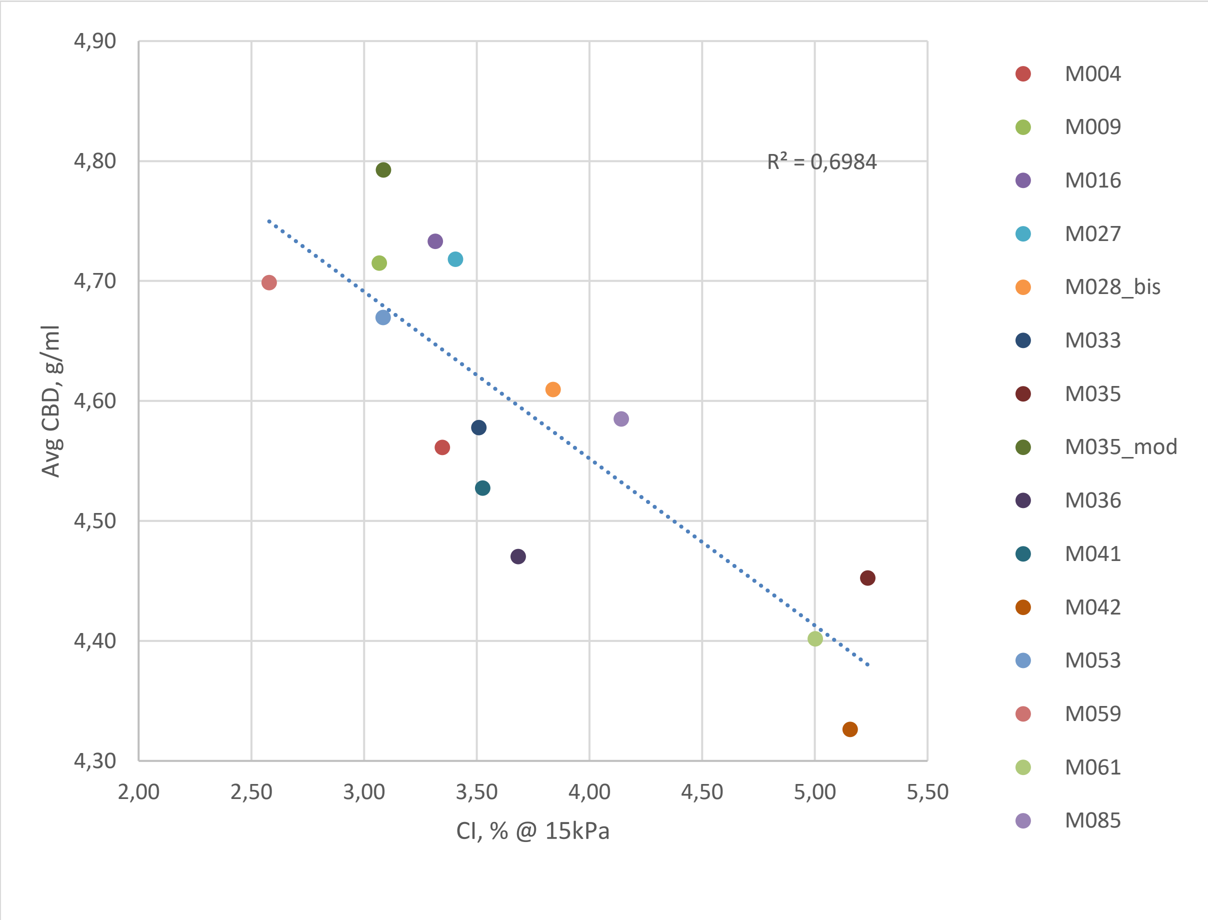

Figure 8 Trendline for CBD and CI

3.3 Permeability test

An overview of the data from the permeability test can be seen in table 5. The PD for all powders and a graph overviewing the permeability test where the CBD and PD is plotted can be seen in figure 9, & 10.

All powders performed well in the permeability test with very little variation between powders the biggest difference being between M053 having the highest PD of 0,42 mbar and M041 having the lowest PD of 0,36 mbar. The difference of a total of 0,06 mbar isn't deemed enough to truly evaluate differences between the powders. From the plotting of CBD and PD in figure 10 there seems to be a trend towards higher CBD giving a higher PD. The powders of note from performing worse in SLM processes, namely M035, M035_mod, M036, M042, and M053 do not deviate from the powders that perform well. Indicating that permeability might not be a good test for evaluating these powders at the set air velocity.

Table 5 Overview of Data from Permeability Test. Bad performing powder in SLM processes are highlighted in red. CBD – Conditioned Bulk Density, PD – Pressure Drop.

	Avg CBD, g/ml	No of Replicates CBD	PD, mbar @ 15.0kPa	No of Replicates PD
M004	4,56	3	0,39	1
M009	4,72	3	0,40	1
M016	4,73	3	0,39	1
M027	4,72	3	0,36	1
M028_bis	4,61	3	0,41	1
M033	4,58	3	0,38	1
M035	4,45	3	0,40	1
M035_mod	4,79	3	0,42	1
M036	4,47	3	0,36	1
M041	4,53	3	0,36	1
M042	4,33	3	0,37	1
M053	4,67	3	0,42	1
M059	4,70	3	0,40	1
M061	4,40	3	0,40	1
M085	4,59	3	0,41	1

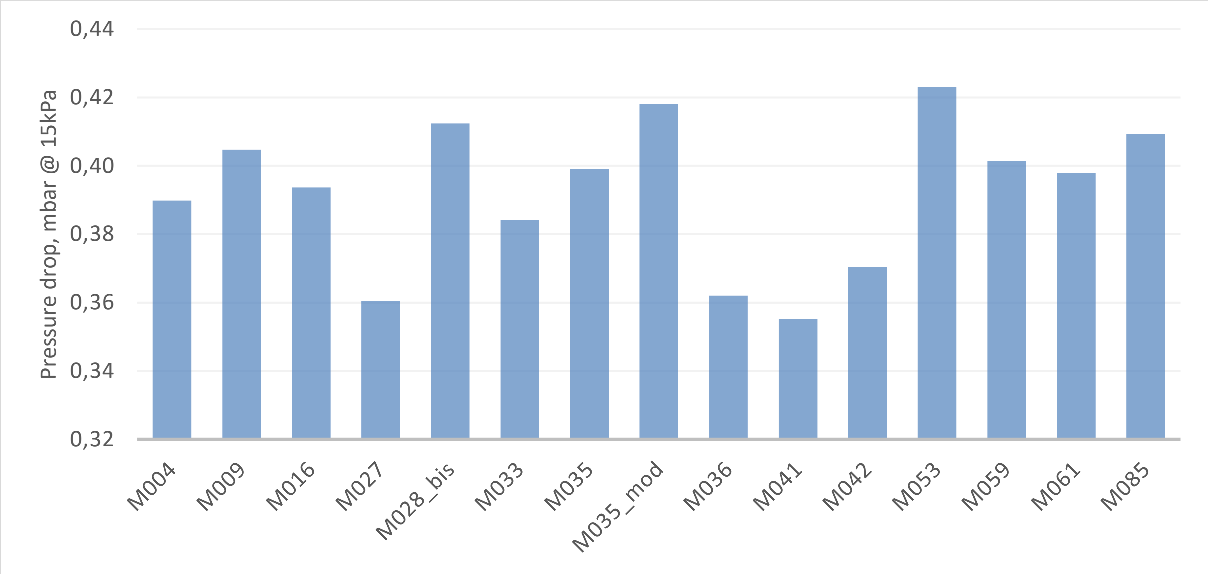

Figure 9 Overview of the Pressure drop for all powders.

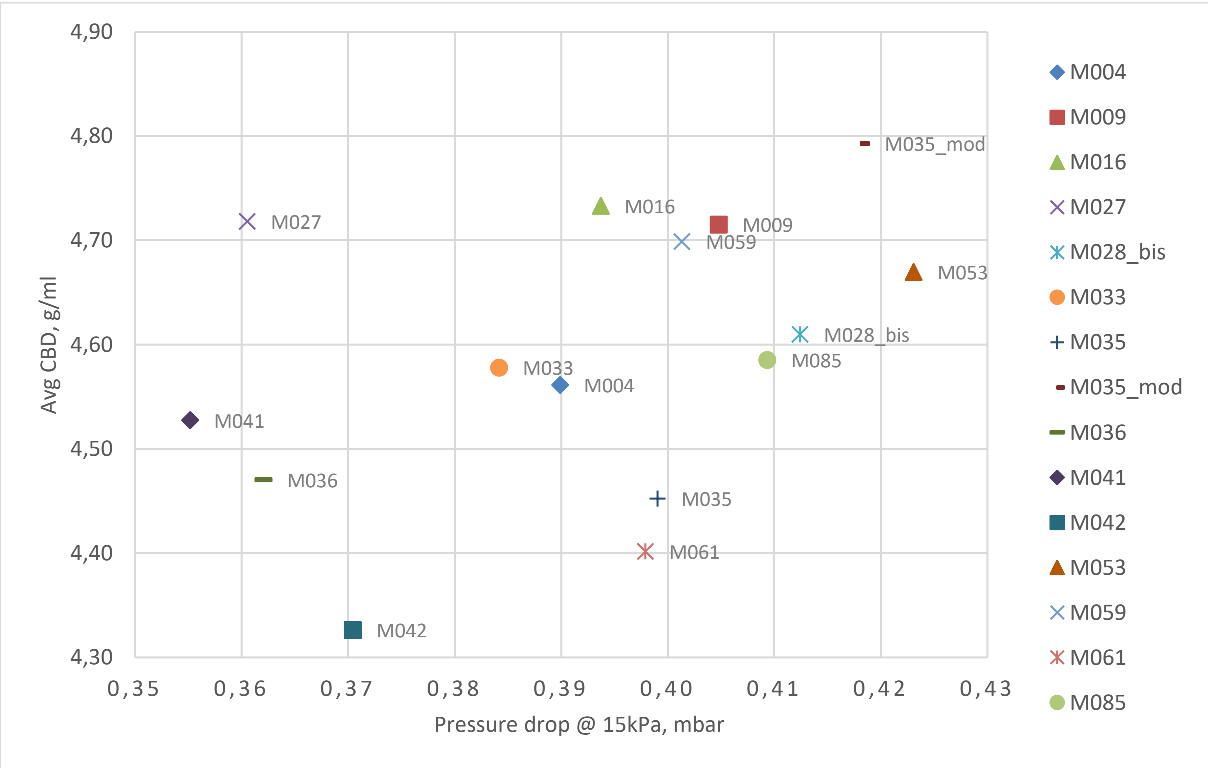

Figure 10 Overview of the Permeability test, plotting Avg CBD and PD at 15kPa.

3.4 Aeration test

An overview of the data from the Aeration test can be seen in table 6. A graph of the AR_30 for all powders can be seen in figure 11, and a graph overviewing the Aeration test where the BFE and AR_30 is plotted can be seen in figure 11. From the AR_30 it is clear that the M035 powder preforms the worst, but most of the other powders have similar AR_30 except M009, M035_mod, M053, and M061 that preformed above the other powders. The powders of note from SLM production all preform in the lower end of the AR_30, except for M053 and M035_mod.

From figure 12 a correlation may be indicated between BFE and AR, where the powders with higher BFE also can be seen to have the highest AR_30, with some outliers, namely M009 and M0061. No truly deviating powders except M035, M035_mod, and M009 can be seen through the Aeration test alone.

Table 6 Overview of Data from the Aeration Test. Bad performing powder in SLM processes are highlighted in red. BFE – Basic Flow Energy, AE_30 – Aerated flow Energy at 30 mm/s, AR_30 – Aeration ratio, STD – Standard Deviation.

	BFE, mJ	AE_30, mJ	AR_30	STD AR_30
M004	704,08	270,85	2,60	0,15
M009	734,90	246,32	2,98	0,06
M016	803,89	292,99	2,74	0,08
M027	809,17	309,23	2,62	0,11
M028_bis	734,07	269,96	2,72	0,09
M033	742,68	303,38	2,45	0,13
M035	646,92	295,36	2,19	0,14
M035_mod	863,91	260,05	3,32	0,01
M036	800,32	317,55	2,52	0,12
M041	664,06	266,36	2,49	0,01
M042	639,23	257,46	2,48	0,05
M053	880,91	297,87	2,96	0,05
M059	924,38	303,74	3,05	0,26
M061	778,41	329,12	2,37	0,08
M085	635,18	261,48	2,43	0,06

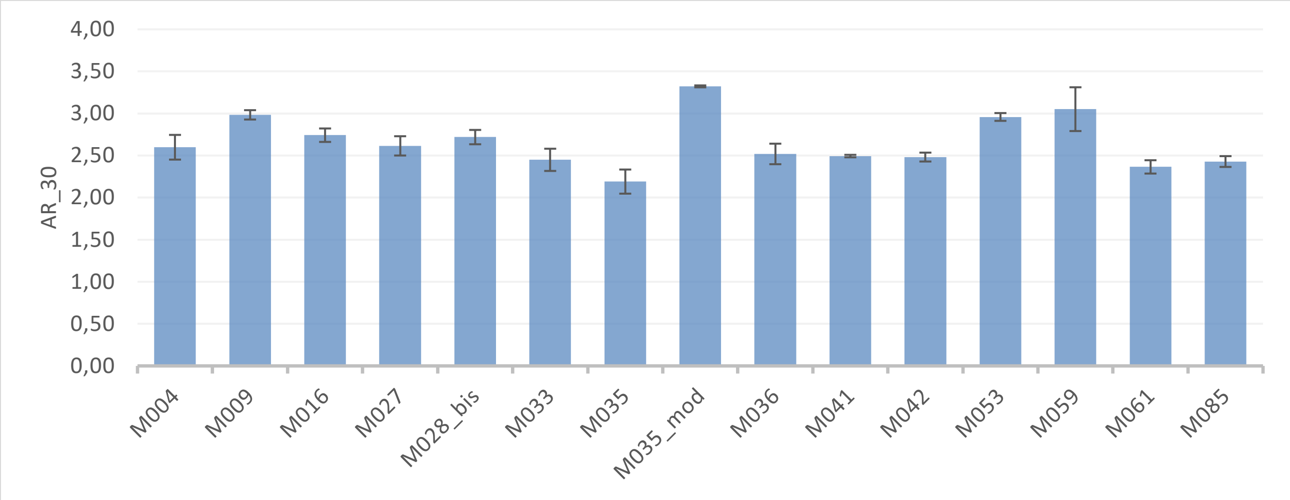

Figure 11 Overview of the Aeration Ratio of all powders with Standard deviation in error bars.

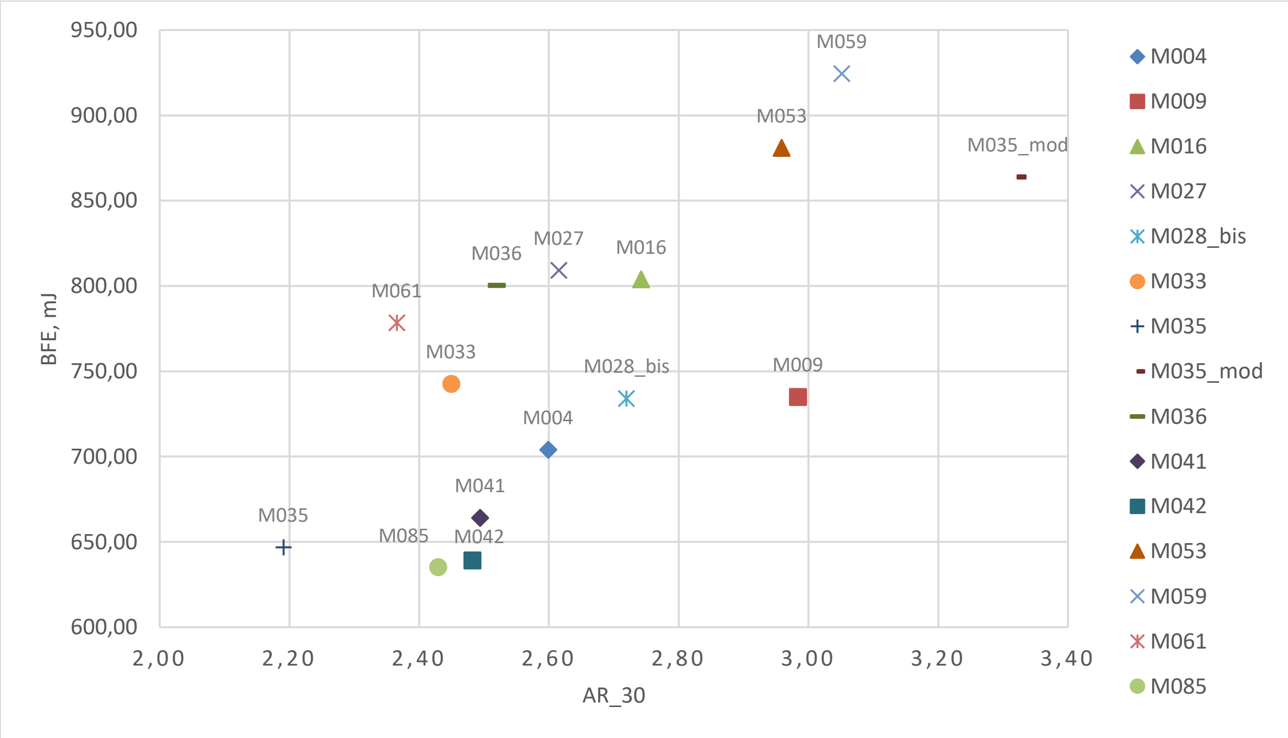

Figure 12 Overview of the Aeration test. BFE- Basic flow energy, AR_30 - Aeration Ratio

3.5 Conditioned Bulk Density & Aeration Ratio

Plotting the CBD and AR_30 from previous test in figure 13, a clear deviation from some of the powders that performed worse in SLM processes, namely M035, M061, and M042. Seeing that there may be a corelation between CBD and AR for well preforming 316L powders in SLM processes. The last powders of note being M053 and M035_mod is however preforming very well in this graph as in previous tests.

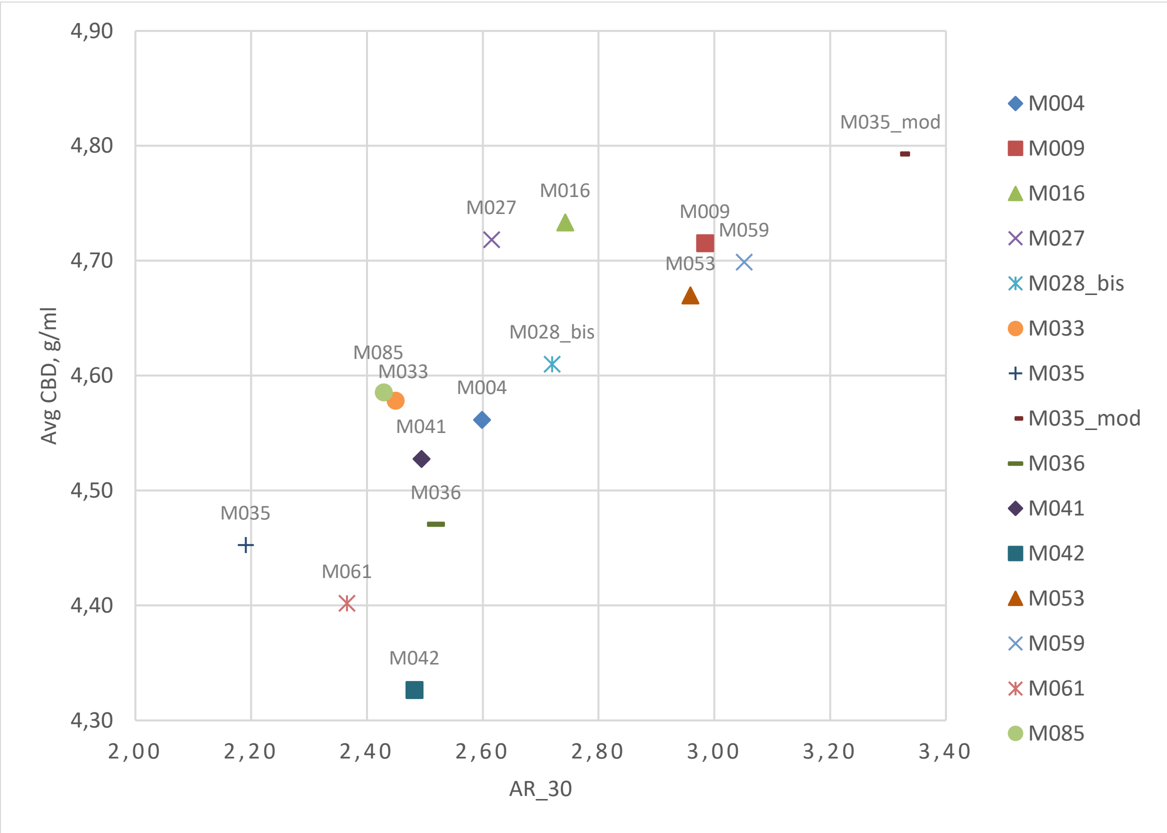

Figure 13 Graph of Conditioned Bulk Density & Aeration Ratio for all powders.

3.6 Compressibility & Aeration Ratio

Plotting the CI and AR_30 from previous test in figure 14, the same deviating powders noted in figure 13 can be seen. namely M035, M061, and M042. Seeing that there may be a corelation between CI and AR for well preforming 316L powders in SLM processes. As seen in figure 13, M053 and M035_mod is performing well in this graph as well indicating that the powders should be preforming well in SLM processes where it has not.

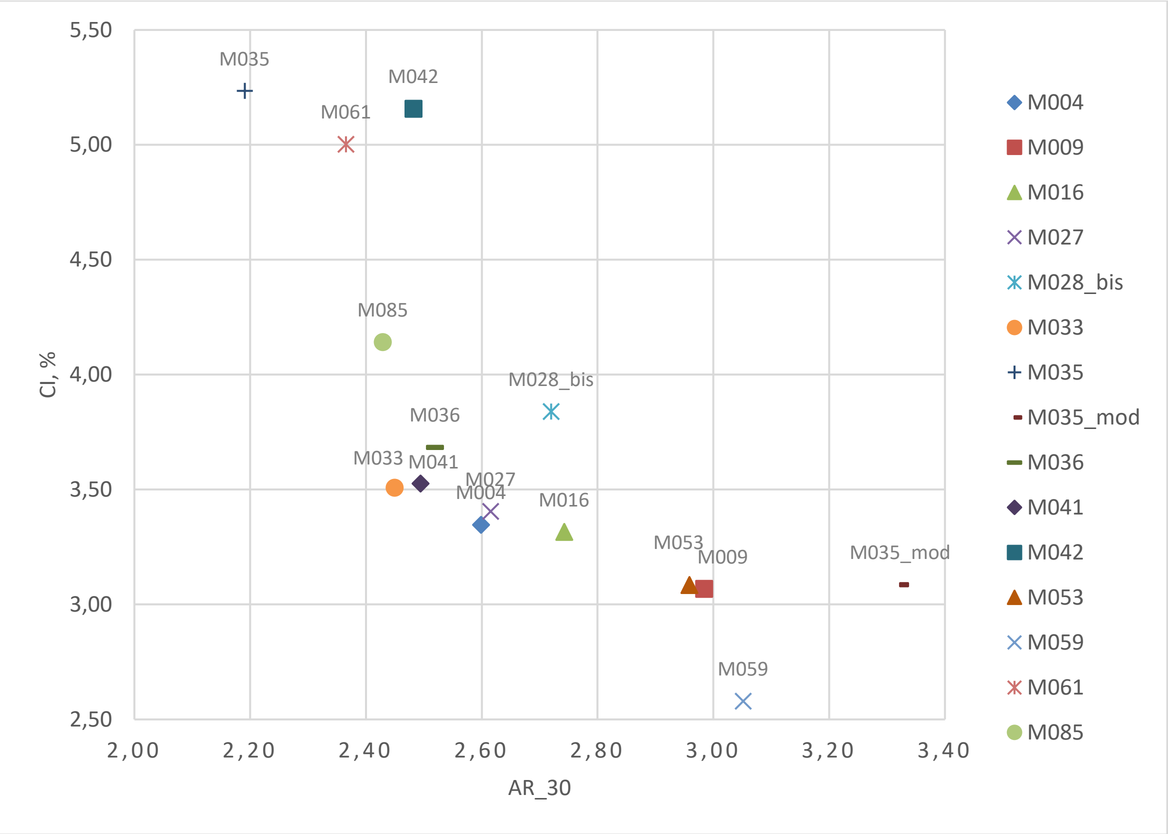

Figure 14 Graph of Compressibility Index & Aeration Ratio for all powders.

3.7 AM suitability factor

The AM suitability factor is calculated using equation 3, and the AMS' for each powder can be seen in figure 15. Another AMS factor was calculated excluding the PD called AMS'' can also be seen in figure 16 and is calculated using equation 4. In the complete AMS factor (AMS'), it is clear that the M061 and M035 fared the worst in general, followed by M036, M053, and M042. This includes all of the worse performing powders except M035_mod, as well as M036 that have worked well within the SLM process.

When removing the PD from the equation the M035, M036, M042, and M061 still deviate from the other powders whereas M053 now is in the upper regions without any clear deviation. The same thing can still be seen in the M035_mod as it is clearly one of the best preforming powders according to the AMS''.

$$AMS' = \left(\frac{1}{\rho_c} + CI + PD + BFE + AE\right)/5 \qquad (3)$$

$$AMS'' = \left(\frac{1}{\rho_c} + CI + BFE + AE\right)/4 \qquad (4)$$

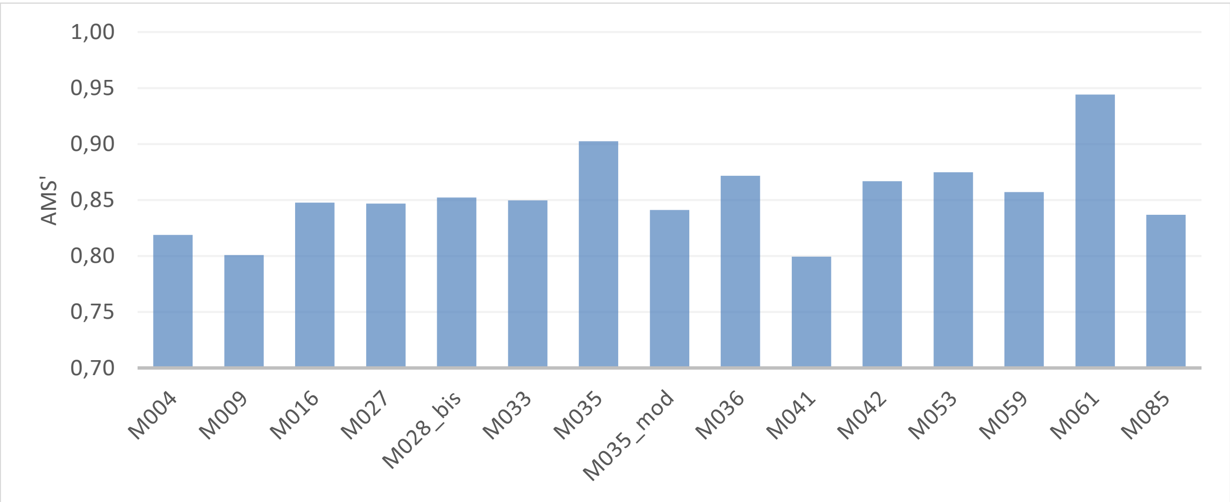

Figure 15 Overview of the AM Suitability factor from all tests and powders.

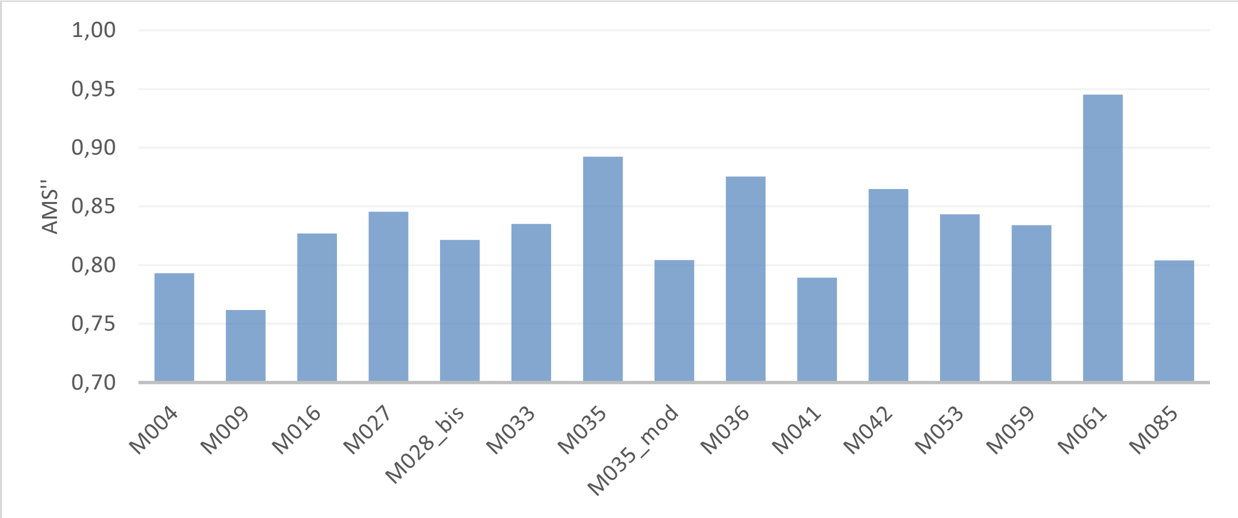

Figure 16 Overview of the AM Suitability factor from all tests and powders where, Pressure Drop is excluded.

4. DISCUSSION

4.1 Result discussion

From the gathered data there seems to be a clear correlation between CBD and CI that can be seen in figure 7 & 8 where the trend line in figure 8 shows the correlation the clearest. From the study there is evidence for powders with low CBD, and high CI & AR to preform worse in the SLM process. The Compressibility and Aeration test therefore show promising results in differentiating 316L powders for SLM processes. These findings are in line with the literature (5, 6, 10-12, 15). The Permeability test showed no significant result other than all of the powders performed well, this can be a reason behind the conflicting results in the literature (7, 10). Meaning that the Permeability test might not be a suitable test for SLM powders. A thought of why this might be the case is that during the Permeability test the applied pressure compresses the powder to a similar packed density, as seen in the compressibility test the powders with the highest CI also had the lowest CBD and vice versa, meaning that there might be a correlation between CI and CBD. This correlation can best be seen the trend line for the compressibility test in figure 8. Meaning that when compressed the density of the packed powder would be similar. Applying a low constant pressure with increasing air velocity might give more meaningful information as the powder would act more like its conditioned state, another approach is increasing the airflow as the settings used may not be suitable for the powder used. When combining aspects from the Compressibility and Aeration test seen in figure 13 & 14 all but one of the powders that performed bad during SLM processes clearly deviate from the others. These powders have low CBD, and AR, and high CI which also is associated with bad preforming powders in the literature (5-8, 10-12, 15).

The AM Suitability factor reflects what have been seen in the other tests as it is a summation of the indices of interest (10, 12). However, when viewing the AMS factors the M036 powder that performed well in SLM processes is one of the worst performing powders according to the AMS factor. This is because the M036 powder performed in the lower end on all tests but did not truly deviate from any of them, meaning that the AMS factor can be a tool for finding deviating powders, but has to be used in conjunction with the collected data to see if there were any true deviations during the tests. Another problem with the AMS factor is that it only evaluates the powder overall performance compared to the other powders in the study and cannot be a true indicator of performance as it would change if other powders where removed or introduced.

Lastly the M053 and M035_mod powders have to be addressed, these powders is said to perform worse in the SLM process but have performed well in all tests, the only deviating data being the high BFE of both powders, this shows that these three tests alone aren't enough to get a clear picture of powder flowability within the SLM process, and the tests have to be supplemented or modified to get a more holistic picture of the process.

4.2 Method discussion

The methods of gathering the data, namely the FT4 have been observed to be sensitive and reliable with promising results according to the literature (3, 5-12), as it has been able to differentiate poor performing powders through testing and verified through printing. The main weakness of the results from this study were the amount of data gathered, as seen in the variation of the CBD, CI, and AR. More replications of the tests could have given a more accurate view of the results although the gathered data should be enough for a result to be made.

The settings used for the compressibility test seems sufficient for a clear result and are in line with the literature that have showed similar results (11, 15). Other studies used the compressibility test, but did not specify the settings used, but are assumed to use the standard (10, 12).

As seen in the results for the Permeability test no clear deviations could be seen, and modification of the test could be of interest. A higher air velocity could be required as seen in the Aeration test that was increased from the standard om 10 mm/s to 30 mm/s could show more clear results. As seen in a study by Lyckfeldt (15) who used 10 mm/s instead of the standard 2 mm/s when evaluating 316L stainless steel powders. As mentioned in the result discussion the test could also have been modified to use a lower constant pressure with increasing airflow.

The Aeration test could also have been further modified with even higher air velocity as no powder actually reached AE close to zero. But the data extracted from the test still shows clear differentiations in the powders, and the AR from the tests can still be used as an indicator of the cohesive forces between the particles.

No true analysis was made to evaluate the removal of PD from the AMS factor other than noting the difference between AMS’ and AMS’’. No further analysis was made into the differences between the AMS factors as no true difference between the arrangement of poor performing powders can be seen between them. The AMS factor is only a tool of overviewing the combined results and should not be used to evaluate the true performance of powders in AM production and thus have no true impact on the results of the study.

It is clear that further studies are needed to standardise the tests dependent on the metal powder used and process it is used for, but this study is one of the steps needed for continued progress.

5. CONCLUSION

Powder rheology is a complex topic with a myriad of factors to measure, and there is a clear need for standardising and evaluating flowability tests for a clearer overview.

- Can the FT4 by Freeman technology be used to evaluate 316L stainless steel powders used in SLM processes?

The evidence in the literature and study points towards that the FT4 can be a powerful tool in evaluating 316L stainless steel powders used in SLM processes as long as the settings for the tests are appropriate to the powder that is being tested. The tests can differentiate indices of flowability that correlate to better performance in AM processes, the most applicable from this study being CI and CBD.

- Are the Compressibility, Permeability, and Aeration tests well suited to measure flowability for 316L stainless steel SLM powders?

The compressibility showed to be best suited with the settings used, being able to differentiate most of the poor performing powders. Aeration did also show promising results but further changes in the settings may be needed. The permeability test was not shown to be suitable with the settings used, but with higher air velocity it may still be suitable and further studies are needed.

- What settings are best suited for the Compressibility, Permeability, and Aeration tests for 316L stainless steel SLM powders?

The compressibility test showed reliable data at 1-15 kPa and no further changes are believed to be necessary. The Permeability test wasn’t suitable at 2 mm/s air velocity, 10 mm/s was observed to be adequate for 316L stainless steel powder in the literature and further studies are needed to evaluate the correct settings. The Aeration test did show promising results at 30 mm/s air velocity, but further increase of air velocity may be needed for a clearer result as no powder reached fluidization (AE close to 0).

In conclusion further research and tested needs to be done within the field of powder rheology and AM processes.

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