Evaluating the spreadability of metal powders for additive manufacturing applications using a SpreadStation Powder Analyzer

Abstract

The spreadability of several metal powders manufactured for additive manufacturing applications is measured for a range of layer thicknesses under different application conditions including a range of spreading speeds, different spreader geometries, a range of powder feeding geometries and spreader application pressures and different environmental conditions. The powder spreadability analyzer used for the measurements is a new instrument commercially produced by Mercury Scientific Inc. Data presented include spreading efficiency, mass per spreader travel and spreading uniformity per spreader travel.

Introduction

The ability of a powder to form a layer in a powder AM printer is critical to producing high quality parts. This ability is referred to as powder spreadability. There are many official and unofficial definitions of powder spreadability but there is no consensus on how to test it. Many printers have various in situ techniques for analyzing powder layer formation but these techniques are more for process monitoring rather than predictive testing. These techniques require an available printer and a large quantity of powder. For predictive tests what is needed is a device the uses a small amount of powder to create a powder layer similar to AM printers and can quantify the quality of the layer. Several tests and test devices have been proposed [1,2,3,4]. These include test beds that automatically spread a test powder and manual spreading devices Typically the measurement performed is an optical analysis of the top surface of the powder layer. In some cases the density of the layer is measured by weighing the powder and calculating the spread layer volume.

For this application, a new device has been introduced commercially to measure powder spreadability. This powder spreadability analyzer creates up to four simultaneous layers of powder using various spreader geometries, spreader speeds and powder feeding options. The analyzer then measures the quality of the powder layer using optical techniques and by measuring the mass of material exiting the spreader. The test powder can be spread on various build plates or on a powder bed.

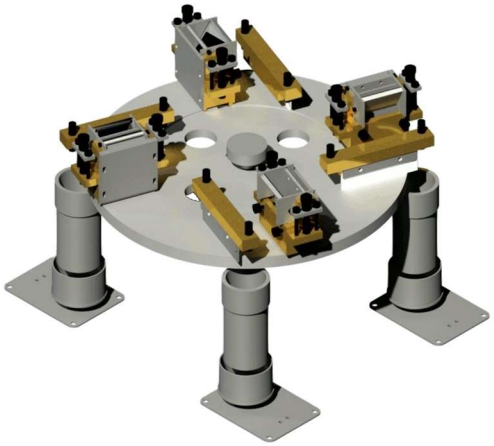


Figure 1. Spreadability analyzer solid build plate with four spreading assemblies.

For a powder to form a layer on a build plate there must be relative motion between the spreading device and the build plate. In most AM printers the spreading device moves over the build plate to spread the powder. In the powder spreadability analyzer, the build plate is moved under the spreading device to spread the powder. The build plate is rotated relative to the spreading device to keep the system small for controlling environmental conditions and to provide unlimited travel for the build plate [Figure 1]. This simplifies the design of the device and also makes it easier to mount measuring systems as they are stationary. After being spread, the powder is removed from the build plate by an angled scraping blade and transferred to a measuring balance to be weighed. The instrument can be equipped with multiple spreaders and balances.

Figure 2. Spreading assembly with spreading base, spreading plate and powder feeder installed

Figure 3. Powder feeder

The spreading assembly [Figure 2] for the analyzer consists of three parts: 1) a spreading base, 2) a spreading plate, and 3) a powder feeder [Figure 3]. The spreading plate is mounted on the spreading base and can move in the vertical direction to create a gap between the build plate and the spreading plate to allow powder spread. The spreading device moves up and down with any unevenness in the build plate to maintain a constant spreading gap. Many spreading geometries are available including flat, rounded, flexible and counter rotating cylinder. The spreading base maintains the powder behind the spreading plate. The powder feeder delivers the powder to the spreading area. The angle and gap of the feeder can be adjusted as well as the pressure on the powder in the spreading area. Up to four spreading devices can be mounted on the analyzer to spread four layers simultaneously. When the test powder has been loaded in the powder feeder, the movement of the build plate is started and the powder is spread in a layer on the build plate where it is measured.

Several measurements are made to assess the powder layer. The primary measurement is the mass of powder that exits the spreader relative to the motion of the build plate. After exiting the spreading device the powder is moved off of the build plate and onto a balance by an angled scraping blade. The balance measures the mass of powder removed from the build plate over time. Before reaching the blade, images

of the powder are taken and the thickness of the powder bed is measured using a distance sensor. The density of the bed is calculated from the height of the powder or spreading gap and the travel of the build plate. Channels and waves in the powder layer are detected using image analysis techniques on the powder images.

These measurements allow the layer uniformity and density to be measured over the course of the spreading until no more powder exits the spreading device. The spreading efficiency is the spreading density of the layer relative to a layer of solid powder material at the thickness of the spreading gap. The spreading rate is the mass of powder in the layer per centimeter traveled by the build plate. The standard deviation of the spreading rate is the standard deviation of the mass of powder being spread taken every one second. The spread uniformity compares the spreading rate at the beginning of the measurement and at the end of the measurement to the average spread rate. A uniformity of zero means there is no variation in the spreading rate. A negative uniformity means less powder is being spread at the end of the test as compared to the beginning. A positive uniformity means more powder is being spread at the beginning of the test than at the end. The fractal dimension is the smoothness of the mass in the spread layer.

Additional measurements can be made from the images of the spread powder including the uniformity of the surface and duration and width of gaps or channels in the spread layer.

To demonstrate the function of the spreadability analyzer and the data it produces several metal AM powders were tested. The powders were tested using a flat spreader and a round spreader at several spreading speeds. The powder feeder and pressure on the powder in the spreading area was changed to measure the effect of pressure on layer formation. Layers were formed on a flat build plate. The spreading efficiency, spreading density, layer thickness, and layer uniformity were measured.

Materials

Two sets of two 316L austenitic stainless steel powder samples labeled Set A and Set B were tested. Each set consisted of a virgin sample and a recycled version of the same material. For Sample Set A, the recycled material went through two printing cycles. For Sample Set B, the recycled material went through eight printing cycles. These materials were characterized extensively in [7] and [8] using various measurements including SEM images.

An additional sample set of nickel alloy powders were also tested consisting of a virgin material and a recycled material labeled Set C. The virgin material was reported to be acceptable and the recycled material unacceptable for an AM printing application.

Experimental

Measurements of powder spreadability were made using the SpreadStation Powder Analyzer from Mercury Scientific (Newtown, CT). The analyzer was equipped with a flat and rounded spreading plate with spreading gaps from fifty to two hundred micrometers. Powders were tested at spreader speeds from fifty to two hundred millimeters per second. The analyzer was equipped with a machine vision camera and LED lighting to capture images of the spread powders and a laser triangulation distance sensor to measure spread layer thickness.

The low pressure powder feeder used had a feed angle of 60 degrees and a feeding gap of 4.6 millimeters. The high pressure feeder consisted of a rectangular opening with a weight on the powder to change the pressure on the powder in the spreading area. The build plate consisted of a stainless steel disc. The spreading plate consisted of a flat plate and a rounded plate.

All samples were tested in as is condition. Some samples were then exposed to humidity by placing them in an open pan in an oven with a relative humidity of 40 percent and a temperature of 50 degrees Celsius for two hours with mixing every 30 minutes to expose additional surfaces to the oven humidity. These sample were then tested. After testing these samples were dried at 100 degrees Celsius for 16 hours and then at 200 degrees Celsius for two hours with mixing every 30 minutes. Samples were then cooled and tested again.

Some samples were also exposed to segregation stress. 75 cm^3 of Set A and Set B samples were poured into a closed core flow funnel. A core flow funnel has a shallow angle so that the powder flows in a first in last out pattern. The funnel was then opened and the powder flowed into a second closed core flow funnel. The second funnel was then opened and the powder flowed into a third closed core flow funnel. The final funnel was then opened and the first 25 cm^3 of powder exiting the funnel was collected and tested. Set A and Set B samples were also exposed to segregation stress using a pan sifting method. 100 cm^3 of each sample was transferred to a flat pan. The pan was shaken from side to side for 60 seconds to create motion in the sample. The top half of the sample was then scraped from the powder bed and collected. Then the lower layer was collected. Each pan layer was then tested.

For all tests, 40 grams or roughly 10 cm^3 of sample were tested for each test. Test time was 30 to 50 seconds from the start of spreading to the end of spreading. The total travel of the spreading assemblies was 200 to 300 centimeters which is equivalent to a 2 to 3 meter long build plate.

Spreader bases and powder feeders were removed and wiped with a dry towel to clean them between samples. The build plate was rotated for 200 cm at 50 millimeters per second to clean it for the next test. This required 33 seconds.

Repeat testing was performed on the Set A Virgin sample after the other tests. 120 cm^3 of sample was mixed and 40 $cm^3$was taken for each test. The tested sample was remixed into the larger portion for the next repeat.

Results and Discussion

The spread layer thicknesses used in this study were selected to match the effective layer thickness of the powder layers in a typical fusion powder bed AM printer. This effective layer thickness has been measured to be five to ten times the leveling height of the build platform [5,6]. For a typical twenty or thirty micrometer leveling height the effective layer thickness over the printed parts is 100 to 200 micrometers [5,6].

Spreadability at different spreader speeds

Table 1. Summary of the spreadability data for Set A samples with a flat spreading plate, a 150 µm spreader gap and multiple speeds

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Virgin 50 mm/s	49.3	3.95	206	8	0.8	3.07
Set A Virgin 100 mm/s	38.3	3.06	157	5	17.5	4.22
Set A Virgin 150 mm/s	31.4	2.51	129	9	6.2	5.16
Set A Virgin 200 mm/s	22.8	1.83	94	6	5.7	7.01
Set A Recycled 50 mm/s	49.8	3.99	208	11	-7.7	2.76
Set A Recycled 100 mm/s	42.3	3.39	178	10	-5.0	3.64
Set A Recycled 150 mm/s	33.3	2.66	141	10	-18.4	4.58
Set A Recycled 200 mm/s	31.9	2.71	217	11	-18.9	6.23

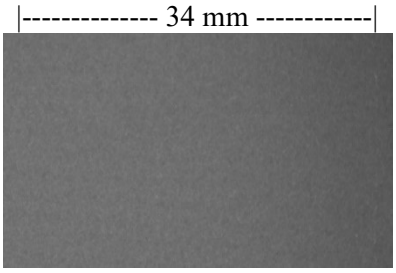
A summary of the spreadability data for Set A samples with a flat spreading plate, a spreading gap height of 150 micrometers and spreading speeds of 50, 100, 150 and 200 millimeters per second is given in Table 1. The data indicates that the spreading efficiency calculated from the spreading gap height drops with spreading speed for both the virgin and recycled material. The spread rate is also less uniform at faster spreading rates as evidenced by the increasing fractal dimension. Table 2 presents the measured layer thickness and measured layer density for the data set in Table 1.

Table 2. Summary of the measured layer thickness for Set A samples with a flat spreading plate, a 150 micrometer spreader gap at multiple speeds

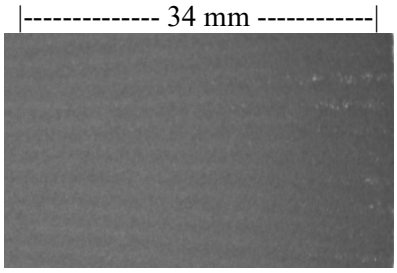
Sample	Measured layer thickness µm	Measured Layer Density g/cm^3	Measured Spread Efficiency %
Set A Virgin 50 mm/s	158	3.75	46.9
Set A Virgin 100 mm/s	117	3.92	48.9
Set A Virgin 150 mm/s	100	3.78	47.2
Set A Virgin 200 mm/s	72	3.82	47.8
Set A Recycled 50 mm/s	171	3.49	43.7
Set A Recycled 100 mm/s	135	3.77	47.1
Set A Recycled 150 mm/s	106	3.76	47.0
Set A Recycled 200 mm/s	88	3.68	45.9

The thickness of the spread layer decreases below the spreading gap height at speeds above 50 mm/s. This reduces the spreading efficiency calculated from the spreading gap height as the powder layer is no longer being spread at the gap height. However, the measured layer density remains relatively constant across all the spreading speeds. The powder layer that is spread has a consistent density with increasing speed even though the thickness of the layer is decreasing as the spreading speed increases. The implication of this is that these powders will spread uniformly at faster spreading speeds but the melt pool thickness will decrease with increased speed. The recycled material has slightly better spreadability under the tested conditions but its uniformity decreases with bed travel. This indicates that the recycled material is more affected by vertical pressure in the spreading zone compared with the virgin material.

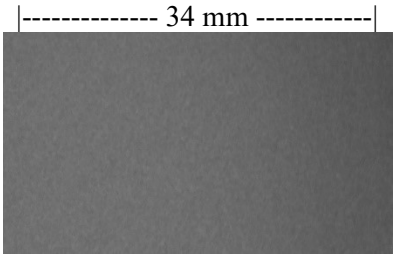
Images of the spread layer for the Set A data in Table 1 are presented in Figure 4. The images show that the powder layer becomes thinner and less uniform as the spreader speed increases. Thinner layers would affect all of the parts in a build run while uniformity issues would potentially affect only certain parts in the build.



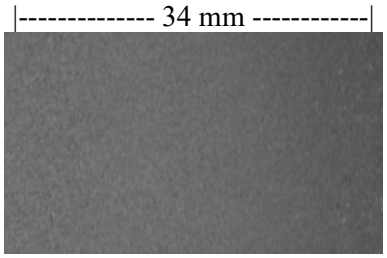
4.a: Set A Virgin 50 mm/s



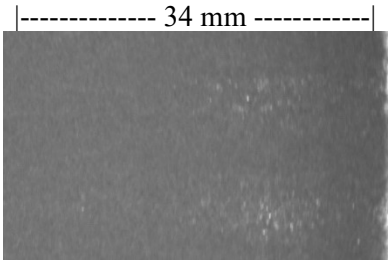
4.b: Set A Recycle 50 mm/s



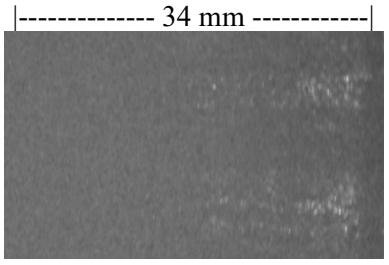
4.c: Set A Virgin 100 mm/s



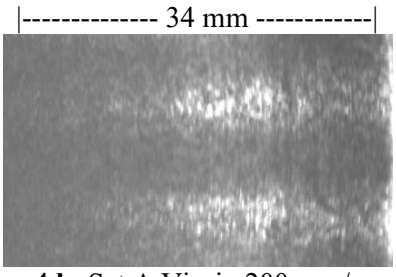
4.e: Set A Recycle 100 mm/s



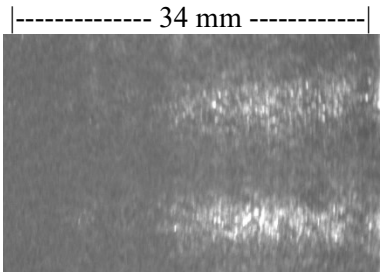
4.f: Set A Virgin 150 mm/s



4.g: Set A Recycle 150 mm/s



4.h: Set A Virgin 200 mm/s



4.i: Set A Recycle 200 mm/s

Figure 4. Images of Set A samples tested with a flat spreading plate, a 150 µm spreader gap and multiple speeds

Spreadability at different spreading gap heights

Table 3. Summary of the spreadability data for Set A samples with a flat spreading plate, spreading speed of 50 mm/s and multiple spreader gaps

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Virgin 50 µm gap	48.0	3.84	66	7	1.2	5.27
Set A Virgin 100 µm gap	48.2	3.86	134	10	6.1	3.02
Set A Virgin 150 µm gap	49.3	3.95	206	8	0.8	3.07
Set A Virgin 200 µm gap	52.9	4.24	297	10	1.7	2.80
Set A Recycled 50 µm gap	42.8	3.42	60	8	-16.3	5.63
Set A Recycled 100 µm gap	48.3	3.86	136	9	-8.4	2.75
Set A Recycled 150 µm gap	49.8	3.99	208	11	-7.7	2.76
Set A Recycled 200 µm gap	56.7	4.54	318	11	2.6	2.39

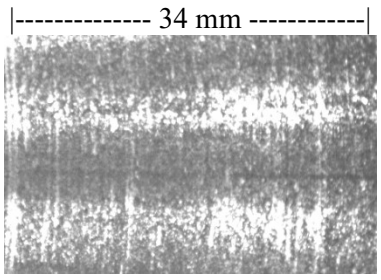
A summary of the spreadability data for Set A samples with a flat spreading plate, a spreading speed of 50 mm/s and spreading gap heights of 50, 100, 150 and 200 micrometers is given in Table 3. The data indicates that the spreading efficiency calculated from the spreading gap height increases with spreading gap height. The spread rate is also more uniform at larger spreading gap heights as evidenced by the decreasing fractal dimension. Table 4 presents the measured layer thickness and measured layer density for the data set in Table 3.

Table 4 Summary of the measured layer thickness for Set A samples with a flat spreading plate, a 50 mm/s spreader speed and multiple spreader gaps.

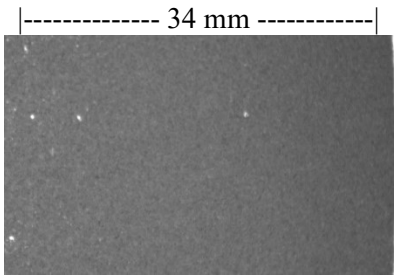
Sample	Measured layer thickness µm	Measured Layer Density g/cm^3	Measured Spread Efficiency %
Set A Virgin 50 gap	61	3.15	39.4
Set A Virgin 100 gap	112	3.49	43.1
Set A Virgin 150 gap	158	3.75	46.9
Set A Virgin 200 gap	202	4.19	52.3
Set A Recycled 50 gap	35*	*	*
Set A Recycled 100 gap	110	3.51	43.9
Set A Recycled 150 gap	171	3.49	43.7
Set A Recycled 200 gap	214	4.24	53.0

*sample too uneven to measure accurately

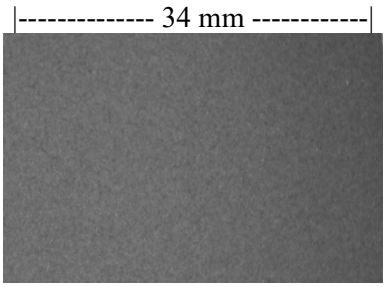
The thickness of the spread layer is at or slightly above the spreading gap height for all of the powders tested. The measured layer density increases with spreading gap height. The virgin material had better spreadability at the 50 micrometer spreading gap but the recycled material spread better at the larger gaps.



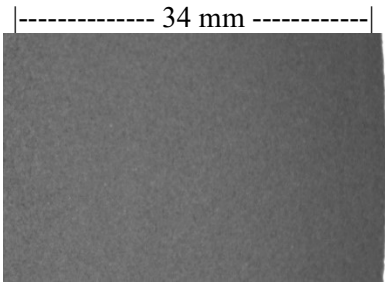
6.a: Set A Recycle 50 µm spreading gap



6.b: Set A Recycle 100 µm spreading gap



6.c: Set A Recycle 150 µm spreading gap



6.d: Set A Recycle 200 µm spreading gap

Figure 6. Images of Set A Recycle samples tested with a flat spreading plate, spreading speed of 50 mm/s and multiple spreader gaps

Images of the spread layer for the Set A Recycle data in Table 3 are presented in Figure 6. The images show that the powder layer becomes thicker and more uniform as the spreader gap increases.

Spreadability with a round spreading plate

Table 5. Summary of the spreadability data for Set A and Set B samples with a round spreading plate, a spreading gap of 150 µm and a spreader spreading speed of 50 mm/s

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Virgin As Is	52.5	4.20	207	13	7.2	2.63
Set A Recycled As Is	52.7	4.22	220	11	0.3	2.48
Set B Virgin As Is	44.0	3.52	184	11	1.8	3.25
Set B Recycled As Is	42.9	3.43	179	12	-0.7	3.49

A summary of the spreadability data for Set A and Set B samples with a round spreading plate, a spreading gap height of 150 micrometers and spreading speeds of 50 millimeters per second is given in Table 5. The round spreading plate showed an increase in spreading efficiency for the Set A samples but little change for the Set B samples compared with the flat spreading plate data in Table 11.

The layer thickness as presented in Table 6 was increased over the flat spreader heights for the Set A Virgin sample but not for the Set A Recycled sample. The layer thickness of the Set B samples was not measured for the flat spreader. Both spreading assemblies used the same powder feeder. The pressure from the weight of the powder in the feeder is applied directly to the spreading zone for the flat spreading plate whereas the pressure from the powder feeder is behind the spreading zone for the rounded spreading plate.

Table 6. Summary of the measured layer thicknesses for Set A and Set B samples with a round spreading plate, a spreading gap of 150 µm and a spreader spreading speed of 50 mm/s

Sample	Measured layer thickness µm	Measured Layer Density g/cm^3	Measured Spread Efficiency %
Set A Virgin As Is	177	3.56	44.4
Set A Recycled As Is	144	4.39	54.9
Set B Virgin As Is	144	3.67	45.9
Set B Recycled As Is	136	3.80	47.5

Spreadability of a printing and non-printing powder

A summary of the spreadability data for Set C samples with a flat spreading plate, a spreading gap height of 150 micrometers and spreading speeds of 50,100 and 150 millimeters per second is given in Table 7.

Table 7. Summary of the Spreadability data for Set C samples with a flat spreading plate, a 150 µm spreader gap and multiple speeds

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set C Virgin 50 mm/s	43.4	3.47	182	9	-1.8	3.16
Set C Virgin 100 mm/s	38.3	3.29	174	8	2.1	3.51
Set C Virgin 150 mm/s	29.4	2.52	134	9	-5.5	4.88
Set C Recycled 50 mm/s	28.6	2.45	130	10	3.6	5.00
Set C Recycled 100 mm/s	21.5	1.85	97	5	1.4	6.29
Set C Recycled 150 mm/s	15.2	1.30	69	6	-2.3	8.03

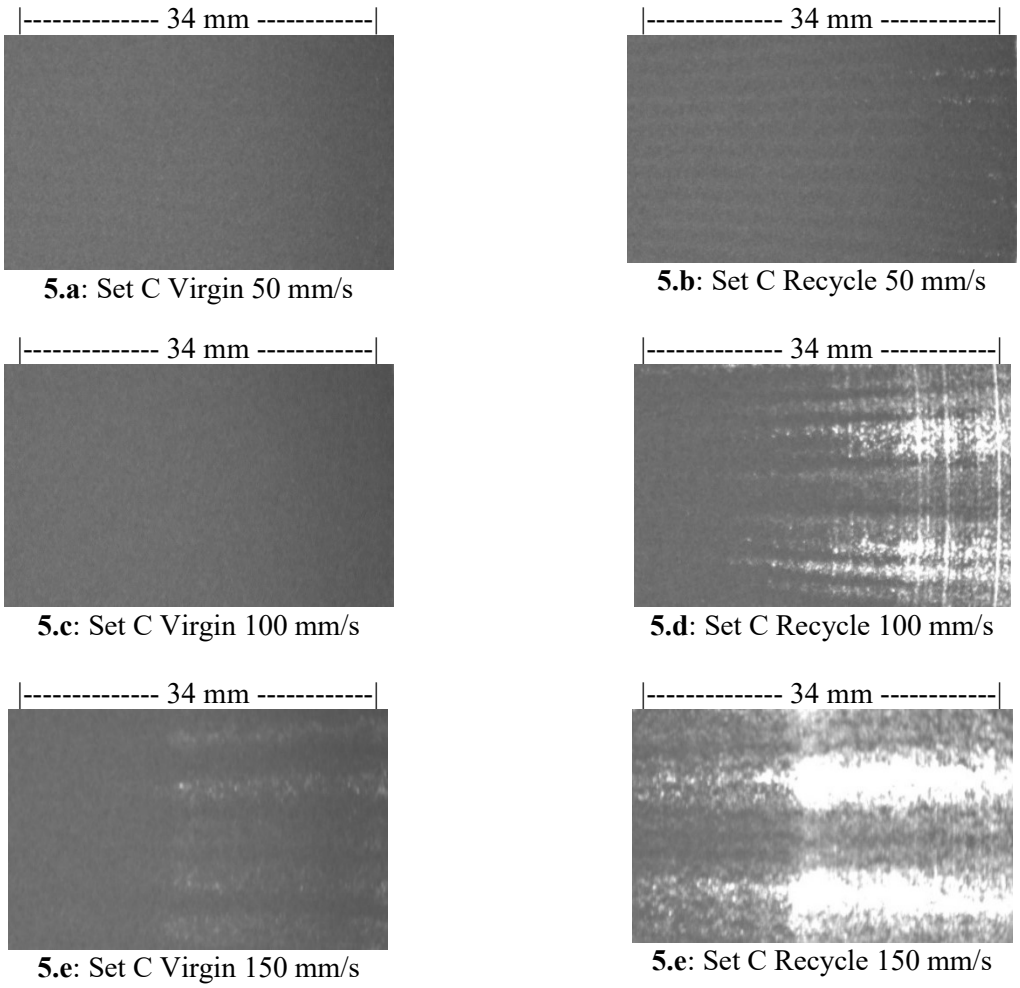
The data for the Set C samples shows speed sensitivity similar to the speed data for Set A and Set B samples. The difference between the sample sets is that the Set A and Set B samples were acceptable for their AM application. For the Set C samples the recycled material was unacceptable. The test data indicated a clear difference between the spreadability of the virgin and recycled material with the recycled material having roughly half the spreading efficiency and spreading rate of the virgin material.

Table 8 presents the measured layer thickness and measured layer density for the data set in Table 7. The thickness of the spread layer is below the spreading gap height for all of the powders tested. Even though the layer thickness is thinner the virgin powder shows an increase in density with spreader speed. This was not the case for the recycled material. Table 8. Summary of the measured layer thickness for Set C samples with a flat spreading plate, a 150 µm spreader gap and multiple speeds

Table 8. Summary of the measured layer height for Set C samples with a flat spreading plate, a 150 µm spreader gap and multiple speeds

Sample	Measured layer thickness µm	Measured Layer Density g/cm^3	Measured Spread Efficiency %
Set C Virgin 50 mm/s	132	3.94	45.9
Set C Virgin 100 mm/s	118	4.18	48.6
Set C Virgin 150 mm/s	86	4.43	51.5
Set C Recycled 50 mm/s	73	5.02	58.4
Set C Recycled 100 mm/s	72	3.87	45.0
Set C Recycled 150 mm/s	15	-	-

Images of the spread layer for the Set C data in Table 7 are presented in Figure 5. The images show that the powder layer becomes thinner and less uniform as the spreader speed increases.



5.a: Set C Virgin 50 mm/s

5.b: Set C Recycle 50 mm/s

5.c: Set C Virgin 100 mm/s

5.d: Set C Recycle 100 mm/s

5.e: Set C Virgin 150 mm/s

5.e: Set C Recycle 150 mm/s

Figure 5. Images of Set C samples tested with a flat spreading plate, a 150 µm spreader gap and multiple speeds

Spreadability with increased pressure on the test powder

A summary of the spreadability data for Set C samples with a flat spreading plate, a spreading gap height of 150 micrometers, a spreading speed of 50 millimeters per second spreading layer pressures of 1.1 kPa, 1.8 kPa and 2.5 kPa is given in Table 9.

Table 9. Summary of the Spreadability data for Set C samples with a 150 µm spreader gap, spreader speed of 50 mm/s and multiple bed pressures.

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set C Virgin 0.0 kPa	43.4	3.47	182	9	-1.8	3.16
Set C Virgin 1.1 kPa	35.1	3.01	159	10	-6.4	3.86
Set C Virgin 1.8 kPa	32.4	2.78	158	10	-2.4	4.25
Set C Virgin 2.5 kPa	36.2	3.11	165	9	-0.9	3.66
Set C Recycled 0.0 kPa	28.6	2.45	130	10	3.6	5.00
Set C Recycled 1.1 kPa	25.7	2.20	117	12	6.4	5.67
Set C Recycled 1.8 kPa	31.7	2.72	144	12	3.3	4.57
Set C Recycled 2.5 kPa	29.6	2.54	134	14	20.9	6.45

The spreading pressure reduced the spreadability of the virgin sample but increases the spreadability of the recycled sample. The virgin material showed an initial decrease and then a increase in spreadability with pressure. The recycled material showed an initial decrease and then an increase.

Table 10. Summary of the measured layer thickness for Set C samples with a with a 150 µm spreader gap, spreader speed of 50mm/s and multiple bed pressures.

Sample	Measured layer thickness µm	Measured Layer Density g/cm^3	Measured Spread Efficiency %
Set C Virgin 0.0 kPa	132	3.94	45.9
Set C Virgin 1.1 kPa	138	3.28	38.2
Set C Virgin 1.8 kPa	129	3.24	37.7
Set C Virgin 2.5 kPa	140	3.33	38.8
Set C Recycled 0.0 kPa	73	5.02	58.4
Set C Recycled 1.1 kPa	98	3.38	39.4
Set C Recycled 1.8 kPa	130	3.14	36.6
Set C Recycled 2.5 kPa	135	2.82	32.8

Table 10 presents the measured layer thickness and measured layer density for the data set in Table 9. The pressure did not affect the layer thickness for the virgin samples compare with the low pressure feeder.

However the recycled material shows a significant increase in the layer thickness with pressure compared with the low pressure feeder. The recycled material also shows an increase in layer thickness from 1.1 kPa to 1.8 kPa pressure.

Spreadability changes with humidity exposure and drying

The sensitivity of the spreadability of the Set A and B samples to humidity and segregation was tested in addition to testing the as received samples. Samples were tested with a flat spreading plate, a spreading gap of 150 micrometers and a spreading speed of 50 millimeters per second. A summary of the spreadability of the humidity exposed and dried samples is presented in Table 11.

Table 11. Summary of the as is, humidity exposed and dried spreadability data for Set A and Set B sample tested with a flat spreading plate, a spreading gap of 150 µm and a spreading rate of 50 mm/s.

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Virgin As Is	47.0	3.76	197	7	-0.2	2.8
Set A Virgin Humid	48.0	3.83	200	16	13.9	3.27
Set A Virgin Dried	42.1	3.37	177	8	-0.3	3.25
Set A Recycled As Is	51.1	4.09	213	21	14.3	2.67
Set A Recycled Humid	40.4	3.23	170	10	-11.5	3.55
Set A Recycled Dried	45.4	3.63	191	11	-7.4	3.16
Set B Virgin As Is	43.9	3.51	182	15	4.9	3.06
Set B Virgin Humid	5.8	0.46	27	21	-89.7	11
Set B Virgin Dried	23.1	1.84	99	25	-61	6.76
Set B Virgin Dried after 5h	35.5	2.84	147	17	-24.5	4.52
Set B Virgin Dried after 16h	38.1	3.05	163	32	-46.9	3.80
Set B Recycled As Is	49.3	3.94	207	14	9.0	3.38
Set B Recycled Humid	36.2	2.89	152	8	-8.5	4.43
Set B Recycled Dried	42.0	3.36	177	12	-8.6	3.12

Sample Set A Virgin had little sensitivity to humidity exposure while the other samples displayed a worsening spreadability. Sample Set B Virgin stopped spreading with humidity exposure. The spreading gap was increased to 200 micrometers and the sample started spreading again as shown in Table 12.

Table 12. Summary of the Sample Set B Virgin Humidity Exposed Spreadability data

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set B Virgin As Is 150 Gap	43.9	3.51	182	15	4.9	3.06
Set B Virgin Humid 150 Gap	5.8	0.46	27	21	-89.7	11.0
Set B Virgin Humid 200 Gap	54.1%	4.329	301	32	-8.8	2.60

After drying most of the samples improved their spreadability but not to the levels of the as is samples. Sample Set B Virgin stopped spreading immediately after drying then had poor spreadability after a second test. The tested powder was then sealed in a container and tested again after 5 hours and then again after 16 hours and the spreadability improved a great deal. This change in spreadability appeared to be due to static charge build-up on the sample powder. This could have been the result of powder flow testing that was performed on all of the samples prior to spreadability testing. This could explain why all of the dried samples had poorer spreadability than the as is samples. Presumably the As Is samples would have contained more moisture than the dried samples which could have helped to mitigate static charge build up after flow testing.

Table 13. Ranking Spreadability of As Is samples

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Recycled As Is	51.1	4.09	213	21	14.3	2.67
Set B Recycled As Is	49.3	3.94	207	14	9.0	3.38
Set A Virgin As Is	47.0	3.76	197	7	-0.2	2.8
Set B Virgin As Is	43.9	3.51	182	15	4.9	3.06

Table 14. Ranking Spreadability of humidity exposed samples

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Virgin Humid	48.0	3.83	200	16	13.9	3.27
Set A Recycled Humid	40.4	3.23	170	10	-11.5	3.55
Set B Recycled Humid	36.2	2.89	152	8	-8.5	4.43
Set B Virgin Humid	5.8	0.46	27	21	-89.7	11

Table 15. Ranking Spreadability of dried samples

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Recycled Dried	45.4	3.63	191	11	-7.4	3.16
Set A Virgin Dried	42.1	3.37	177	8	-0.3	3.25
Set B Recycled Dried	42.0	3.36	177	12	-8.6	3.12
Set B Virgin Dried	23.1	1.84	99	25	-61	6.76

Tables 13, 14 and 15 present the ranking of the spreadability of the as is, humidity exposed and dried Set A and Set B samples. The ranking of the powders changed with the condition of the powders indicating that the sensitivities of the virgin and used powders to humidity and drying changed with use in the application or recycling process.

Spreadability changes with segregation

Figure 6. Image of the segregation pan top surface for Set B Recycle after sifting. Larger particles can be seen on the top surface.

Set A and Set B samples were subjected to segregation pressure by flowing them through multiple core flow funnels and by pan sifting. A summary of the funnel segregation data is given in Table 16 and the pan segregation data is given in Table 17. Set B Virgin and Set A Recycled showed lower spreadability after the funnel flow while Set A Virgin and Set B Recycled showed a small improvement. For the pan segregation test, Set A Virgin showed a small reduction in spreadability in the bottom sample whereas the other samples showed a large improvement in the bottom pan. In pan segregation larger particles move to the top of the pan as illustrated in Figure 6.

The data are interesting because the spreadability improved for the sample cuts with smaller particles. It appears that the larger particles created jamming in the spreading gap that reduce the spreadability. In general, the spreadability of Set A Virgin was the least sensitive to segregation stress. Segregation potential is controlled mainly by the width of the particle size distribution and the flowability of the material.

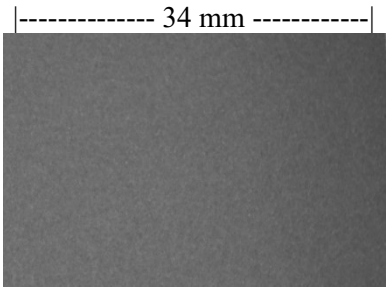
Table 16. Summary of the spreadability data for funnel segregated Set A and Set B tested with a flat spreading plate, a spreading gap of 150 μm and a spreading rate of 50 mm/s

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Set A Virgin As Is	47.0	3.76	197	7	-0.2	2.8
Set A Virgin Funnel	50.7	4.06	212	14	8.7	2.97
change	3.7	0.3	15	7	8.9	0.17
Set A Recycled As Is	51.1	4.09	213	21	14.3	2.67
Set A Recycled Funnel	44.5	3.56	187	7	-1.5	2.95
change	-6.6	-1.34	-26	-14	-15.8	0.28
Set B Virgin As Is	43.9	3.51	182	15	4.9	3.06
Set B Virgin Funnel	35.2	2.82	148	40	2.0	8.27
change	-8.7	-0.69	-34	25	-2.9	5.21
Set B Recycled As Is	49.3	3.94	207	14	9.0	3.38
Set B Recycled Funnel	52.4	4.19	214	34	6.3	2.98
change	3.1	0.25	7	20	-2.7	-0.4

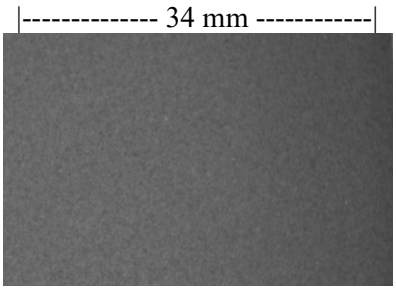
Table 17. Summary of the spreadability data for pan segregated Set A and Set B samples tested with a flat spreading plate, a spreading gap of 150 µm and a spreading rate of 50 mm/s

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif %	Fractal Dim.
Set A Virgin Seg Top	45.7	3.65	191	9	+7.7	3.26
Set A Virgin Seg Bottom	44.5	3.56	187	8	3.3	2.99
change	-1.2	-0.09	-4	-1	-4.4	-0.27
Set A Recycled Seg Top	38.1	3.05	159	19	-24.6	3.75
Set A Recycled Seg Bottom	53.7	4.30	224	11	-5.4	2.23
change	15.6	1.25	65	-8	19.2	-1.52
Set B Virgin Seg Top	27.4	2.19	119	22	-42.3	5.4
Set B Virgin Seg Bottom	34.3	2.75	148	33	-54.1	4.00
change	6.9	0.56	29	11	-11.8	-1.4
Set B Recycled Seg Top	35.0	2.80	144	18	-22.7	4.39
Set B Recycled Seg Bottom	41.4	3.32	174	11	3.1	3.56
change	6.4	0.52	30	-7	25.8	-0.83

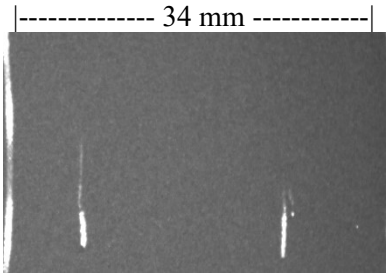
Images of the bottom and top pan segregated sample data for sample Set A in Table 17 are presented in Figure 7. The layer created with the top pan material for the recycled sample contains continuous channels in the bed surface.



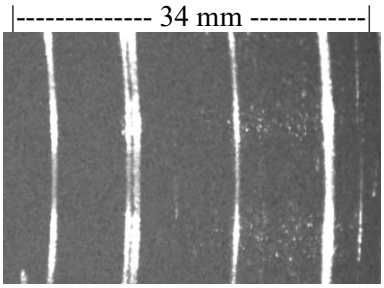
7.a: Set A Virgin pan bottom



7.b: Set A Recycle pan bottom



7.c: Set A Virgin pan top



7.d: Set A Recycle pan top

Figure 7. Images of Set A pan segregated samples tested with a flat spreading plate, a spreading gap of 150 µm and a spreading rate of 50 mm/s

Repeatability

The repeat testing data for sample Set A Virgin are presented in Table 18. Samples were tested using a flat spreader with a 150 micrometer spreading gap and a spreading speed of 50 mm/s. The measurement data was repeatable but showed a negative trend in spreadability as the sample was tested over and over again. This negative trend appeared to be caused by the test powder acquiring a static charge from handling during testing. To assess this hypothesis the sample testing was stopped for two hours to allow the sample to stabilize and then the powder was exposed to air from an anti-static blower with gentle mixing for 30 seconds. The samples was then tested two more times. This data is labeled DI in the table and are repeats 6 and 7. The spreadability returned to the original level in the first test. This demonstrates the sensitivity of the analyzer to small changes in a test sample and the high repeatability of the data when the sample is not changing. These data also demonstrate how easily static charge can be generated on a dry powder and how much it affects spreadability.

Table 18. Summary of the thickness for repeat the measurements for Set A Virgin samples with a flat spreading plate, a 150 micrometer spreader gap and a 50 mm/s speed

Sample	Spread Eff. %	Layer Density g/cm^3	Spread Rate mg/cm	Spread Rate SD mg/cm	Spread Unif. %	Fractal Dim.
Repeat 1	50.4	4.03	209	13	8.0	2.83
Repeat 2	50.0	4.01	206	16	12.2	2.67
Repeat 3	49.4	3.95	206	15	12.8	2.65
Repeat 4	49.7	3.97	206	15	12.2	2.83
Repeat 5	48.5	3.88	201	15	14.3	2.93
Repeat 6 DI	50.9	4.07	210	16	12.2	2.81
Repeat 7 DI	49.8	3.98	207	16	14.4	2.84

Table 19. Summary of the thickness for repeat the measurements for Set A Virgin samples with a flat spreading plate, a 150 micrometer spreader gap and a 50 mm/s speed

Sample	Measured layer thickness µm	Measured Layer Density g/cm^3	Measured Spread Efficiency %
Repeat 1	161	3.76	46.9
Repeat 2	160	3.75	46.9
Repeat 3	159	3.73	46.6
Repeat 4	162	3.68	46.0
Repeat 5	161	3.60	45.0
Repeat 6 DI	160	3.80	47.5
Repeat 7 DI	161	3.73	46.6

Table 19 presents the measured layer thickness and measured layer density for the data set in Table 18. The thickness data are repeatable but do not show a trend with charging. The measured spreading efficiency does have the same trend as the spreading efficiency based on the spreading gap. This indicates that static charge reduces the density of the spread layer but not the thickness of the layer for this sample.

The repeat data illustrates an important point about powder testing. The powder test can change the powder. In this case the powder acquired a static charge. In other cases the powder particles can break into smaller particles, can agglomerate into larger particles, can segregate, etc. The best way to avoid these issues is to test a sample once and then get a fresh sample. This can also be problematic if the sample is not well mixed. Samples can also be taken and added back into a larger sample portion. That was done in this case but the larger portion was not large enough to absorb the static changes.

The repeat data (and the other data collected) also illustrates an important point about powders in an AM printer. Handling and using a powder in an AM printer can change the powder. This change can be transient or permanent. In this case spreading the powder in the analyzer caused the powder to acquire a static charge that affected its spreadability. From experience it is known that the static charge would reach a point were the powder no longer spread at all. This is a transient issue as the static charge would eventually dissipate. Production engineers often complain about their printers suddenly having problems. The repeat data gives an example of how this can happen.

Summary and Conclusions

The spreadability of several AM powders was tested at different spreading speeds, with different spreading gaps and with different powder feeding systems using the SpreadStation Powder Analyzer. The data showed that the spreadability as measured by the instrument changed with spreading variables and that some materials were more sensitive to spreading variables than others. In addition, using and recycling the powders changed their spreadability and their sensitivity to spreading variables. The conditions of the samples were changed with humidity exposure, drying and segregation stress and the samples were tested again. The analyzer data show that spreadability of the samples also changed with the condition of the sample powder.

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