



EXAMENSARBETE INOM TEKNIK,
GRUNDNIVÅ, 15 HP
STOCKHOLM, SVERIGE 2020

Image based analysis on powder spreadability in powder bed additive manufacturing

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Abstract

Additive manufacturing is an increasingly popular industry that has gained significant traction in the last decade. Today there exists no way to predict how a powder will spread in a powder bed additive manufacturing machine or how well it will form into thin layers. This is important because major costs can be saved by using a test that predicts the spreading behaviour of powder. This ability to be spread will be given the name *spreadability*.

To test the spreadability of powder, a machine that mimicked the pushing of the powder in powder bed additive manufacturing was used. Since there exist no metric for spreadability, the study decided to attempt to quantify the spreadability with the help of image analysis. In the image analysis the area of the powders was measured, and through a comparison of the area against a bounding geometry, a measurement for spreadability can theoretically be attained. To further validate the results and simultaneously search for possible correlations, the experimental data was compared against flowability data obtained from angle of repose and Hall flowmeter.

The results showed that the method of choice worked well for measuring the area and gave data that could be used to interpret spreadability. The data also showed what seems to be a correlation with the flowability data. While no definitive conclusions could be drawn due to a small sample size, the collected data does seem promising for future work.

Sammanfattning

Additiv tillverkning är en alltmer populär industri som har fått stor uppmärksamhet under det senaste decenniet. Idag så finns det inga sätt som man kan förutse hur ett pulver kommer att bredas ut i en pulverbädd additiv tillverkningsmaskin eller hur bra den är på att bilda tunna lager. Detta är en viktig kunskap att förstå då stora kostnader kan sparas in genom att använda ett test som förutser utbredningsförmågan av pulver. Denna förmåga får namnet *spridbarhet*.

För att kunna testa spridbarheten hos pulver, används en maskin som härmar puttandet av pulver i en pulverbädd additiv tillverkningsmaskin. Eftersom det inte finns någon metod att mäta spridbarhet med, så valde denna studie att försöka kvantifiera spridbarheten via en bildanalys. Med denna bildanalys kunde arean av pulver mätas och genom att jämföra denna mot en avgränsande geometri kan mätdata för spridbarheten teoretiskt fås fram. För att kunna validera resultatet, och samtidigt se om det finns en korrelation, jämfördes det med flytbarhetsdata från rasvinkelmätare och Hall flödesmätare.

Resultaten visade att metoden klarade av att mäta arean, och gav resultat som kan användas för att tolka spridbarhet. Den data som framtogs visade också att det möjligtvis kan finnas en korrelation mellan spridbarhet och flytbarhet. Även om något klart svar inte kan ges på grund av en liten provstorlek, så verkar resultaten vara lovande för framtida arbeten.

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1. Introduction

1.1 Background

Additive manufacturing (AM) is a subject that is becoming increasingly popular. In part, this is because AM produces near-net-shape components, and that it can use materials that are difficult to machine [1]. This makes AM useful for highly specialised industries and start-ups [2].

The most common metal AM process used is the powder bed technique, in which a powder is spread to a thin layer on a build platform and a heat source, most commonly either a laser or an electron beam, selectively melts regions of the layer in a specified pattern. This allows powder particles to collect in the melt pool and solidify as a solid mass to form a dense region. This process is then repeated until the product has been built [3]. The quality of the final product largely depends on the layer being a constant thickness, having a constant particle size distribution and not having any gaps. These factors dictate how well the powder particles will be packed together and how precisely the component geometry can be achieved [4]. A good understanding for how a metal powders are able to be spread is therefore very important for this subject.

To reduce the amount of effort needed to develop a new powder for powder bed AM, a test is required to predict how well the new powder will form thin layers. This property is given the name *spreadability*. Ideally, any test would use conditions that are representative of the additive manufacturing process. This will avoid the need for a powder to be tested with a full-scale printing trial, which is very expensive. It will, therefore, be easier to develop new powders for AM and enable the application of such manufacturing techniques to many new alloys and industries. The benefits of AM can, therefore, be realised as quickly and widely as possible.

Today there exists no metric to quantify the propensity of a powder to be spread into thin layers. This also means that there is no accepted way for how to test and measure it. Clearly, both shortcomings must be overcome to result in a reliable and practicable test. A lack of a single metric for spread behaviour makes it more difficult to correlate the spreadability with other powder characteristics, such as flow properties, that are already in use. Therefore, it is useful to know if any of the already existing measuring techniques can be used instead of a specialised test for spreadability.

1.2 Goals

The goal of this study is to see if a method of image analysis can be derived and is capable of measuring the spreading capabilities of powder. To achieve this, the method needs to be both repeatable and reproducible, so that it can be standardised. This will be done using ImageJ, an open source and freely available image analysis program, to analyse images taken during an experimental procedure that is meant to simulate how the powder is spread during an actual AM process. The study will also see if any of the standard flowability methods in use today correlate to the chosen spreadability method.

1.3 Scope

Because there are several different AM techniques, all which work in different ways, each would require their own case studies in order to find a different test method to represent how the powder is being used in their processes. Due to time restrictions, this study will focus solely on the techniques and materials with the greatest current industrial relevance: powder bed AM and steel powders.

1.4 Ethical and Environmental impacts

One of the largest problems today for many of today's heavy industries is how to reduce their environmental impact. AM solves many of these problems through that it is flexible and the components it can produce can be near-net-shaped. This reduces both the material and energy usage when making products using AM, compared to traditional subtractive methods [5].

AM can also be used to make more efficient structures. It can, for example, integrate cooling canals into tools and machinery. It can also be used to make parts lighter by optimizing the structural design [6]-[7]. This makes AM a very attractive technology for many lightweight products. An example of an industry that heavily benefits from this aspect of AM is the aviation industry. The design freedom offered by AM makes it possible to combine multiple parts and components into a singular part. This aspect of AM has been taken advantage of by leading aircraft companies such as Boeing and GE to reduce not only the weight of certain parts but also the time needed to make them [8].

The additive manufacturing this thesis is evaluating is a new industry which can help with ethical and social questions regarding issues within society, such as poverty. AM makes it easier to move complicated assemblies further downstream, which means that both industrial and life-essential products can be manufactured on demand in poorer areas. Because AM can potentially be an easy way of improving and creating infrastructure, it can lead to an increase of education and manufacturing in rural areas, which in turn could lead to a reduction in poverty [9].

2. Theory behind method

2.1 Common methods of additive manufacturing

There exist four commercially viable metal-based additive manufacturing methods today. These are Powder Bed, Directed Energy Deposition, Sheet Lamination and Binder Jetting. Directed Energy Deposition is analogous to inkjet printing: the metal is deposited only where it is needed and is then melted near the nozzle, on top of material that has been deposited in previous passes. In sheet lamination, sheets of metal are stacked and bound together. Each new layer is then machined to provide an additional layer to the component. In Binder Jetting, powder is deposited onto a build plate by a blade or roller and a binding agent is then used to glue the particles together. This is repeated until a model is complete, where the model is then put into an oven where the binding substrate melts away. The remaining metal powder is able to hold its shape and is then sintered to remove porosity. Powder bed techniques are similar to binder jetting, except that the binder agent is replaced by a heat source that melts the powder and fixes it into place [3].

2.2 Powder bed additive manufacturing

In powder bed additive manufacturing processes, powder is transferred onto a build plate to form a rectangular region of powder (the powder bed) using a blade or roller to form a thin layer 20-100 micrometres thick (figure 1). A laser or electron beam is used to melt powder in a desired pattern. This is then repeated until the model is complete. All the powder that was not melted or that was not needed can be recovered after the manufacturing process is complete and used again, which makes the method material efficient [10].

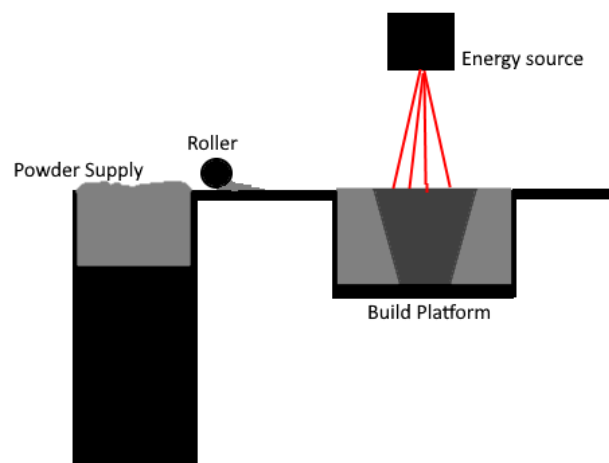


Figure 1: Schematic illustration of a powder bed method.

2.3 Image Analysis

Spreadability is simply the ability for a medium to be spread easily. However, this can be measured in numerous ways. For instance, if a powder has good spreadability, it will be easier to spread it over a large area. If the powder has poor spreadability, then it will show difficulties being spread. But there are more factors to consider in a powder bed, one of the most important parameter for a good quality of the powder bed is an evenly spread powder, as an uneven spread can lead to defects such as an increased porosity and an uneven heat gradient across the powder bed [4]. Thus, a powder that spreads over a larger area can still be considered to have a poor spreadability if it spreads unevenly. Based on this, it is more intuitive to try and base the spreadability on the appearance of the powder layer, as this could be a way to gauge how evenly it spreads.

There are numerous ways to interpret the spreadability based on powder bed's appearance. One idea is to try and categorize the different shapes that the powder forms. This of course requires manual inspection, which will be time consuming if a large quantity of images is analysed. Another way would be to compare the area of the powder against a bounding geometry. Then the powder with worse spreadability would fill less of this bounding geometry because of its tendency to form small clusters that stick out from the main body. This method also has the benefits of potentially being fully automated, which would shorten analysing time and reduce intake of external bias and is therefore chosen as the primary way to gauge the spreadability.

2.4 ImageJ

ImageJ [11]-[12] is an image analysis program written in Java and distributed free of charge. It allows for various manipulation of images, macro recordings and external plugins. ImageJ was chosen for two reasons: firstly, it is easy to use and does not need sophisticated hardware and secondly, it is open source. This means that there is no licensing needed to use the program and that other people can improve upon the original software and code written for it. It is also legal to use the program for commercial projects, which means any industry can use any output from this project legally.

There exists other software that can also provide an image analysis. One popular choice is MATLAB, which is a software designed specifically to solve mathematical problems using its unique scripting language designed for easy manipulations of matrices and functions. MATLAB has various plugins and toolboxes designed for image processing, such as its Image Processing toolbox. The main reason for not using MATLAB is because it requires a license to be used commercially or privately.

2.5 Other powder testing methods

There exist other methods that are used to quantify powder characteristics. These tests are designed to test the flow of powders rather than how they behave when spread. However, both powder spreading and flow require particles to move past each other and so it is possible that flow and spreadability are correlated. Therefore, flow tests could potentially be used instead of a new spreadability test.

2.5.1 Flowmeter

There are several different flow meters versions: Hall (figure 2), Gustavsson and Carney being the three most common. The principle behind them are all the same, a fixed mass of powder is poured through a funnel and the time it takes to flow through is measured. A shorter time means that the powder flows better. The difference between the three flowmeters is the size of their orifice and the steepness of the funnel. Carney has a larger orifice, which allows for more powder types to flow through, although it is only used if the powder is unable to flow through the regular Hall flowmeter. Gustavsson is designed with a cone angle of 30° compared to Hall and Carney, which have a cone angle of 60° . This design is meant to help powder that is mixed with additional additives to flow better, as they tend to get stuck on the steeper angle [13].



Figure 2: An example of a Hall flowmeter apparatus.

Today there are no well-founded evidence to show that any correlation between this flow time and spreadability exists [14], which is unfortunate because it is one of the more well known, straightforward methods that is widely used in industries.

2.5.2 Angle of Repose

The angle of repose is defined as the steepest angle a material can form a pile without being subjugated to flow. This angle indicates the level of cohesive behaviour within the powder, such as friction and binding force. There are different ways to measure this angle, but the one this study will utilize is a device similar to a flowmeter, where the powder is being poured through a funnel and onto a flat surface, where it forms a pile. The angle of repose is defined as the angle between the flat horizontal surface and the slope of the pile (figure 3) [15]. While an assumption that the interparticle forces plays a role in how a powder is spread can be made, there exists no data to suggests that a powder's angle of repose is correlated to its spreadability.

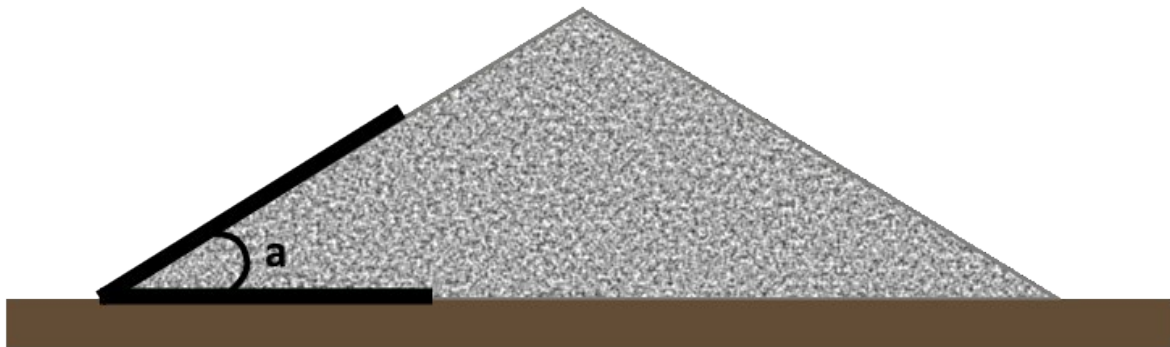


Figure 3: Illustration on how angle of repose is measured.

3. Method and experiments

3.1 Experimental equipment

The experiments were made using a TQC Sheen AB4120 film applicator (figure 4), which is primarily used for testing the coverage performance of paint. To make it relevant to AM, the glass plate that was supplied with the machine was covered with silicon carbide grinding paper ("sandpaper") with a roughness of P120, which is equivalent to surface features approximately 70 μm high. The reason for this was to try and mimic the rough surface of a powder bed, which will have features of a similar size.

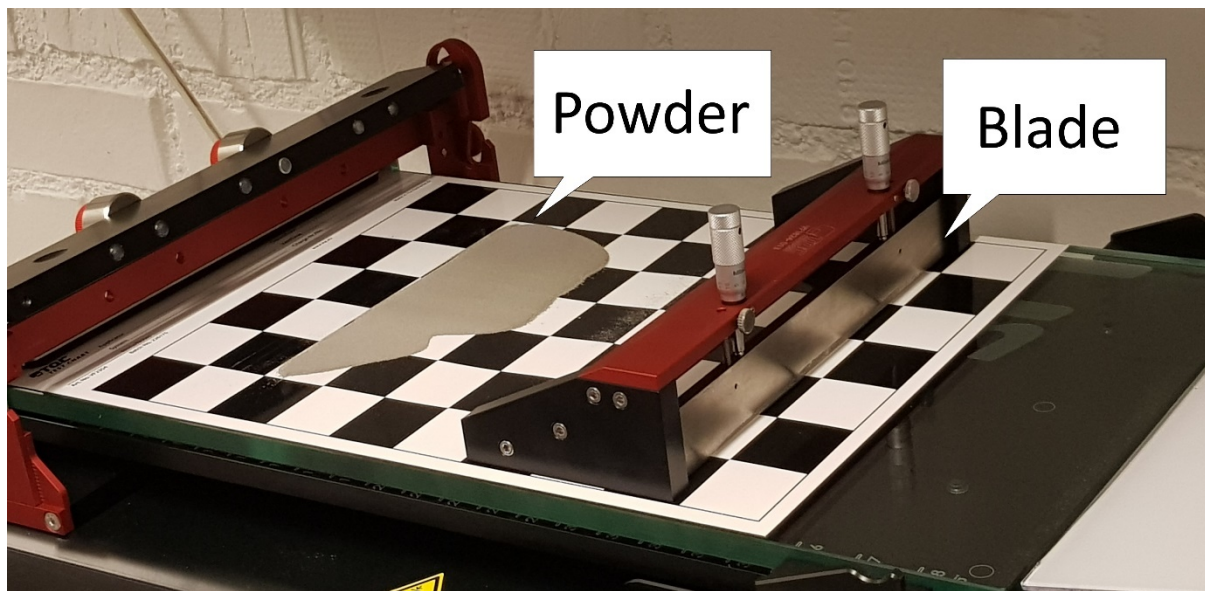


Figure 4: Photograph of TQC Sheen film applicator. For the tests in this study, the region that has a checkerboard on it was covered with sandpaper to emulate the roughness of a powder bed.

3.2 Test procedure

The TQC Sheen device must be changed to fit the needs of powder spreadability testing. Which material that is tested and what surface it is tested on are important considerations to make. Machine settings also needs to be accounted for. The speed at which the blade moves (the *recoater speed*) and the height of the blade above the test plate must be considered, as these could have a significant effect on the powder.

The tests were done using three samples of powder. Powder 1 is of a different composition compared to powder 2 and 3, which both are of the same material. Powder 1 has a particle size of 20 μm , powder 2 has a particle size of 22 μm and powder 3 has particle sizes ranging between 20 to 53 μm . A fixed mass of 10 grams was used during the experiment and the powders samples were each weighted before being laid onto the plate. This was done to ensure that a similar starting condition for each powder was achieved, as this will help improve the repeatability of the test. To make the data comparable, the three powders was assumed to have the same density. The variance of the powder area can then be attributed by the thickness of the powder layer and not some variance in volume across the three samples.

After the powder had been laid, the blade is fixed at the desired height and the speed of the blade is set. In this test, different blade speeds up to 200 mm/s were tested on the powder samples. The blade then spreads the powder. After the spreading is done a photo is taken of the powder, so that the results can be analysed. The photo is taken directly above the powder as this gives the largest amount of visible area to analyse and minimises distortions and parallax.

3.3 Image analysis procedure

Image analysis in ImageJ can be performed using a macro, which executes a set of processing steps automatically. Processing can also be done on a batch of images in one procedure. With these two factors combined, the entire analysis procedure should be able to be fully automated. The image analysis is done utilizing various tools from ImageJ and can be broken down into the following steps:

The first step is to limit the size of the picture by cropping unnecessary parts. This step is vital as it streamlines the rest of the process. This step is vital as it minimises the computational expense of the rest of the process. It also drastically reduces the intake of unnecessary information that will affect the other steps. The cropping should be done around the region of the powder (figure 5).

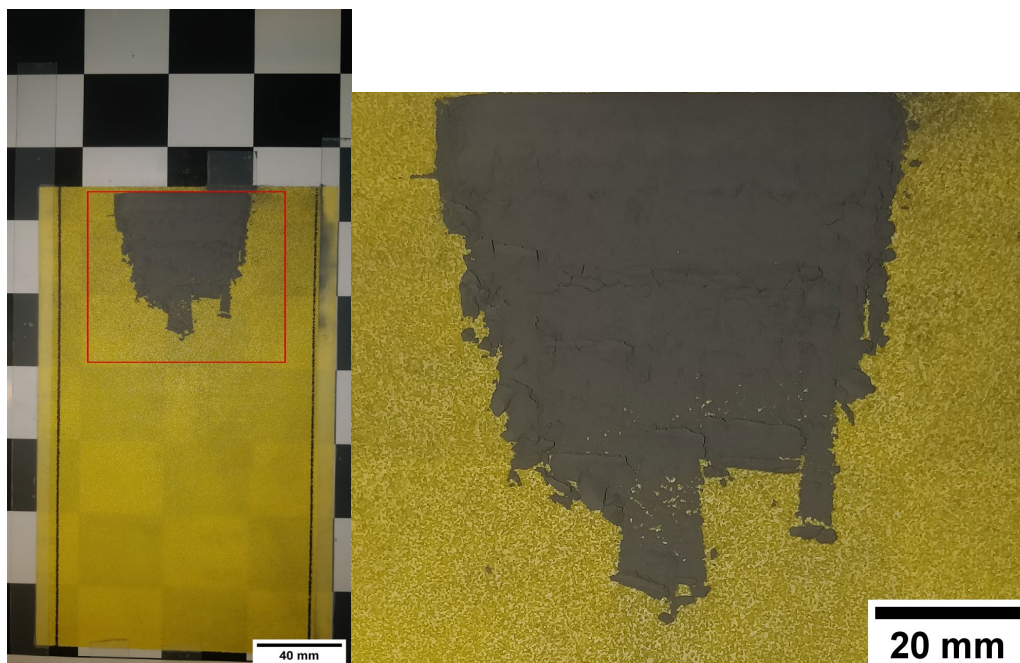


Figure 5: Example on how to crop the image, the red box represents the selection made in ImageJ.

Cropping can be automated using the region of interest (ROI) manager in ImageJ, which controls all the selections made in an image. With the ROI manager, a selection which to crop the image after can be decided upon and then this selection can be used on all the other images. This of course requires all pictures to be taken from the same position and angle, so that the locations in the image stays the same. This can easily be achieved by using a tripod or similar equipment to lock the camera in one position before the experiment begins.

After the image has been cropped, a method called *thresholding* can be applied to the image. A threshold can be defined as segmenting an image into a foreground and background [16], where each pixel is classified as either type based on whether a property of the pixel is below or above an applied limit. A property can be the pixel's colour, hue, saturation, intensity etc. The purpose of a threshold is to aid with the image analysis, as certain areas of interest cannot be properly analysed without one.

The threshold can be applied in ImageJ using its in-built automatic threshold plugin, which will try to find the best upper and lower threshold levels for an image (figure 6). A problem with this plugin is that it is not always capable of producing an accurate enough threshold for an image. This problem occurs when there is not a good enough contrast between the foreground (in this case the powder) and the background.

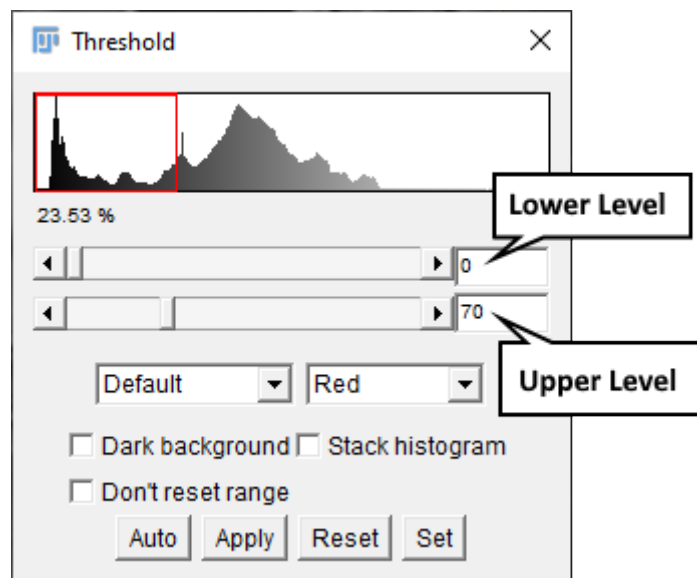


Figure 6: Popup window for manual binary threshold. The “default” in the centre left box refers to which algorithm the threshold will be applied with, while the “red” is the colour of the threshold.

A solution to this problem is to manipulate the colour of the image. ImageJ displays colours using the RGB colour model where each pixel within an image is given a red, green and blue value. These colours can be separated using the *Split Channel* plugin, which will create three new single colour images based on the original image's colour intensity (figure 7). The intensity of the colour represents the amount of it being found within the original image, a high intensity signifies a large amount of colour in that region while a low intensity signifies a low amount colour.

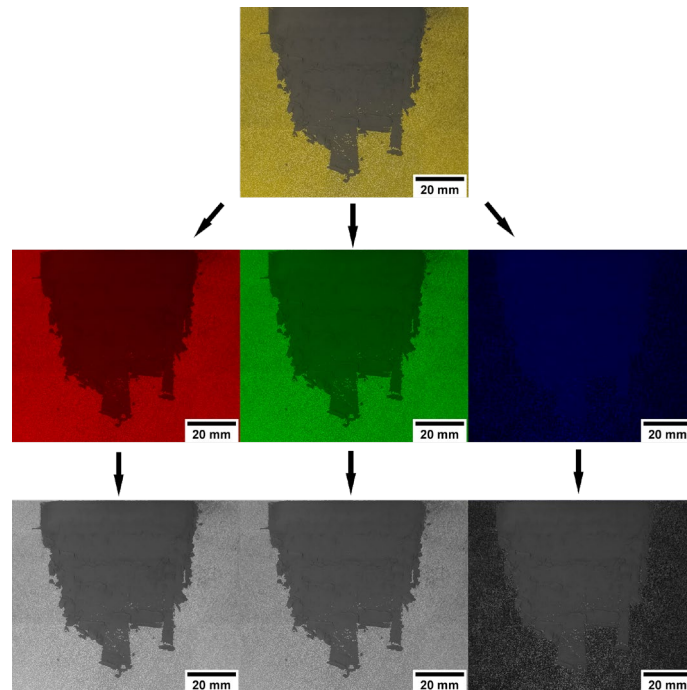


Figure 7: Example of splitting an image into three colour channels. The middle row is a visualization on how the colour intensity of the respective colour is being mapped. The bottom row is the greyscale of the respective values.

The reasoning behind splitting the image like this is to be able to utilize another plugin from ImageJ, called *Image Calculator*, to subtract the intensity of one colour with the intensity of another. Using figure 7 as an example, the colour of the powder is grey, meaning the red, green and blue values will all be around the same value. This can be observed in the image, as the intensity around the powder is very similar across all the images. Meanwhile, yellow is made using red and green colours, meaning they will be found in a larger quantity compared to the blue. This can be observed in the image, as the red and green images are bright around the yellow region, while the blue is dark.

By subtracting the intensity of the blue image from either the red or green image, an image with a dark powder region will be created, while the background will stay relatively bright (figure 8). This image has a clear contrast between the powder and the background and is thus easy to apply a clean threshold on (figure 9).

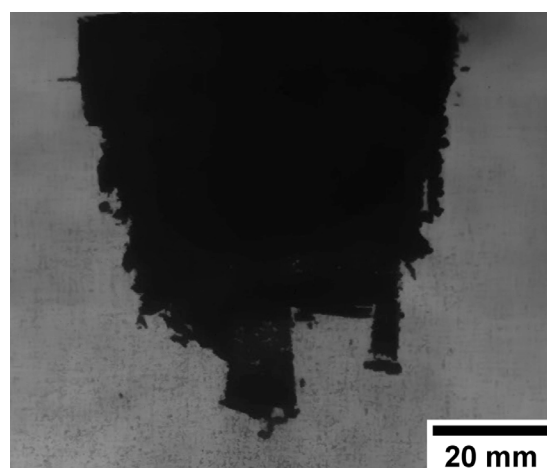


Figure 8: Result from subtracting the blue colour channel from the red one.

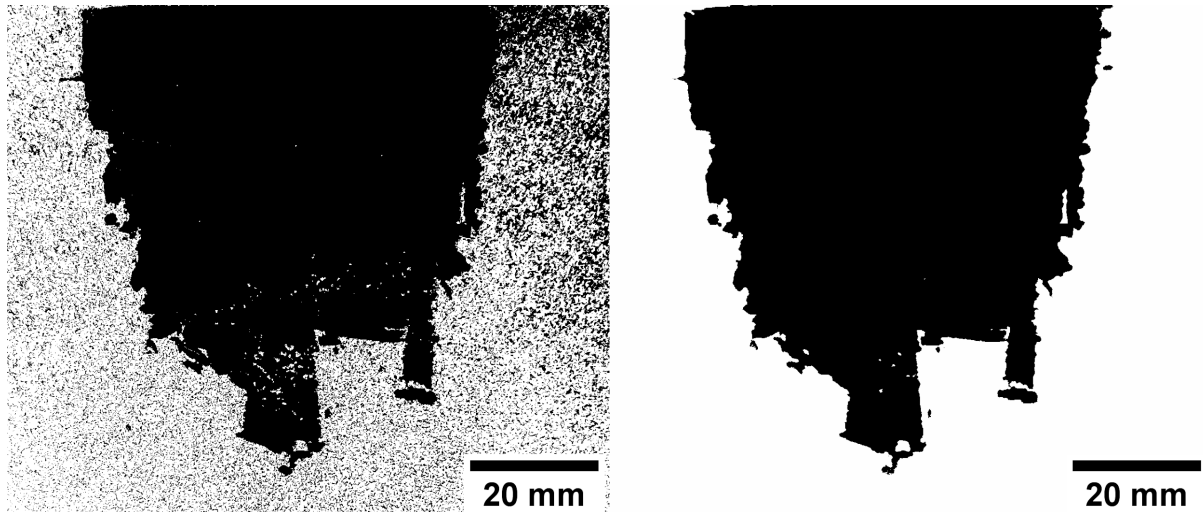


Figure 9: A threshold applied on the image. The left image is a threshold applied to a greyscale image without using the colour subtracting method, while the right one is applied to an image using the colour subtracting method.

Once the threshold is applied, the image can be properly analysed. This was done using an inbuilt plugin called *Particle Analysis*. With this, ImageJ scans the image for edges and then highlights them. In this inbuilt script there exists various options to optimise the edge detection. One particularly useful feature is the ability to limit how large an area must be in order to be highlighted. This will help eliminate small scattered amount of powders or dark spots that might still be present in the image.

Once the particle analysis is done, a bounding geometry can be applied around the selection made by the particle analysis (figure 10). Because of how the powder spreads, the best geometry to use is a *convex hull*. A convex hull is defined as: "... smallest convex polygon that contains all the points of [interest in a plane]" [17]. This means that the convex hull can potentially be a representation of the area that the powder would have formed if it would have spread without irregularities. A convex hull can be applied easily using the inbuilt plugin called *Convex Hull*.

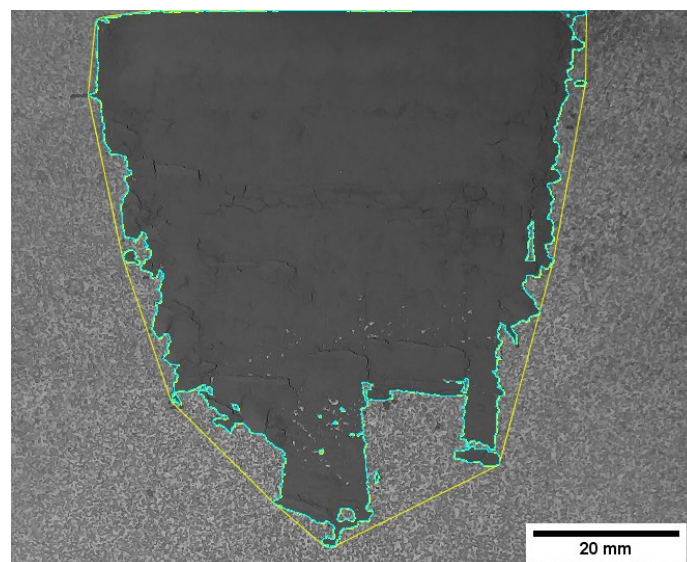


Figure 10: The yellow selection is the applied convex hull.

The area of the convex hull can then be measured in ImageJ using the measuring tool and then be compared against the area of the powder. This tool can also measure other properties by adjusting certain settings, the most significant setting being the minimum bounding rectangle. This setting will provide information about the width, height and position on the smallest, encapsulating rectangle around the powder. This rectangle can then also be compared against the area of the powder.

While having two measurements that describe an outer area might seem redundant, there are cases where a convex hull will be almost the same shape as the powder (figure 11). In such a case, a rectangle might be better suited as a measurement index.

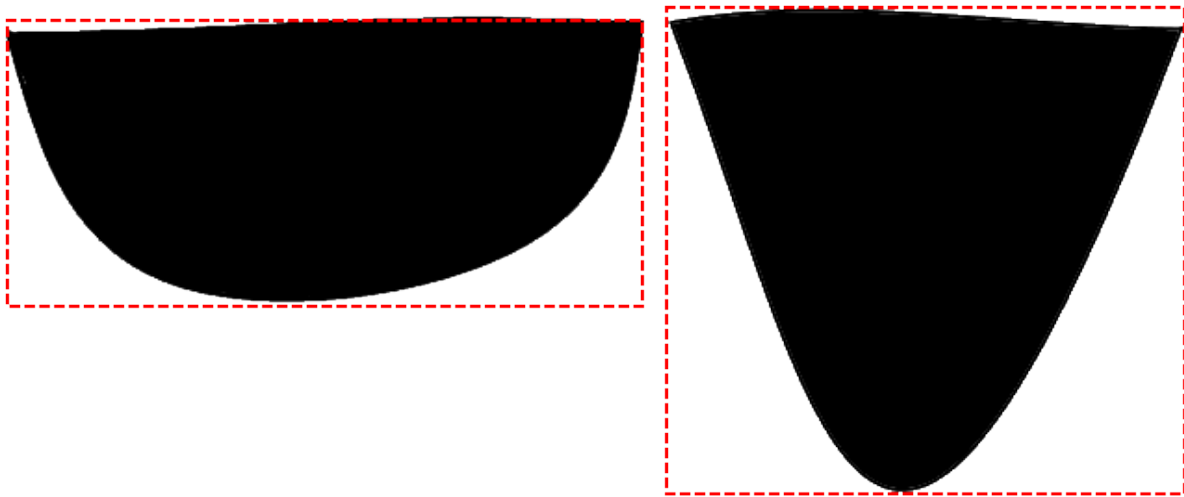


Figure 11: Schematic representation on two different shapes where the convex hull would be close or identical to the original shape while the minimum rectangle will be different. As both shapes are different, they could give a different indication of spreading.

The above-mentioned steps can be summarised as following:

- Area selection of the general vicinity of the powder's location, so that it can be cropped for more accurate results.
- Applying a *threshold* to identify where the powder was after spreading. If a sufficient threshold cannot be achieved, methods to increase the contrast must be used. A proposed method is utilising colour subtraction to create a clearer image.
- Highlight the outline of the powder and applying a bounding geometry around it.
- Saving results from measurements.

One could see these steps as necessary to fulfil to be able to fully automate the process.

4. Results

4.1 Image analysis

The experiment was carried out on three different powder samples. Figure 12 summarises the spreadability index of the powder with respect to the convex hull, while figure 13 summarises the spreadability index with respect to the bounding rectangle.

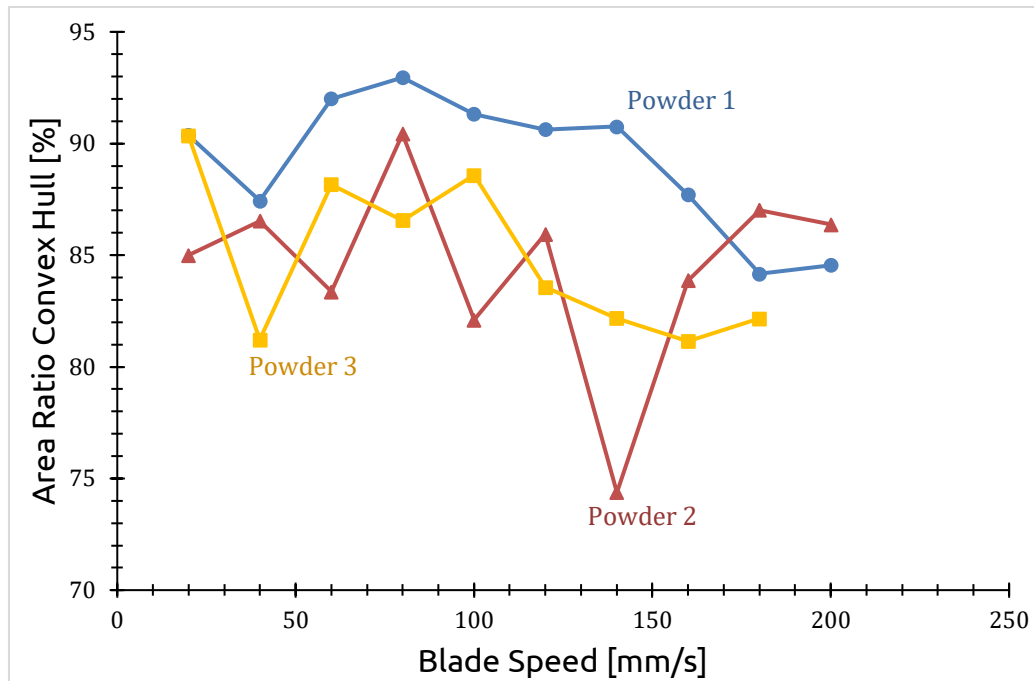


Figure 12: The ratio between the area of the powder and the convex hull for the three powders at different blade speeds.

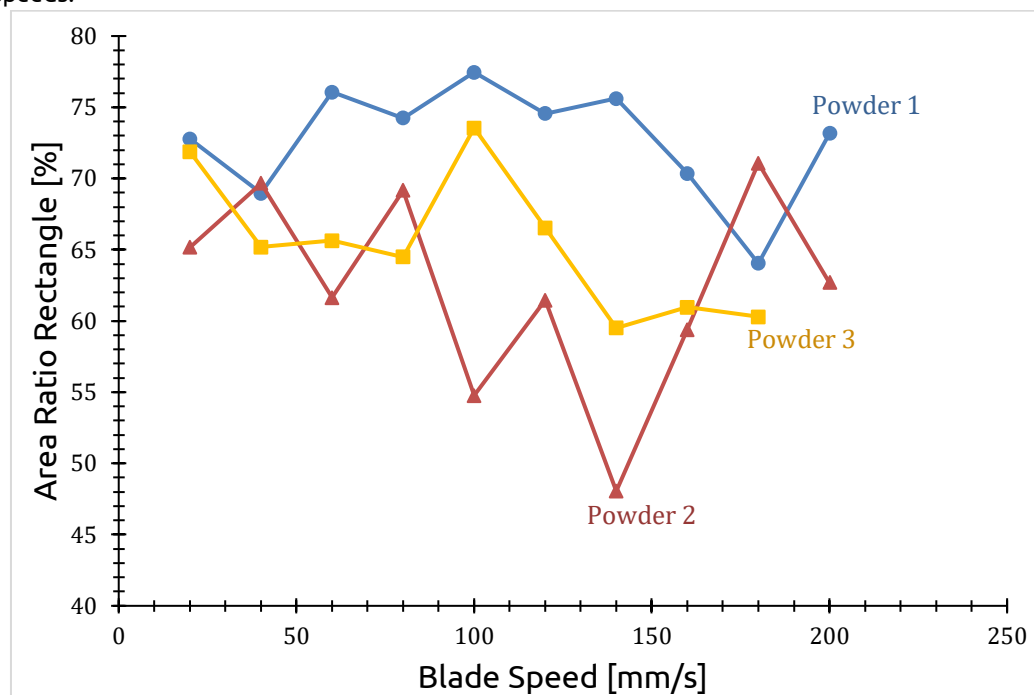


Figure 13: The ratio between the area of the powder and the bounding rectangle for the three powders at different blade speeds.

Alongside the spreadability index the area of the different powders were also recorded and is presented in figure 14. This area was calculated from the assumption that all three powders had the same density and volume.

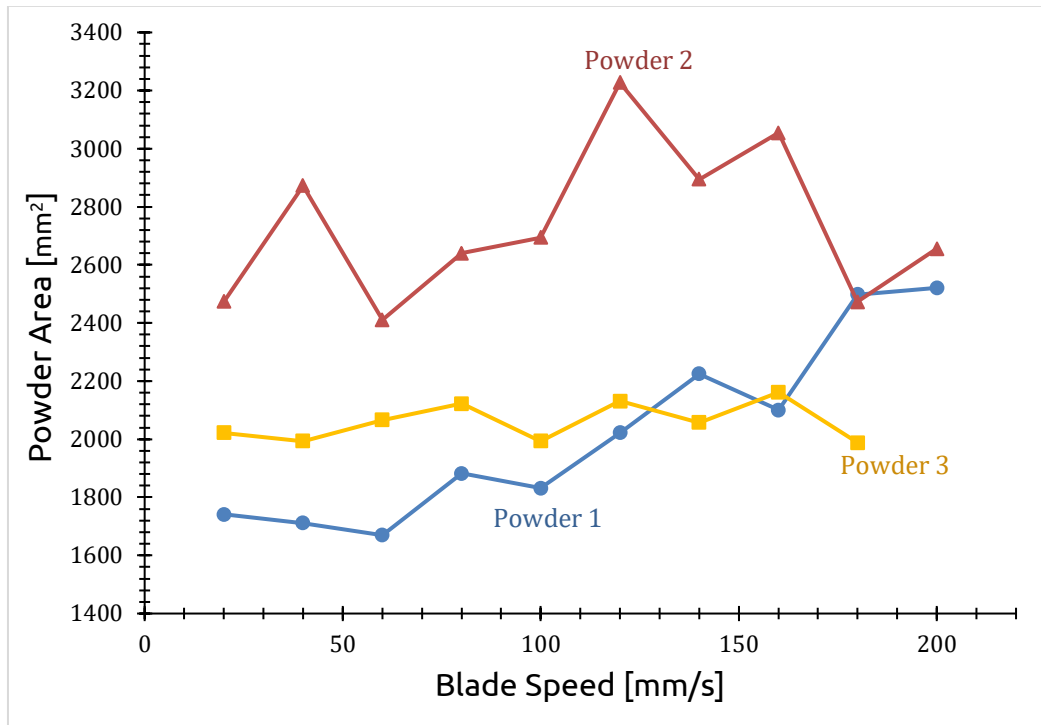


Figure 14: Change in powder area with respect to the blade speed.

The images created from ImageJ was also saved to be able to analyse the effectiveness of the image analysis procedure. Figure 15, 16 and 17 contains four sample images from the three different experiments.

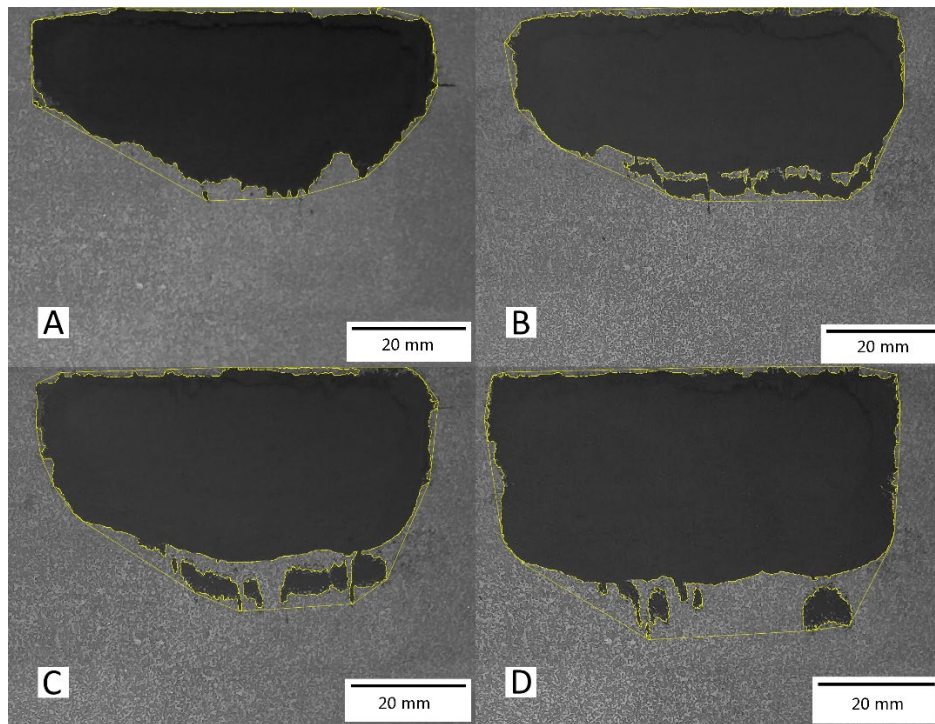


Figure 15: Four sample images from powder 1. Each image is the result from a different blade speed. Image A with a blade speed of 20 mm/s, image B with 100 mm/s, image C is with 160 mm/s and image D is with 200 mm/s.

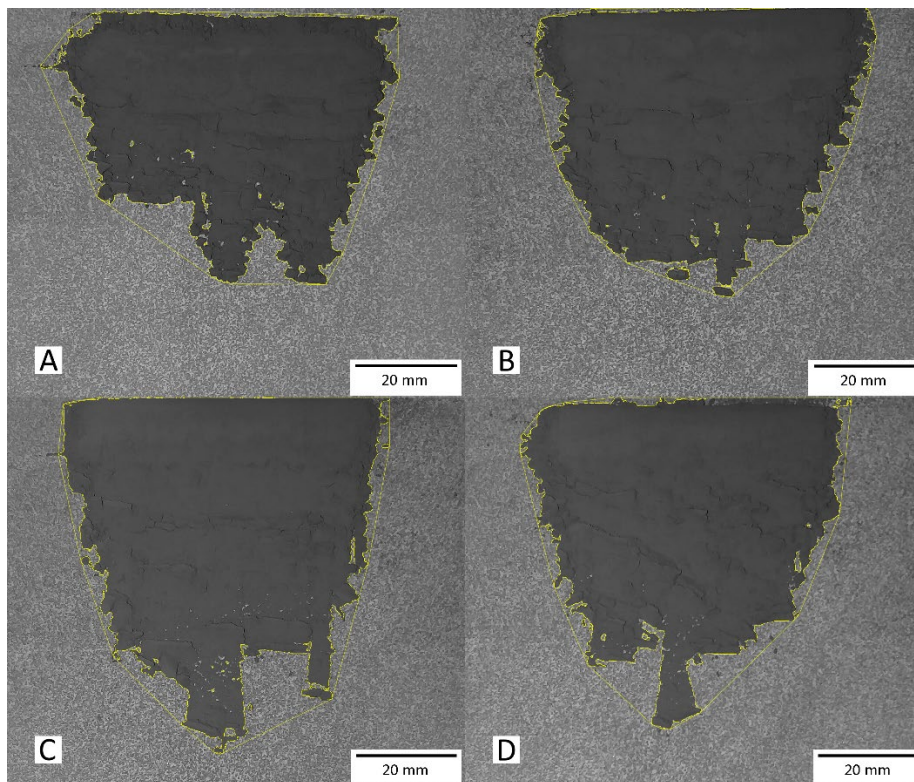


Figure 16: Four sample images from powder 2. Each image is the result from a different blade speed. Image A is with a blade speed of 20 mm/s, image B with 80 mm/s, image C with 160 mm/s and image D with 200 mm/s.

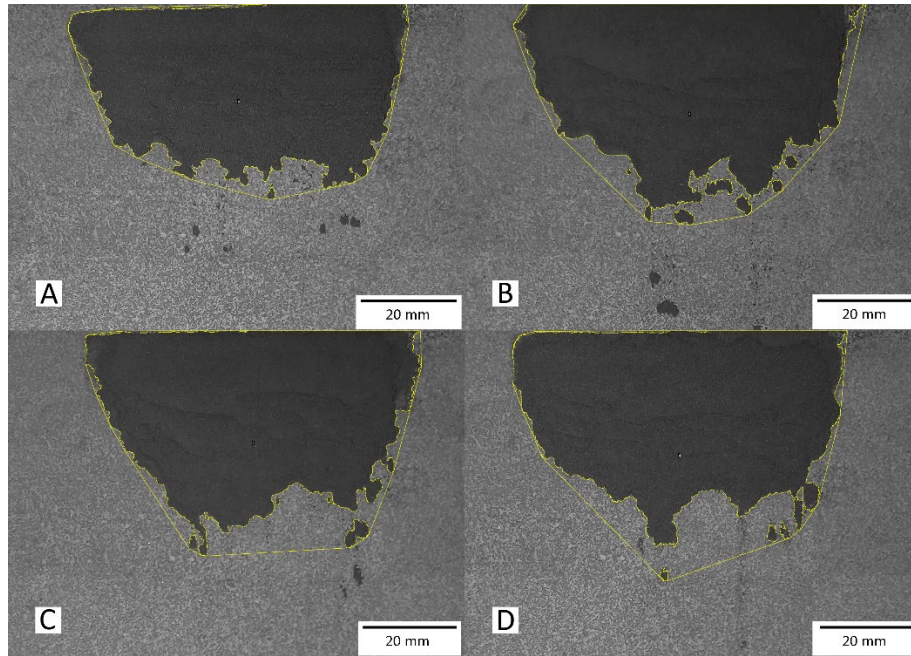


Figure 17: Four sample images from powder 3. Each image is the result from a different blade speed. Image A is with a blade speed of 20 mm/s, image B with 80 mm/s, image C with 120 mm/s and image D with 180 mm/s.

4.2 Results flowmeter

The flowtime for the powders where measured using a Hall flowmeter and is presented in table 1. Out of the three samples only powder 1 was able to flow through the funnel. Powder 2 and 3 were also tested using Carney flowmeter, but they did not flow through that either.

Table 1: Flow time for all the powders. Lower time equals better flowability.

Sample	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Mean time (s)
Powder 1	15.5	15.2	15.1	15.3
Powder 2	No Flow	No Flow	No Flow	No Flow
Powder 3	No Flow	No Flow	No Flow	No Flow

4.3 Results angle of repose

The angle of repose was investigated for the three powder samples and is presented in table 2. Powder 2 was unable to flow through the funnel in this test.

Table 2: Angle for all the powders. Lower value means better flowability.

Sample	Mean of Trial 1 (°)	Mean of Trial 2 (°)	Mean of Trial 3 (°)	Mean (°)
Powder 1	28	26	30	28
Powder 2	No Flow	No Flow	No Flow	No Flow
Powder 3	35	30	32	32

5. Discussion

5.1 Discussion of the powder bed results

5.1.1 Powder 1

The area ratio is almost always the highest for powder 1. It is also relatively stable for powder 1 at lower blade speeds, which is not unsurprising since the increase of powder area at higher blade speed might generate more scatters around the powder. This can be observed in figure 15 (C and D), which both is taken after a higher blade speed. The area coverage with respect to the convex hull decreases at these higher blade speeds. This might suggest that the spreadability decreases at higher blade speeds and while that is a fair assessment, the general spreading shape of the powder stays the same at all blade speeds. This could mean that the spreadability does not necessarily decrease, but that the increased scatter from the powder gives the impression that it does, since the scatters will significantly increase the area of the bounding geometries while only slightly affect the total area of the powder.

5.1.2 Powder 2

The area of powder 2 fluctuates a lot, as is evident from figure 14. This behaviour can more clearly be seen in figure 16. The shape of the powder is often irregular, and it seems that the surface is not even and very rough. This rough surface signifies that the powder is thicker and thinner in different areas which is unwanted in additive manufacturing. This is also mirrored in both figure 12 and 13, as the area ratio of powder 2 also fluctuates a lot in these graphs as well.

5.1.3 Powder 3

Powder 3 appears to be the most stable out of the three graphs in figure 14, as it has very little variation in the size of the powder area. This suggests that the blade speed has very little influence on the actual area. This can also be observed in figure 17, as the shape of the powder stays similar across the different blade speeds. This could mean that the spreadability of the powder is good, but that the friction between the powder particles is too high for the increased blade speed to affect the size of the area.

This stableness cannot be so readily observed in the graphs (figure 12 and 13), as the powder shows some fluctuations across all the blade speeds. It does appear to be more stable than powder 2 though, as it does not show as many extremes in the graphs, which could mean better stability and is perhaps an indication of better spreadability.

5.1.4 Comparison

All the powders were tested with the same machine settings, including the height of the blade during operation. Because the powder's thickness cannot be thicker than the height of the blade, a larger area will mean a more uneven spread. This is because the volume of the powder is constant, which means the only way for the area to differ between the powders is if the powder is thinner, typically varying at different spots. This can also be observed in all the figures (15, 16 and 17).

Powder 1 has on average the highest area coverage out of the three powders, only having slightly lower value than powder 2 at the highest blade speeds. This could be an indication that it has the best spreadability of the three powders. The other two powders are more difficult to analyse because their area ratios vary a lot across different blade speeds. This makes determining the spreadability based on just one test data impossible for these powders, since different blade speeds can give drastically different values. However, from the data, it seems like powder 2 fluctuates a lot more than powder 3, which might suggest that powder 2 tends to form more uneven shapes. Based on this, it might be more suitable to use this fluctuation of the data as the metric to determine the spreadability of the powders, instead of using just one data point.

5.1.5 Comparison between flowability and our spreadability index

Powder 1 was the only powder that flowed through the flowmeter. This means that it has the best flowability out of the three when judging only by the flowmeter. In the angle of repose test, powder 1 showed the best flowability yet again, but unlike the flowmeter test powder 3 also showed some decent flow as well. So, judging the flowability based on both these tests, it seems like powder 1 has the best flow, powder 3 has the second-best flow and powder 2 has the worst flow.

One can draw some similarities between these results and the results from the spreadability measurements. Powder 1 seems to have the best spreadability and powder 3 seems to be slightly better than powder 2. This suggests that a correlation between the spreadability and the flowability of a powder could exist.

Out of all the three powders, only powder 1 exhibit a reliable effect of recoater speed. It is logical to draw the conclusion that a higher blade speed would results in a larger area, as the powder is being exposed to a larger velocity. This could also mean that powder 2 and 3 have a rougher surface, perhaps more friction is present in the powder. This phenomenon was also observed in the flowability tests, where it was difficult for powder 2 and 3 to flow through the funnels.

5.1.6 Comparison between bounding box and convex hull

It seems that both bounding geometries, convex hull and rectangle, give similar looking graphs. The bounding rectangle always have a lower total ratio for each powder, which is logical since the area of the rectangle cannot be smaller than the convex hull. But other than the absolute values, there are clear similarities in the behaviour of the graph. This could mean that other than for some rare cases, such as the one illustrated in figure 11, there is no significant reason for using one over the other. However, it is suggested that both are to be considered in case a powder is behaving in a similar manner to that showed in figure 11.

5.2 Evaluation of the method

Based on the results obtained, the method seems promising in its capacities of analysing spreadability. Nonetheless, there are some drawbacks with the method which generates errors within the image analysis and will be discussed in this section.

5.2.1 Difficulties with darker spots

One problem is that with certain images, the threshold applied would not only select the edges of the powder, but also some darker spots in the background. This can be observed in the upper right of the figures 13 (D) and 14 (B or D). This, while minor, creates an incorrect representation of the powder area.

Curiously, this problem seems to not occur in any of the images of powder 1. This does give the impression that the problem could be related to poor spreadability, since it is only present in powders with poorer spreadability. An alternative explanation could be given that is unrelated to spreadability. Since the problem is most notable in tests done with powder 3, the dark spots could be a small amount of powder particles from the previous test that got stuck in the sandpaper. This is also backed up with the fact that the darker spots are more present in the top regions of the images compared to the lower portions, as this is the starting position of the powder. This could mean that to remedy this problem, an alternative background material needs to be chosen instead of the sandpaper, one that does not have the same surface roughness.

5.2.2 Problems with powder clusters

Another, more subjective problem, also occurred in certain images. In figure 14 (All), small powder clusters can be observed both far away and close to the main body of the powder. This creates some difficulties in defining what to be considered as important contributors to the spreading index. It is reasonable to assume that the smaller clusters close to the main body should be included as a representation of the total area, but including the ones farther away might give misrepresented data, since they will heavily skew the results obtained from the convex hull and the bounding rectangle if compared against images which has less powder clusters far away. Also, the pattern and distance of these scattered clusters will probably vary each time these tests are performed, which would further fluctuate the results if they are included.

In an actual AM machine, the supply of powder for each build layer is sufficient to cover the entire build plate, which would mean that even if a powder has a tendency to scatter powder clusters away from itself, the resulting powder would either fly off the build plate or be covered later. By using this fact and the aforementioned complications, the decision to exclude the far away powder clusters were made in this study. Creating a macro that can exclude far away powder is not difficult, but the downsides is that it introduces longer computation times for each image and human bias into the analysis.

6. Conclusions

The method is capable of producing results using bounding geometries. The data it provides, however, fluctuate a lot between all the powders. This fact alone makes the data unreliable if only a small number of tests is run. However, the amount of fluctuation between the powders seems to differ, which means that it might be possible to compare the area ratios over several tests and use this difference as a metric instead.

The method was able to consistently find the area of the powder, with some minor inaccuracies. The most prevalent problem being the presence of what is likely small powder particles in the sandpaper, which made it difficult for the program to only select the edges of the powder. It might be possible to minimize, if not outright remove, this problem by using better surface than sandpaper.

Judging by the data, it might be possible to conclude that the flowability of the powders impacts its spreadability and the data seems to somewhat correlate with the results obtained from the flowmeter and angle of repose.

Ultimately these conclusions are drawn from a small sample size and low amount of data, so it is not possible to draw any definite conclusions without performing more experiments.

7. Future work

Further testing of the repeatability and reproducibility of method is needed. The easiest way to achieve this is to use a larger data sample in future experiments. Also, this test only focused on steel powders and because of that no other material powder was used. Therefore, future experiments should also consider using other materials in order to verify that the method is applicable on other materials as well.

There might have existed problems with the sandpaper background, so a better background in conjunction with better lighting is recommended for future works. This could also validate if the method works outside of our experimental conditions.

Other metrics, such as mass or density-based ones, could also be used to quantify the spreadability. These experiments would then use a fixed area to measure the weight of the powder on it and could for example use the area density as a metric for spreadability.

8. Acknowledgments

We would firstly like to thank our supervisor Christopher Hulme-Smith, assistant professor at KTH Process department, for helping us start with this project and for helping us think outside the (bounding) box. We would also like to thank Vignesh Hari, a master student at KTH Material science and engineering, for helping us with the experimental data.

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