

Evaluation of carbon fibre powder scrapers used in metal additive manufacturing

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ABSTRACT

Powder Bed Fusion (PBF) is an Additive Manufacturing process which builds parts, layer by layer, by melting the cross-section of the part onto a powder layer. Aeroswift is a PBF machine, designed and built in South Africa. A carbon fibre brush powder scraper was designed for Aeroswift, which would be flexible, work for extended periods of time and have the ability to operate at high temperatures. Uncertainty regarding the quality of the powder layer produced by this scraper called for the need of an evaluation method. Different methods of evaluating the quality of a powder layer were investigated. A Laser Line Scanner proved to be the best option due to its accuracy and quantitative evaluation abilities. Different powder scrapers were used to scrape layers, which was measured with a Laser Line Scanner. Results showed this method could indeed be used for a quantitative evaluation of a powder scraper and as a result be used to compare and qualify a powder scraper. A conclusion was drawn that the Aeroswift designed powder scraper performs comparably to a commercial carbon fibre brush scraper and produces a satisfactory powder layer.

Key words: Additive Manufacturing, Powder Bed Fusion, Selective Laser Melting, Aeroswift, powder layer evaluation

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	I
ABSTRACT	II
CHAPTER 1 INTRODUCTION.....	1
1.1 Problem statement	2
CHAPTER 2 LITERATURE SURVEY	3
2.1 Additive Manufacturing.....	3
2.2 Common AM technologies.....	3
2.2.1 Powder Bed Fusion	3
2.2.2 Fused Deposition Modelling (FDM).....	7
2.2.3 Stereolithography (SLA)	7
2.2.4 Binder Jetting	8
2.2.5 Laser Engineered Net Shaping (LENS™).....	8
2.2.6 Atomic Diffusion Additive Manufacturing (ADAM)	9
2.3 Aeroswift.....	9
2.4 Defects in SLM.....	12
2.4.1 Warpage.....	12
2.4.2 Balling	14
2.5 Layer deposition and powder scraping	14
2.5.1 Types of powder scrapers	15
2.6 Process monitoring.....	19
2.6.1 Online Quality Control – Visual Inspection.....	20
2.6.2 High-resolution imaging	22

2.6.3	Laser Line Scanner	25
2.6.4	Vision System.....	26
2.7	Titanium powder.....	29
CHAPTER 3 EXPERIMENTAL PROCEDURE.....		32
3.1	Methodology	32
3.2	Experimental setup.....	33
3.3	Procedure.....	35
3.4	Summary	38
CHAPTER 4 RESULTS AND DISCUSSION.....		39
4.1	Powder analysis	39
4.2	Powder scraper tests	39
4.3	Other analysis.....	47
CHAPTER 5 CONCLUSION		49
REFERENCES.....		50

LIST OF TABLES

Table 2-1: SLM vs. EBM (Bhavar, et al., 2014).....	6
Table 2-2: Flagship machine comparison	11
Table 2-3: Advantages and disadvantages of each powder scraper	18
Table 2-4: Advantages and disadvantages of process monitoring methods.....	29
Table 3-1: Composition of typical Grade 5 Ti64 powder	34
Table 3-2: Data set sample	37
Table 4-1: Aeroswift scraper 2 - line section 1	40
Table 4-2: Aeroswift scraper 2 - line section 2	41
Table 4-3: Aeroswift scraper 2 - line section 3	41
Table 4-4: Aeroswift scraper 2 - line section 4	41
Table 4-5: Aeroswift scraper 2 - line section 5	42
Table 4-6: Aeroswift scraper 2 - line section 6	42
Table 4-7: Aeroswift scraper 2 - line section 7	42
Table 4-8: Aeroswift scraper 2 - line section 8	43
Table 4-9: Aeroswift scraper 2 - line section 9	43
Table 4-10: Standard deviation of line 1 on layer 1	48

LIST OF FIGURES

Figure 2-1: Illustration of PBF (EOS, n.d.)	4
Figure 2-2: Schematic of an EBM machine (ARCAM, n.d.).....	5
Figure 2-3: Fused Deposition Modelling schematic (Jin, et al., 2015)	7
Figure 2-4: SLA schematic (Nikhil, n.d.)	8
Figure 2-5: Schematic of binder jetting (Jackson, n.d.)	8
Figure 2-6: LENS TM (Aliakbari, 2012).....	9
Figure 2-7: The Aeroswift machine	10
Figure 2-8: Parts built on the Aeroswift machine.....	11
Figure 2-9: Difference in supported and unsupported overhangs (Vora, et al., 2015)	12
Figure 2-11: Delamination and crack formation due to residual stresses (Zaeh & Branner, 2010).....	13
Figure 2-10: Warpage of flat unsupported geometries (Vora, et al., 2015).....	13
Figure 2-12: Balling effect.....	14
Figure 2-13: Solid blade scraper.....	15
Figure 2-14: Carbon fibre brush.....	16
Figure 2-15: Stereoscope images of carbon fibre brush	16
Figure 2-16: Metal comb scraper.....	17
Figure 2-17: Wiper type powder scraper.....	17
Figure 2-18: Schematic of the experimental set up of Craeghs, et al. (2011).....	20
Figure 2-19: Photo of powder layer obtained by Craeghs et al. (2011)	21
Figure 2-20: Averaged line greyscale graph (Craeghs, et al., 2011)	21
Figure 2-21: Averaged line greyscale graph of worn powder scraper (Craeghs, et al., 2011).....	22

Figure 2-22: Greyscale graph of a worn and damaged powder scraper (Craeghs, et al., 2011).....	22
Figure 2-23: Sample image showing visible weld beads (Kleszczynski, et al., 2012).....	23
Figure 2-24: Different type of errors affecting process stability (Kleszczynski, et al., 2012)	24
Figure 2-25: Second test build with varying process parameters (Kleszczynski, et al., 2012).....	25
Figure 2-26: A Laser Line Scanner (Micro-Epsilon, n.d.)	26
Figure 2-27: Different magnifications used by Cooke & Moylan (2011).....	26
Figure 2-28: Diameter, edge reference and wall thickness checks (Cooke & Moylan, 2011) ...	27
Figure 2-29: Results from the vision system (Cooke & Moylan, 2011)	28
Figure 2-30: Gas atomisation (LPW, n.d.).....	30
Figure 2-31: Typical Ti6Al4V powder	31
Figure 3-1: Tested powder scrapers.....	32
Figure 3-2: Test setup	34
Figure 3-3: High-precision linear bearing	34
Figure 3-4: Dovetail translation stage	34
Figure 3-5: Micro-Epsilon's ScanCONTROL 2960-50/BL.....	35
Figure 3-6: Graph of x- and z-coordinates for line section 5 of line 1	36
Figure 3-7: Graph with added median line and its equation	37
Figure 4-1: TLS Technik Grade 5 Ti64 powder – un-sieved.....	39
Figure 4-2: Line section profile of Aeroswift scraper	40
Figure 4-3: Layer comparison for Aeroswift scraper 1	45
Figure 4-4: Layer comparison for Aeroswift scraper 2	45
Figure 4-5: Layer comparison for Aeroswift scraper 3	46

Figure 4-6: Layer comparison for commercial carbon fibre brush scraper	46
Figure 4-7: Layer comparison for solid blade scraper	46
Figure 4-8: Average number of peaks comparison	47

CHAPTER 1 INTRODUCTION

Additive Manufacturing (AM) is becoming a popular method for manufacturing. This technology is already widely used in the medical- and aerospace manufacturing industries and is starting to be utilised in other industries, such as defence and automotive as well. This technology manufactures a part by adding material to a substrate layer by layer. Powder Bed Fusion (PBF) is one of the more advanced AM processes. The PBF process uses an energy source and scanning method to melt or sinter the cross-section of a part onto a newly laid powder layer. The energy source could either be a laser, in which case it is called Selective Laser Melting (SLM) or Selective Laser Sintering (SLS), or an electron beam, called Electron Beam Melting (EBM). The build platform moves down by one layer thickness (typically between 20 to 50 μm for SLM and 50 to 150 μm for EBM), a new powder layer is added and the next cross-section is scanned. These steps are repeated until all the cross-sections of the part are scanned and the entire component printed. The cross-sections are obtained by running the CAD model through slicing software, (Chua & Leong, 2014).

Aeroswift is an SLM machine, designed and built in South Africa in collaboration between the National Laser Centre (NLC) of the Council for Scientific and Industrial Research (CSIR) and Aerosud Innovation and Training Centre (Aerosud ITC). It has a build volume of 2000 x 600 x 600 mm^3 , which is much larger than currently available commercial machines. Due to the large width of the build platform and other factors, such as preheating to 600°C, a custom powder scraper was designed. The quality of a powder layer is very important in PBF processes and influences the surface roughness of a built part and, to a certain extent, its dimensional accuracy and density. This powder scraper has to fulfil the following specifications:

1. High operating temperature: the machine has a preheat temperature of up to 600°C.
2. Flexible: due to known defects in PBF, such as warpage (Vora, et al., 2015) and balling (Kruth, et al., 2004), a flexible powder scraper is required that would be able to deal with these defects without failing.
3. Durable: the powder scraper should be able to operate for extended periods, as at full capacity, a build could be as many as 12 000 layers.
4. Consistent powder layers: consecutive powder layers should not differ much from the previous layer.
5. Smooth surface: the powder layers produced should have a good surface roughness and should be uniform throughout.

After many iterations and tests on powder scrapers, a carbon fibre brush powder scraper was designed and manufactured. After its implementation, test builds were conducted for

parameterisation. Excessive roughness of consolidated layers caused premature failure of the powder scraper. It was uncertain whether the failures were due to unsatisfactory powder layers or due to the lack of optimised process parameters. Thus, a quantitative method was needed to determine the quality of the powder layer, to show if the layer produced by the powder scraper was sufficient or not.

1.1 Problem statement

A scraper was designed and implemented in Aeroswift. Excessive roughness of consolidated layers caused premature failure of the scraper. Excessive roughness could be caused by poor powder layer quality or process parameters. Current methods are unable to fully quantify a layer. A quantitative method for determining the quality (flatness) of a powder layer is required.

The research objectives are:

- Devise a method for a quantitative evaluation of the performance of a powder scraper.
- Use the devised method to evaluate the carbon fibre powder scraper developed for the Aeroswift system.

The research hypotheses are:

- A Laser Line Scanner could be used to obtain a quantitative evaluation of the performance of a powder scraper, which can be used to compare and develop powder scrapers.
- This evaluation method can determine if the designed and manufactured carbon fibre brush scraper will meet the requirements of the Aeroswift system.

Project exclusions

- Effect of scraping speed on powder layer quality.
- The durability of the powder scraper.
- High temperature (600 °C) tests.

CHAPTER 2 LITERATURE SURVEY

2.1 Additive Manufacturing

Additive Manufacturing (AM), referred to in Layman's terms as 3D printing, is a process that produces a component by adding material to a substrate, layer by layer. AM is the official standard term for all processes that build parts layer by layer, according to the ASTM F42 and ISO TC261 committees (Wohlers Associates, n.d.). Other terms for the technology are: additive processes, additive fabrication, additive layer manufacturing, additive techniques, layer manufacturing, rapid prototyping and freeform fabrication. This type of manufacturing opposes the traditional subtractive manufacturing methodology, which as the name states, uses the removal of material, (Chua & Leong, 2014).

The component or part is obtained through Computer Aided Design (CAD) software and then runs the CAD file through slicing software. The software slices the model into thin layers from bottom to top and converts these slices to a format which is used by the machine. The first form of AM was done by 3DSystems in 1987 and was referred to as stereolithography (SL).

2.2 Common AM technologies

2.2.1 Powder Bed Fusion

PBF has different technologies which uses the same principles. Depending on which manufacturer is referred to, it could be Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Laser Cusing or Electron Beam Melting (EBM). This technology fuses the particles of a powder layer together, using an energy source.

PBF technology will be of main interest in this project. However, other AM processed are briefly discussed in the next sections to highlight different approaches that can be followed for AM. PBF can be categorised in mainly two different technologies, SLM and EBM.

2.2.1.1 Selective Laser Melting

SLM is the most popular PBF technology and was founded at the Fraunhofer Institute for Laser Technology (ILT) in Aachen, Germany, and patent DE 19649865 was registered (Evans, 2014). It uses a laser as the energy source, which is connected to a scanner. The process starts by depositing and scraping a layer of

powder on the build platform. The scanner scans the first cross-section of the part onto the powder layer. When the cross-section is finished being scanned, the bed is lowered by a height of one layer thickness and another powder layer is added by the recoating system. The next cross-section is then scanned. This is repeated until all the cross-sections of the component are done and the part finished.

The layer thickness used in this technology is usually between 20 - and 100 μm . (Aliakbari, 2012). Powder which was not melted/fused during the process could be recovered, sieved and reused (Vora, et al., 2011). Figure 2-1 shows a schematic of the process. Processing is mostly done in an inert Argon atmosphere to prevent oxidation of the build parts and powder. The laser is focussed through an optical path to give the small spot size on the powder bed. Spot sizes range from 80 to 600 μm .

With Selective Laser Sintering (SLS), a plastic powder is used as build material and the particles are fused, or sintered, together by the laser. SLS only uses plastic/ plastic-based materials.

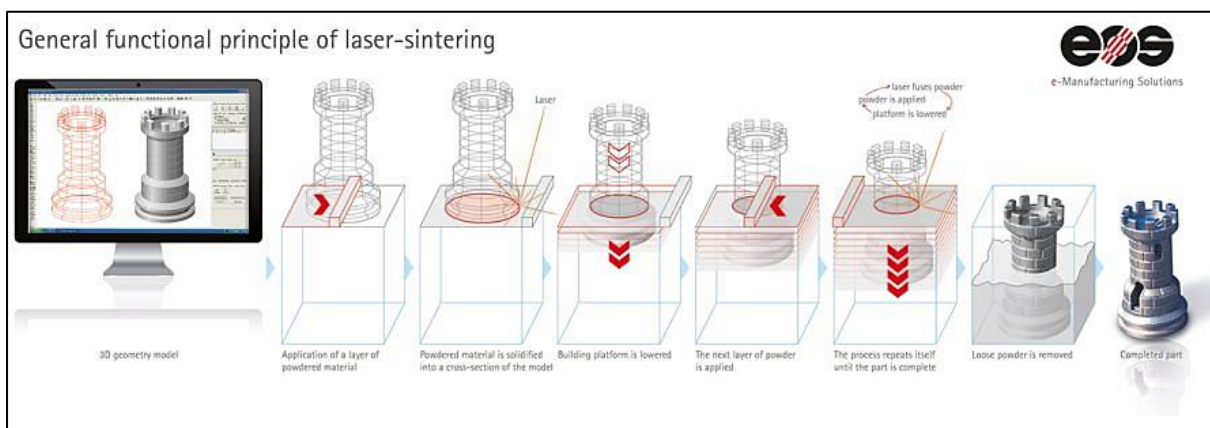


Figure 2-1: Illustration of PBF (EOS, n.d.)

2.2.1.2 Electron Beam Melting (EBM)

EBM uses a powerful electron beam, about 3.5 kW, as its energy source. This process happens in a vacuum instead of an inert Argon atmosphere as with SLM. (Murr, et al., 2012). It is necessary to use a vacuum in EBM because any other atmosphere can influence the quality of the electron beam. One advantages of using a vacuum, instead of an inert atmosphere, is that one can achieve very high preheating temperatures due to the low heat transfer through a vacuum. Heat transfer mostly happens due to radiation and not convection. Another advantage is that the risk of material contamination is much lower. However, creating a

system capable of operating under a vacuum is difficult and more expensive than using an inert atmosphere and thus is only used if necessary. For this reason, SLM uses an inert atmosphere and not a vacuum. A schematic of an EBM machine is shown in Figure 2-2.

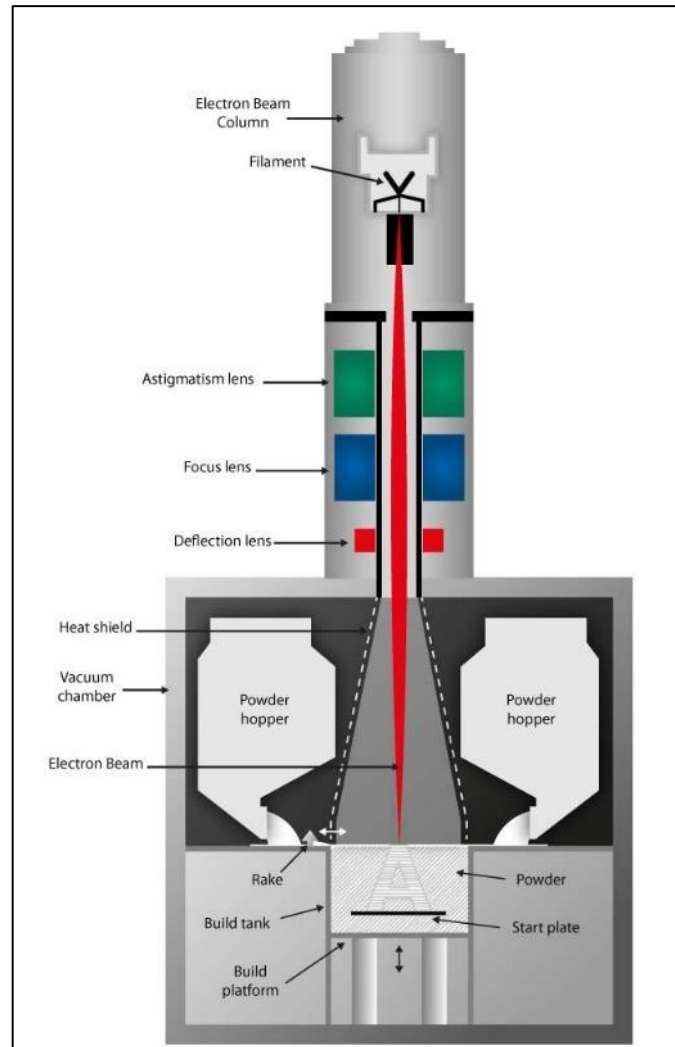


Figure 2-2: Schematic of an EBM machine (ARCAM, n.d.)

Other than using an electron beam, having high preheat temperatures and operating under a vacuum, this process is the same as SLM. EBM's layer thicknesses is around 50 to 150 μm and its surface quality is poorer than that of SLM. Arcam is the sole manufacturer of EBM machines (Körner, 2016). EBM has some advantages over SLM, such as: an electron beam can almost instantaneously jump from one point to another due to the inertia-free electromagnetic lenses and there are little to no residual stresses in the built parts due to high preheating temperatures. However, there are also some disadvantages over SLM, for instance being limited to conductive materials only.

More disadvantages are: optimised process parameters are only available for a limited number of materials and un-melted powder is sintered during the process, making powder removal in confined spaces difficult. The powder scraper used in this technology has to have very high temperature resistance, because of the extreme preheating temperatures. Thus, a metal comb (explained in section 2.5.1.3) is mostly used.

EBM and SLM were compared with one another by Bhavar, et al. (2014:4) and summary drawn up which is shown in Table 2-1. This summary gives one a good idea why SLM is more popular than EBM; even though EBM has a much higher build rate than current SLM machines, its surface quality and dimensional accuracy is less. Because both these technologies fall under PBF, their scraping systems are the same, but the powder scrapers they use would differ. For instance, SLM would use either a solid blade, an elastomer or a carbon fibre brush, where EBM would use a metal comb.

Table 2-1: SLM vs. EBM (Bhavar, et al., 2014)

	SLM	EBM
Power source	One or more fiber lasers of 200 to 1000 W	High power Electron beam of 3000 W
Build chamber environment	Argon or Nitrogen	Vacuum / He bleed
Method of powder preheating	Platform heating	Preheat scanning
Powder preheating temperature (° C) [34,35]	100-200	700-900
Maximum available build volume (mm)	500 x 350 x 300	350 x 380(ØxH)
Maximum build rate (cm³/hr)	20-35	80
Layer thickness (µm)	20-100	50-200
Melt pool size (mm)	0.1-0.5	0.2-1.2
Surface finish [7] (Ra)	4-11	25-35
Geometric tolerance (mm) [12]	± 0.05-0.1	± 0.2
Minimum feature size(µm) [39]	40-200	100

2.2.2 Fused Deposition Modelling (FDM)

Instead of using a powder layer, a thermoplastic is extruded through a heated nozzle to build the component, layer-by-layer (Jin, et al., 2015). This is the most common technology and most household machines are FDM machines.

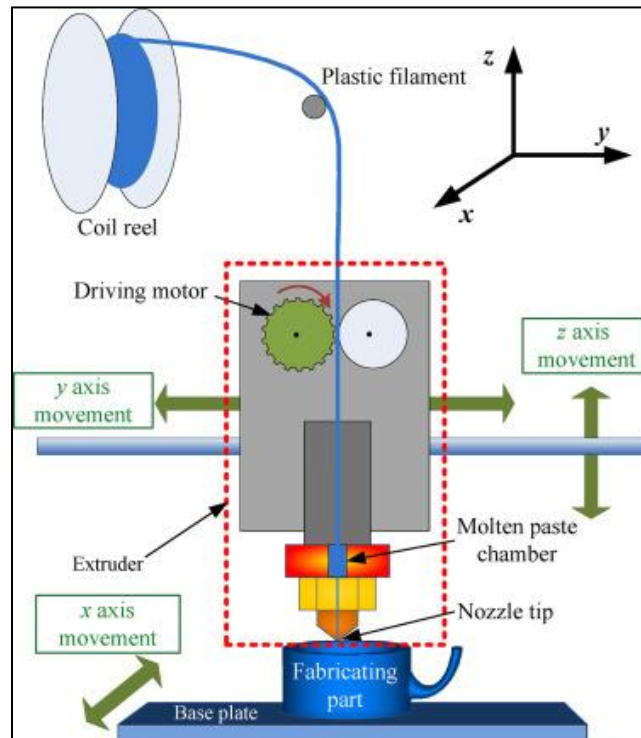


Figure 2-3: Fused Deposition Modelling schematic (Jin, et al., 2015)

2.2.3 Stereolithography (SLA)

This process uses a UV sensitive liquid resin as build material. The cross-section of the part is scanned onto the resin layer by a UV laser, which then hardens the resin. The bed is then lowered by one layer thickness, another layer of resin is spread over the platform and then scanned by the laser again. This process is repeated until all the cross-sections have been scanned (Figure 2-4). The finished part is then removed. (Materialise, n.d.).

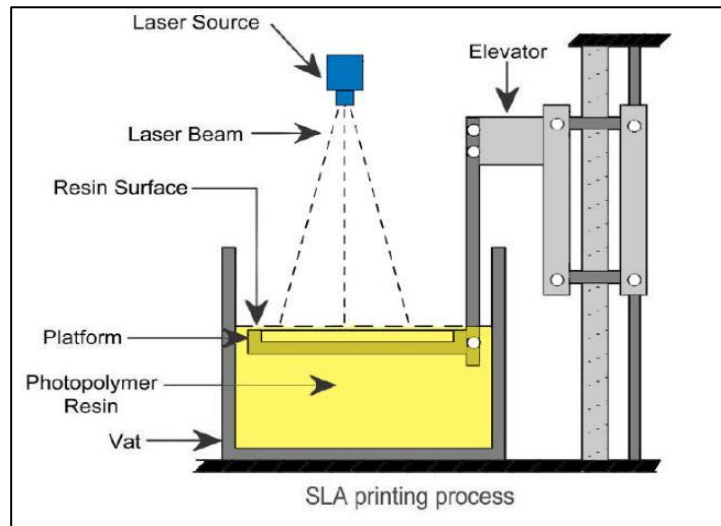


Figure 2-4: SLA schematic (Nikhil, n.d.)

2.2.4 Binder Jetting

Another technology worth mentioning is Binderjet, as it will be referred to in section 2.6.4. Binder jetting works on the same principle as SLS, but instead of consolidating metal powder with a laser, it uses a binder (typically a type of glue) to bind plastic powder together, layer by layer. (Loughborough University, n.d.).

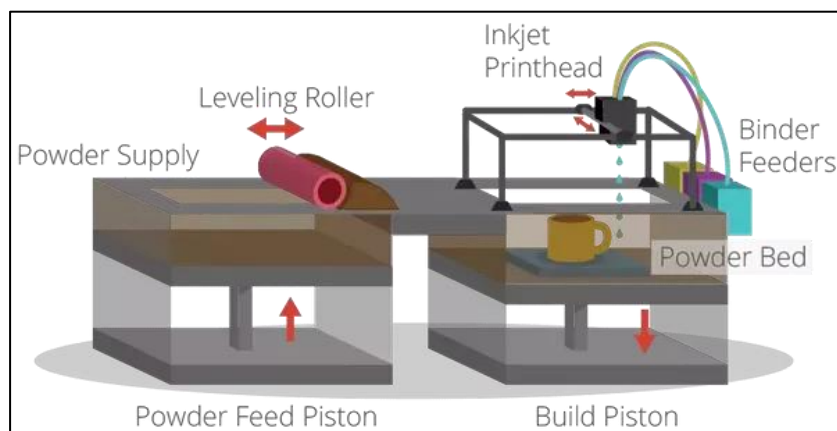


Figure 2-5: Schematic of binder jetting (Jackson, n.d.)

2.2.5 Laser Engineered Net Shaping (LENS™)

LENS™, or also known as Blown Powder, is a metal AM process similar to FDM. It uses metal powder blown through nozzles, to a focus point, into a melt pool on the substrate or previous layer, created by a laser (Figure 2-6). The process happens in a closed system with an inert Argon atmosphere with less than 10 ppm oxygen levels. This process has some limitations such as the inability to build overhangs greater than 20 degrees with the vertical line. One advantage of this process is the ability to use composite powder mixtures. (Aliakbari, 2012, pp. 28-29).

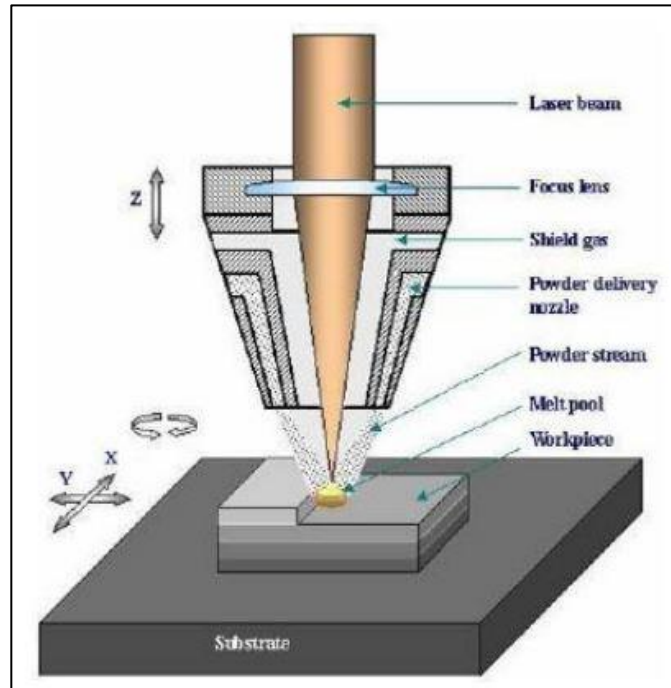


Figure 2-6: LENS™ (Aliakbari, 2012)

2.2.6 Atomic Diffusion Additive Manufacturing (ADAM)

ADAM has only been on the market since late 2017, making it one of the newest AM technologies available today. It works on the same concept as FDM, but uses a metal powder contained in a plastic binder as printing material instead of plastic filament. After the print is completed, the part is sintered in a furnace, burning away the binder and leaving only the metal (AM Staff, 2017). Before printing a part, it is scaled up by 20% to account for the shrinkage during sintering. The largest build volume available for ADAM is 250 x 220 x 200 mm³. ADAM is cheap with respect to other metal AM technologies, however, parts produced are only between 95 and 99% dens.

2.3 Aeroswift

Aeroswift is the machine for which this research project has been done. It is an SLM machine, locally designed and built in South Africa in a collaborative project between the Council for Scientific and Industrial Research (CSIR) and Aerosud Innovation and Training Centre (Aerosud ITC), and will have the largest build volume in the world. Currently, the largest machine in the world is the X LINE 2000R, produced by Concept Laser. The X Line 2000R has a build volume of 800 x 400 x 500 mm³ (x,y,z) and incorporates two 1 kW fibre Lasers. (<https://www.concept-laser.de/en/products/machines.html>). The build volume for Aeroswift, however, is 2000 x 600 x 600 mm³. This results in a build envelope of 720 litres

compared to 160 litres of the 2000R. Aeroswift uses a 5 kW laser, which is also by far the highest power used by any SLM machine in the world. The highest power laser used in commercial machines is 1 kW. Aeroswift is the only SLM machine that incorporates a moving scanner to cover the entire length of the build platform, instead of multiple lasers and scanners.

Aeroswift has the capability to preheat the build platform to 600 °C, where other machines can only achieve 200 °C, as can be seen in Table 2-2. One of the reasons for preheating the build platform is to reduce the residual stresses within the build part, as mentioned in section 2.2.1.2 regarding EBM. Residual stresses are also discussed in section 2.4.1. Another reason is to bring the powder closer to the melting point and, thus, less power absorption is needed to melt the powder. This results in higher scan speeds.



Figure 2-7: The Aeroswift machine

Table 2-2 shows a comparison between Aeroswift and the flagship machines for EOS, SLM Solutions and Concept Laser.

Table 2-2: Flagship machine comparison

	EOS M 400	SLM Solutions 500	ConceptLaser X LINE 2000R	Aeroswift
Build volume (mm³)	400 x 400 x 400	500 x 280 x 365	800 x 400 x 500	2000 x 600 x 600
Laser (kW)	1	4 x 0.4 or 4 x 0.7	2 x 1	5
Scan speed (m/s)	Up to 7	Up to 10	Up to 7	Up to 20
Spot size (µm)	Approx. 90	80 – 115	100 – 500	200 - 600
Preheat temperature (°C)	N/A	Not standard – up to 200	200	Up to 600

The purpose for Aeroswift is to build mainly aerospace parts. The large build volume enables it to build longer parts, not previously possible with commercial machines. Also, if one requires 1000 units of a part, Aeroswift can do it in one or two builds (depending on the size of the part) where other machines will require several more. This cuts on the down time of the machine and in turn reduces the cost per part. The higher build rates further reduces part costs.



Figure 2-8: Parts built on the Aeroswift machine

Aeroswift will mainly build parts from Ti6Al4V (Titanium, 6% Vanadium and 4% Aluminium), although it could produce parts from almost any available metal powder. Ti64 parts are of main interest in the aerospace industry and for this reason it is the focus of the Aeroswift machine. Another project at the CSIR is investigating producing Ti64 powder in South Africa. Along with the other cost reducing factors, using the Aeroswift machine for production parts will be much more cost effective, in relation to other commercial machines.

2.4 Defects in SLM

This section describes the two defects encountered in SLM that could cause damage to the scraper and build failure namely warpage and balling. These two defects have been encountered in test builds on the Aeroswift machine.

2.4.1 Warpage

SLM requires high heat input from a laser in order to entirely melt the powder. After the powder has been melted, it almost instantly solidifies. This rapid melting and solidification of the material introduces thermal variations. When a material melts, it expands and when it solidifies, it contracts, which then produces residual stresses in the part due to the expansion and contraction happening at different rates. Every consecutive layer introduces its own residual stress and these residual stresses are what causes a part to warp or distort (Vora, et al., 2015). Warpage particularly happens when an overhang of a part, is unsupported or inefficiently supported, as shown in Figure 2-9 and Figure 2-. Support structures are used to anchor a part to the baseplate and prevent the overhang from warping or sagging and from moving during processing. However, sometimes the part can tear away from the support structures, or layers can delaminate, due the residual stresses in the part. When this happens, the warped part is higher than the current layer height and will cause damage to the scraper when the next powder layer is deposited or cause the powder deposition system to jam. (Kleszczynski, et al., 2012).

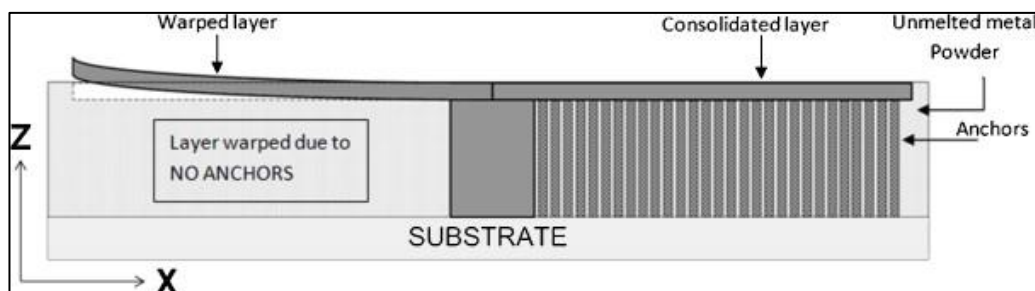


Figure 2-9: Difference in supported and unsupported overhangs (Vora, et al., 2015)

Residual stresses can be drastically reduced with post process heat treatment. Shiomi, et al. (2004) showed that heat treatment at 600-700 °C, for one hour, reduced residual stresses by as much as 70%. They also investigated the effects of preheating the baseplate and the results show a 50% reduction in residual stresses for a preheat temperature of 160°C, but will differ for every material. A chrome molybdenum steel powder mixed with copper phosphate and nickel powders was used. Many commercial machines already incorporate preheated build platforms to reduce the residual stresses during process and in turn, reduce the possibility of warpage. Figure 2- shows delamination of a part from the build plate cracking caused by the residual stresses. Warpage in parts reduce with larger layer thicknesses. (Zaeh & Branner, 2010).

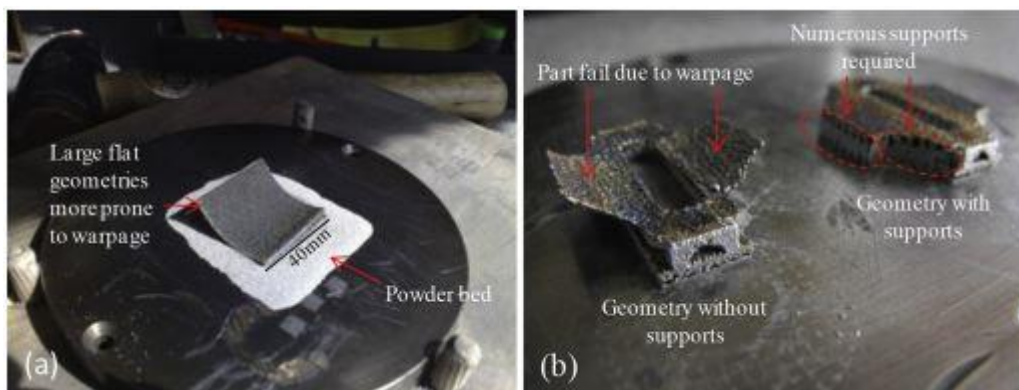


Figure 2-10: Warpage of flat unsupported geometries (Vora, et al., 2015)

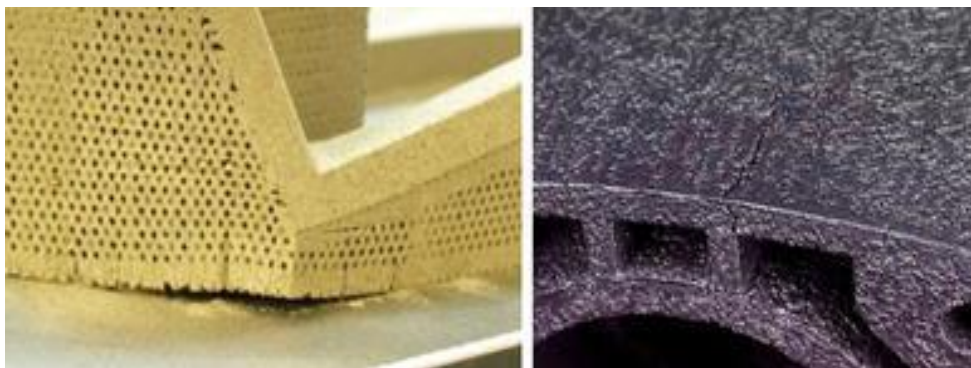


Figure 2-11: Delamination and crack formation due to residual stresses (Zaeh & Branner, 2010)

2.4.2 Balling

Balling is found in SLM processes due to the high-energy input and the melting of powder. It occurs when the molten material does not wet the underlying substrate due to the surface tension, which tends to spheroidise the liquid, as explained by Kruth, et al. (2004:619). The wettability of a material is what determines if balling will occur and is “the tendency of one fluid to spread on, or adhere to, a solid surface in the presence of other immiscible fluids.” (Crain, 2015). Balling is caused by process parameters, such as layer thickness, scan speed, spot size and Laser power (Kruth, et al., 2004). These defects stand out high above the powder layer which will damage the powder scraper when it passes or possibly cause the powder deposition system to jam. Figure 2-10 shows the balling effect encountered on the Aeroswift machine while doing single track experiments. If a powder scraper is flexible enough, balling will not affect it as much, but some damage might still occur. Ideally, the powder scraper should not leave excess powder around these defects, as excess powder will allow the defects to grow in the following layers. Balling decreases when lowering the oxygen levels and is eliminated away if the process parameters are optimised (Li, et al., 2012).



Figure 2-10: Balling effect

2.5 Layer deposition and powder scraping

Layer deposition is the process of creating the layer of powder in a PBF machine. The quality of the powder layer is of the utmost importance and refers to the flatness (surface roughness) of the layer. It is a delicate operation and significantly contributes to the build time, as the layer deposition can take relatively long. From the layer deposition, one can usually determine if a build would be successful or not.

Scraper is the term used in this report for the device responsible for spreading the layer of powder over the build platform. There are many other terms used for it, such as wiper,

spreader, re-coater or coater, smoother and a powder distributor. Defects in the powder layer can cause defects in the build. Such defects are: two consecutive powder layers differ too much (with respect to amount of ridges in the layer), layers are not uniform, layers differ in thickness and damaged scraper or unsatisfactory powder layer due to poorly manufactured scraper. A scraper is seen as a consumable in AM and could be replaced as often as after every finished build, depending on its durability.

2.5.1 Types of powder scrapers

Unfortunately, due to the SLM technology still being new and continuously developed, not much literature is available on powder scrapers themselves. A big reason for this is also that the market is very competitive and the companies do not want to disclose what they have done in order to keep an edge over the competition. Thus, most of the information presented in this literature review was obtained from patents, brief mentions in other articles, observation and personal experience.

2.5.1.1 Blade

A blade scraper is shown in Figure 2-11 below and was patented by EOS (Thomas Mattes, 1997). The blade is made from a hard steel and has, in most cases, a sharp angle of about 30° – 40° . The layer produced by this scraper is accurate, uniform and is almost perfectly flat. From visual inspection of the layers it produces, one can see that the surface finish is good. Blades are also able to operate at high temperatures. A blade is, however, inflexible and any obstacle, such as balling defects or part warpage, encountered while scraping will either damage the blade or cause the scraping system to jam and result in a build failure.

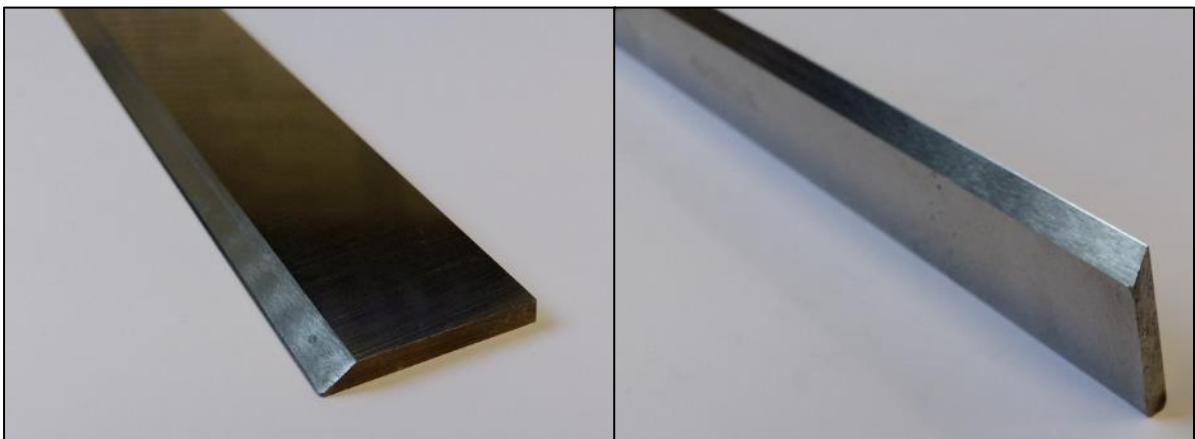


Figure 2-11: Solid blade scraper

2.5.1.2 Carbon fibre brush

This scraper is a brush made from unidirectional carbon fibre, which contains no resin. EOS produces these brushes, but it was first developed and patented by Trumpf (Graf & Lindemann, 2002). These brushes are the most flexible of all scrapers and thus they perform well when encountering defects, such as balling and warpage. They are, however, more prone to damage and the layer they produce is not as good as more solid scrapers. Carbon fibre has the ability to operate at high temperatures and if the components used for manufacturing have high temperature resistance, these brushes can operate at several hundred degrees Celsius. The typical dimensions of a brush is about 1.5 mm high and 0.5 mm thick. A commercial carbon fibre brush scraper is shown in Figure 2-12 and a magnified version in Figure 2-13.



Figure 2-12: Carbon fibre brush

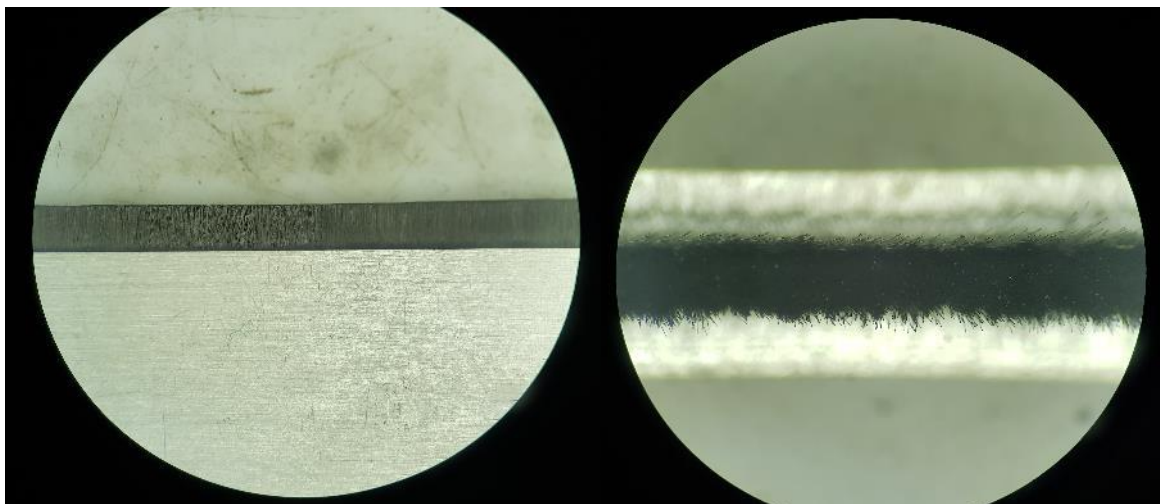


Figure 2-13: Stereoscope images of carbon fibre brush

2.5.1.3 Metal comb

This type scraper is also described as a brush or a rake. It uses shim stock (about 125 μm) which is cut into a comb-like shape as shown in the Figure 2-14. Two rows of the combs are used. The second row is offset to the first row to create a “solid” face. If only one row is used, lines in the powder layer would be created by the gaps between the combs teeth. This type of scraper is used by ARCAM in their EBM machines. These machines have a preheating temperature of 650 °C for processing Titanium and even higher temperatures for Titanium-Alumides (Titanium with a higher percentage Aluminium content), which shows the scraper’s ability to operate at high temperatures. The combs have some flexibility due to the thin shim stock used and the narrow teeth width. However, larger defects will cause the teeth to plastically deform and subsequently the comb will scrape unevenly and poor layers will be obtained.

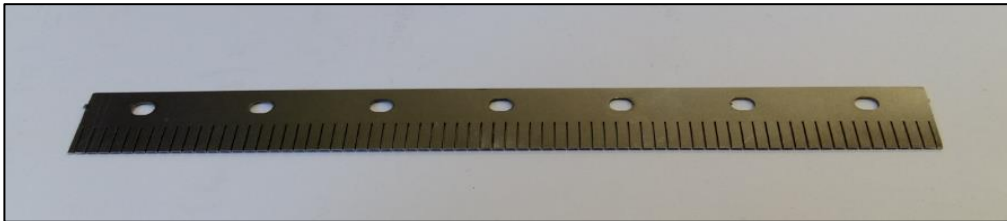


Figure 2-14: Metal comb scraper

2.5.1.4 Wiper

These scrapers are used in SLM Solutions’ machines and are shown in Figure 2-15. They are made from either silicon or a polymer composite. Wipers have some flexibility, but not a great deal. They can deal with small defects, but not much higher than one layer thickness (20 μm in the case of SLM Solutions’ machines). The silicon wipers are more flexible than the polymer composite wipers. A big disadvantage of these wipers is that they cannot operate at high temperatures (more than 200°C).

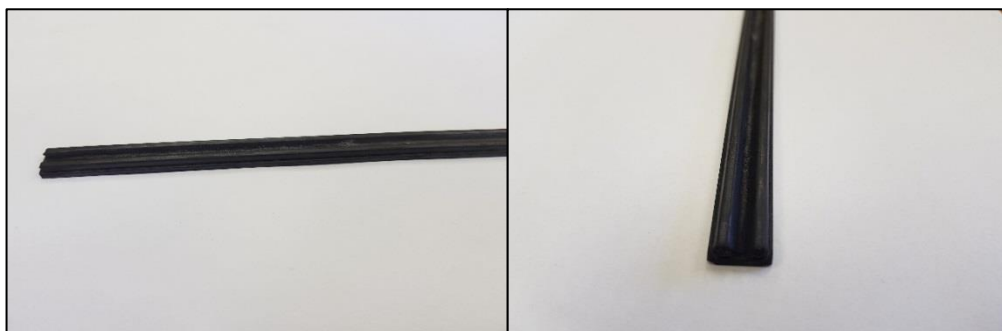


Figure 2-15: Wiper type powder scraper

2.5.1.5 Roller

A roller is the only scraper that makes use of mechanical movement other than that of the powder deposition system. It is a counter rotating solid cylinder. Counter rotating means that the cylinder rotates in the opposite direction to the direction of travel. They are rigid and defects in the build tend to damage the roller or cause it to jam. Damage to the roller results in unsatisfactory powder layers. Rollers are also able to operate at high temperatures. They are made from a ceramic material, in most cases. This type of scraper is not used in any metal PBF machines as they are expensive and more prone to wear.

Advantages and disadvantages of different scrapers are shown in Table 2-3.

Table 2-3: Advantages and disadvantages of each powder scraper

	Advantages	Disadvantages
Blade	Good powder layer quality. High operating temperatures.	Defects cause damage to blade or deposition system to jam. Does not allow for misalignment of the build platform in y-direction. No flexibility
Carbon fibre brush	High operating temperatures. Flexible Allows for misalignment of build platform in y-direction. “Brushes” defects clean, which allows the Laser to re-melt the defect to possibly eliminate it.	Fibres break off during process. Powder layer not as good as solid scrapers.
Metal comb	Good powder layer. High operating temperature.	Teeth plastically deform if defects are much higher than

	Some flexibility.	the current build height. Flexibility is not enough to allow misalignment of the build platform. Leaves excess powder around defects due to width of teeth, causes defect to keep growing.
Wiper	Good powder layer Some flexibility	Lower operating temperatures. Flexibility is not enough to allow misalignment of the build platform in the y-direction.
Roller	Good powder layer. High operating temperatures.	No flexibility. Does not allow for misalignment of the build platform in y-direction. Requires external mechanics to counter rotate the roller.

2.6 Process monitoring

In SLM it is important to be able to monitor the process due to the strict standards and requirements in the medical and aeronautical industry. Being able to monitor the process, and determining errors in the build, is the key to qualifying machines in these industries. There are many things that are constantly monitored during the SLM processes in commercial machines. Some of them are: the laser beam, the melt pool and the quality of the powder layer. With these, one can predict to a certain extent, if a build will have flaws or not. If a part fails or has internal defects, one can investigate what went wrong by going back to the build files and looking at the data obtained during the build. For this project, only

the powder layer monitoring was investigated for the possibility of using it to qualify the Aeroswift powder scraper.

2.6.1 Online Quality Control – Visual Inspection

Craeghs, et al. (2011) developed a method of monitoring the deposited powder layer on their in-house developed SLM machine, which is being used in numerous commercial machines as a standard or add-on feature. The method uses lights to illuminate the powder bed from three directions, the one from the top, one perpendicular to the direction of travel of the powder deposition system and the other one parallel, and a camera. The diagram below shows a schematic of their set-up.

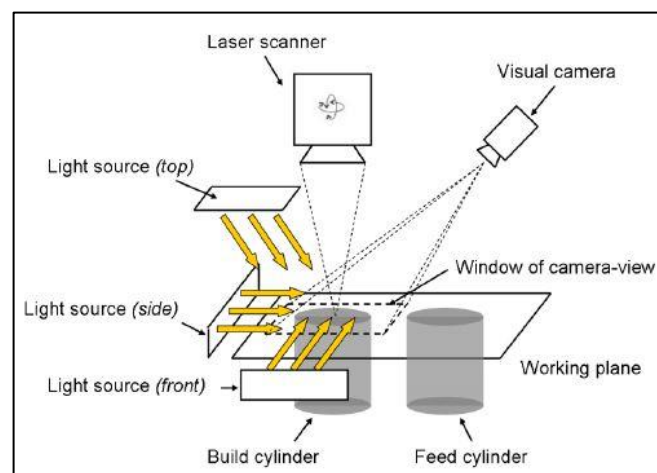


Figure 2-16: Schematic of the experimental set up of Craeghs, et al. (2011)

The camera also has a focusing lens and is aimed at the powder bed.

After a powder layer is scraped, three photos are taken of the powder bed, one with each of the lights on, while the others are off (to have the powder bed only illuminated from one direction). These photos are converted to greyscale images and run through image processing algorithms. Figure 2-17 shows a sample of such a greyscale image obtained by Craeghs et al during their experiments. A line profile is then obtained by averaging five vertical lines in the images (also shown in Figure 2-17). Each point in this line has a greyscale value. These values are plotted on a graph (Figure 2-18) and a mean value is determined. The mean value is indicated by the red line on the graph. A threshold is set for the greyscale values, indicated by the green lines on the graph. If a value surpasses the threshold values, the system will give an error and inform the operator.

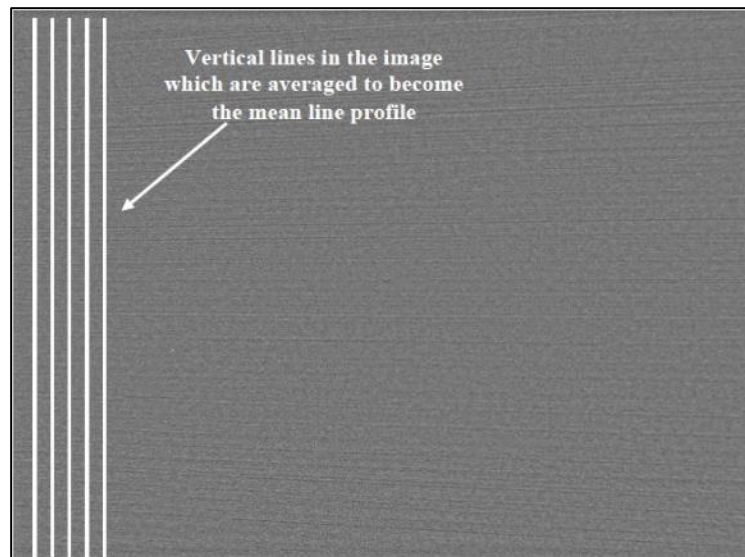


Figure 2-17: Photo of powder layer obtained by Craeghs et al. (2011)

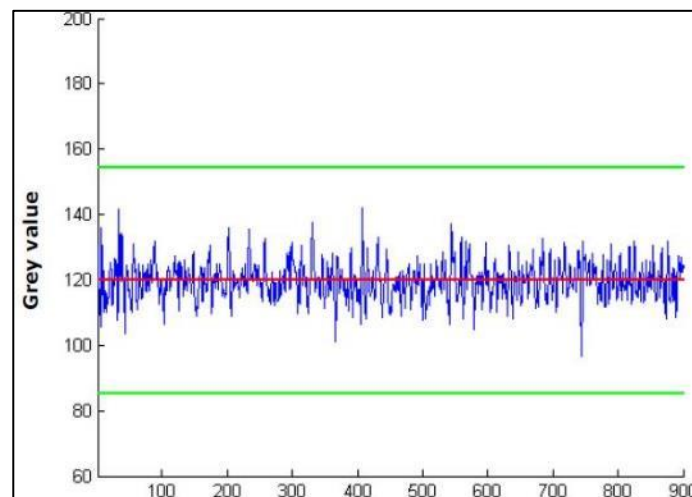


Figure 2-18: Averaged line greyscale graph (Craeghs, et al., 2011)

Every layer is used for comparison to the previous layer in order to determine if there is any significant change between two layers. Figure 2-19 shows the layer produced by a worn and damaged powder scraper and Figure 2-20 shows the resultant graph. It can be observed that the graph has more noise than the graph in Figure 2-18. The reason is that wear on a powder scraper results in smaller shadow lines in the powder layer, which in turn gives higher and lower greyscale values. This method essentially looks at the shadows in a powder layer, as this is what indicates defects and wear in a powder layer.

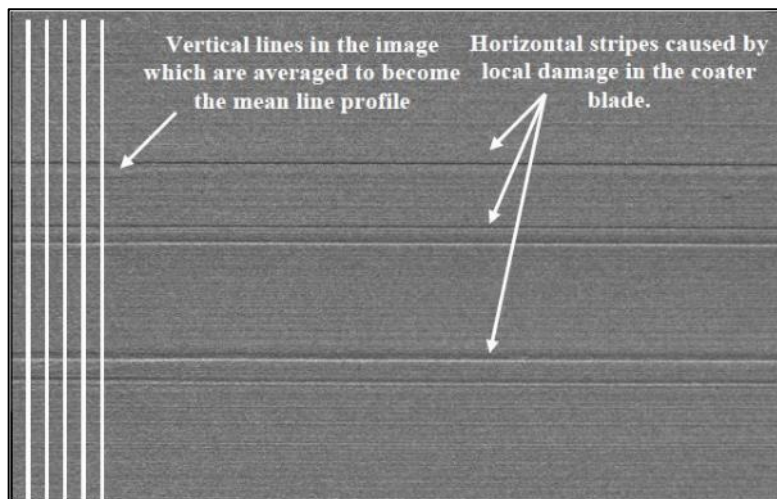


Figure 2-19: Averaged line greyscale graph of worn powder scraper (Craeghs, et al., 2011)

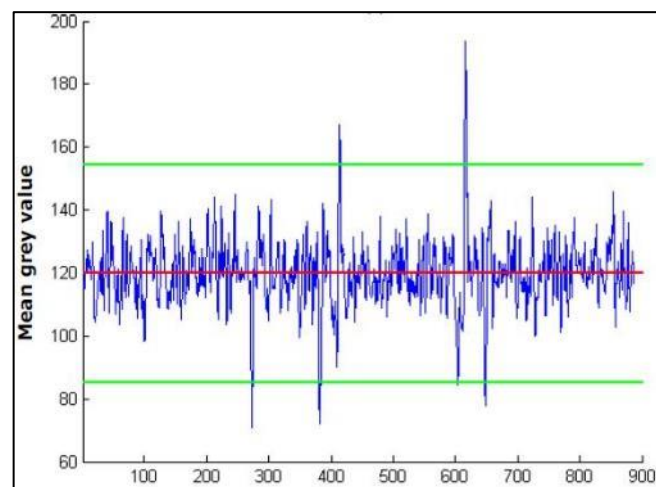


Figure 2-20: Greyscale graph of a worn and damaged powder scraper (Craeghs, et al., 2011)

The high peaks in the Figure 2-20 shows more localised damage to the powder scraper, most probably caused by a defects in the build. If these defects are identified before melting the layer, certain things can be done to improve the powder layer, for instance re-scraping the layer. Commercial machines will automatically try to improve the powder layer by re-scraping, up to three times. If this did not improve the layer quality, the system will await instructions from the operator.

With the method of layer qualification, one can only determine if the powder layer deteriorates over time or suddenly becomes unsatisfactory.

2.6.2 High-resolution imaging

This process was developed by Kleszczynski, et al. (2012) and, is similar to the visual inspection work done by Craeghs, et al. (2011), mentioned in section 2.6.1. It is used for error detection during the build process. They argued that previous work only

monitored the unprocessed powder layer and the current melt pool, not the powder layer after melting. In addition, these systems use complex process monitoring, requires optical modifications (only for melt pool monitoring) and to implement them could be difficult. Their process detects errors, inspects part quality, measures geometrical features and is claimed to be easily implemented.

They used a 29-megapixel Charge-Coupled Device (CCD) camera aimed at the build platform, mounted on the outside of an EOSINT M 270 and three light sources: two parallel and one perpendicular to the direction of travel of the powder deposition system. The resolution of the camera resulted in about 24 $\mu\text{m}/\text{pixel}$ and enabled them to inspect the surface of the part, after melting, at bead level (the point where one can see the weld track of the Laser beam). A USAF 1951 target and a microscope calibration slide in the centre and all four corners was also used to correct the perspective distortion of the camera images.

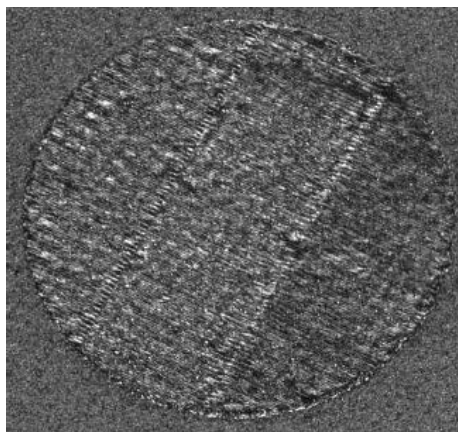


Figure 2-21: Sample image showing visible weld beads (Kleszczynski, et al., 2012)

Two images per layer were taken: one after the powder layer was deposited and one after the powder layer was melted. They purposefully adjusted the build parameters to create known defects encountered in SLM to show the worst-case scenario. Some of the simulated errors are distortion and unsupported overhangs.

Figure 2-22 is explained as follows: a) shows their test build at 5 mm before recoating, b) is after recoating, c) shows detail of b), d) is the first layer on poor support structures after melting, e) is an enhanced area of d) and f) shows a cylindrical test sample after being exposed to contaminated powder.

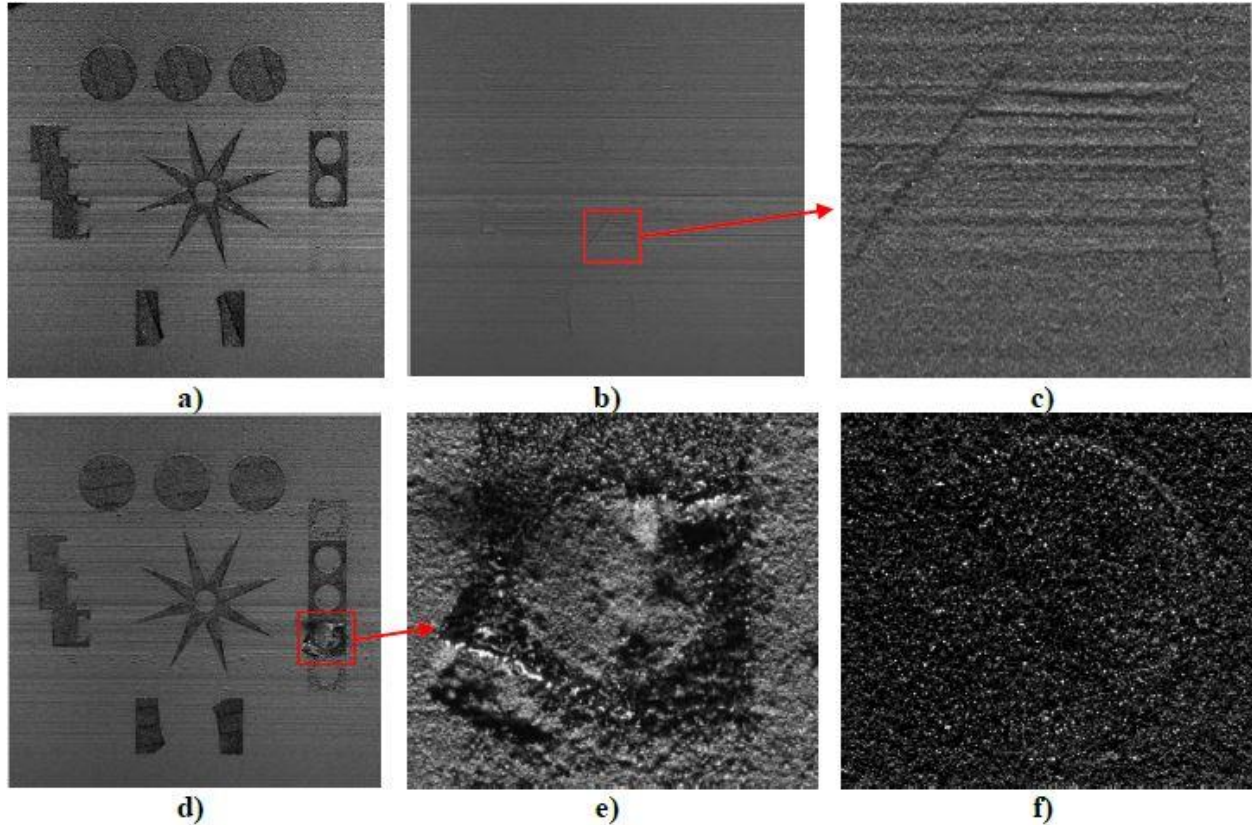


Figure 2-22: Different type of errors affecting process stability (Kleszczynski, et al., 2012)

A second test build was done, consisting of nine cylindrical specimens, as shown in Figure 2-23 b). The three test samples on the left were given low energy input parameters, the middle three optimised parameters and the right three high energy input parameters. The top row was assigned 40% less power, the middle row 30 % increase in hatch spacing and the bottom row a 40% increase in velocity. Reference images were taken of these samples and the spot diameter increased in order to reduce the energy input. Their results are shown in Figure 2-23.

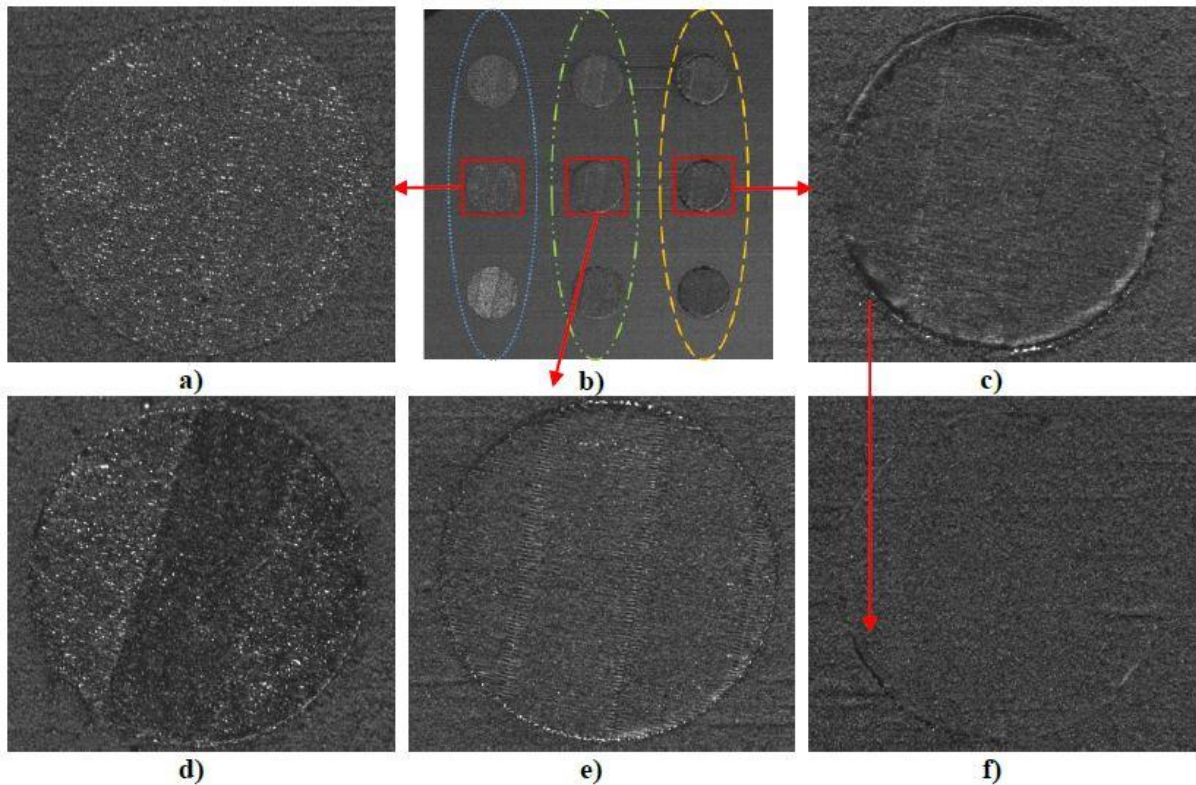


Figure 2-23: Second test build with varying process parameters (Kleszczynski, et al., 2012)

They concluded that these known errors can be detected by using the high resolution imaging process. Also, after detection, certain measures can be taken to correct these errors. By coupling their process monitoring with the process control software, this could be automated. Another conclusion was that their concept is easy to implement in any existing SLM machine.

2.6.3 Laser Line Scanner

This is a device that measures the two dimensional line profile of an object. The profile is measured by using triangulation and given in x- and z-coordinates. A laser line is projected onto an object, the laser light is reflected of this object and diverted through optics onto a highly sensitive sensor matrix. A controller then calculates, from the matrix image, the distance from the scanner to the object for each point in the line profile. (Micro-Epsilon, n.d.). These Laser Line Scanners (LLC) have high accuracies and is ideal for use where non-contact measuring is required. For this reason this technique has been used in this project. The model that was used is Micro-Epsilon's ScanCONTROL 2960-50/BL. It has a z-resolution of 4 μm , 1280 points on the x-axis, can measure at up to 2000 Hz, a midrange measuring distance of 95 mm (z-direction) and a midrange measuring field of 50 mm (x-direction).



Figure 2-25: A Laser Line Scanner (Micro-Epsilon, n.d.)

2.6.4 Vision System

Cooke & Moylan (2011) did research on intermittent process measurements in AM to both improve the process as well as characterize the geometries of the internal parts. They designed a test part which allowed for characterization of the measurement process. A binderjet machine (see section 2.2.4) was used for their experiments. For the measurement system they used a charge-coupled device (CCD) digital camera and a light source to illuminate their build platform. The camera would take a photo after being triggered by the powder scraper when finishing coating a powder layer. Three different magnifications were used and calibrated with a calibration artefact. The three magnifications are shown in Figure 2-24.

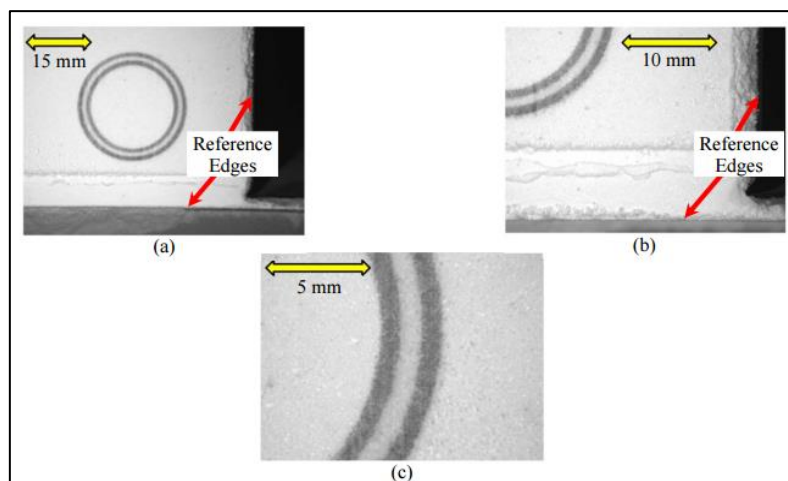


Figure 2-24: Different magnifications used by Cooke & Moylan (2011)

Six photos were taken per layer and an average image generated. The magnification in (a) was used to determine where the built part is with respect to the edges. Magnification (b) was used to compare the inside and outside diameters with an inner

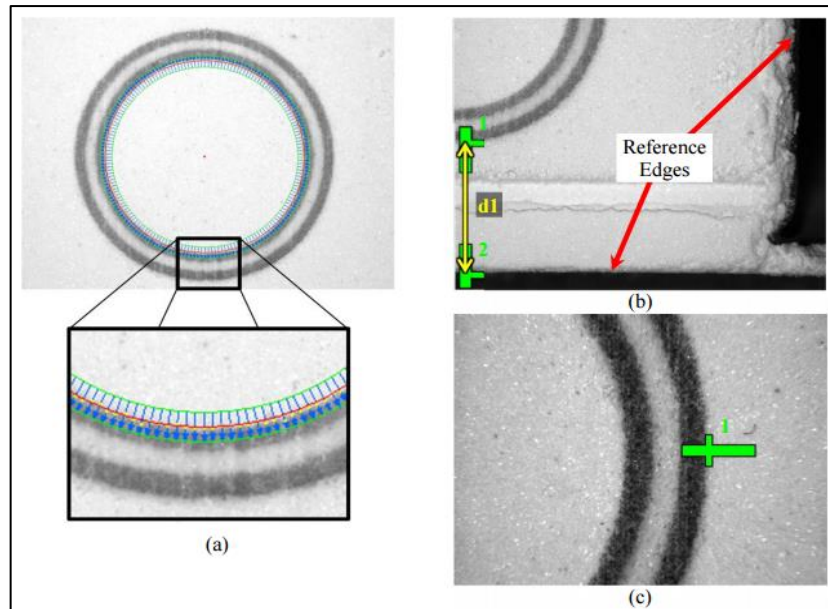


Figure 2-26: Diameter, edge reference and wall thickness checks (Cooke & Moylan, 2011)

and outer boundary. Magnification (c) was to track one edge point.

According to Cooke & Moylan (2011), a process that is well controlled is predictable and repeatable. The aim of their project was thus to determine the part position and geometries for each layer and to investigate the consistency in their test part. They mentioned from the results that there is about a 150 μm deviation between each layer, which is a significant deviation, and that it seems to fluctuate (Figure 2-27).

They concluded that the first magnification, resulting in 0.049 mm/pixel, could be used to predict the final geometry of a part, while the second and third magnifications for process control, and that the system can show under sizing during a build.

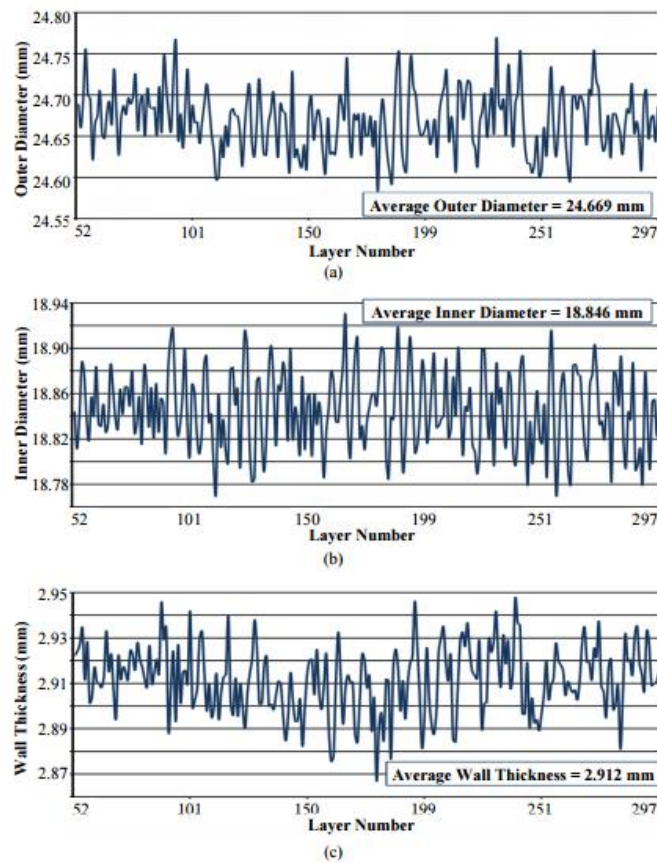


Figure 2-27: Results from the vision system (Cooke & Moylan, 2011)

This method was mentioned to show that it is possible, to a certain extent, to determine the sizes of defects by calibrating the images using a known size object and the shadow it casts. If this method is used along with high resolution imaging of Kleszczynski et al. (2012) and visual inspection of Creaghs et al. (2011), a layer's defects can be quantified. However, the accuracy and resolution of a process like this would be subject to the resolution of the camera and the size of the bed. Even with a 29-megapixel camera with a resolution of 6576 by 4384 pixels, the resultant distance presented by a pixel, for a bed width of 640 mm, is only 97 μm . Thus, the resolution of such a method would not be suitable for this project.

Table 2-4 shows a summary of the advantages and disadvantages of the process monitoring methods listed above. Visual inspection and high-resolution imaging was grouped together due to their many similarities. The vision system was left out because it does not look at the powder layer itself, but.

Table 2-4: Advantages and disadvantages of process monitoring methods

Method	Advantages	Disadvantages
Visual inspection / high resolution imaging	Looks at entire powder bed. Processing time is fast. Hardware is relatively cheap (<R20 000 for a camera with the right specifications)	Does not quantify the powder layer. Requires special image processing software.
Laser Line Scanner	Has a high accuracy (4 μm z-resolution and 40 μm x-resolution). Can fully quantify a powder layer.	Slow processing time. Does not look at the entire powder layer. Post processing calculations are required. An LLC is expensive (about R 60 000)

2.7 Titanium powder

Ti6Al4V (Titanium, 6% Aluminium, 4% Vanadium) powder is one of the most widely used powders in PBF processes and is an aerospace grade material. There are many different methods of producing metal powders, but the most common is gas atomization. With gas atomization, a billet of the metal or alloyed metal is melted in an inert atmosphere or vacuum (Argon atmosphere in the case of Ti6Al4V). The top chamber, where the molten metal is situated, is pressurised in order to force the molten metal through a nozzle. High-pressure gas is then blown into the molten stream. This breaks the molten metal up into particles, which then solidifies. These solidified particles are mostly spherical. (LPW, n.d.). Figure 2-28 shows a diagram of gas atomisation.

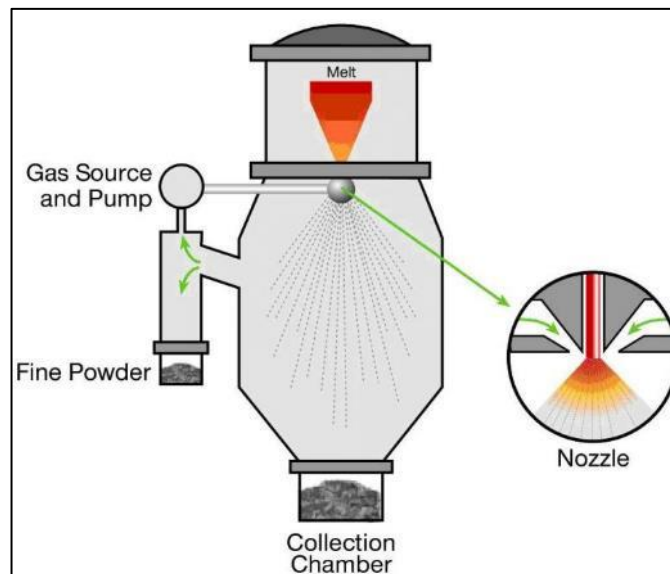


Figure 2-28: Gas atomisation (LPW, n.d.)

Flowability is defined as the ability for a powder to flow (Mercury Scientific, 2008). According to (Leturia, et al., 2014), the flowability of a powder is influenced by the following:

- The physical properties such as geometrical shape, particle size, density, roughness and porosity.
- The bulk properties such as particle size distribution, bulk density and inter particulate forces.
- Environmental conditions such as temperature and humidity.

Flowability plays a large role in PBF as it influences the quality of a powder layer, impacts on the handling of the powder (filling the machine, sieving, extracting un-used powder) and deposition system as well.

In PBF processes, the particle size distribution, geometrical shape and dryness has a larger impact on the flowability. To ensure optimum flowability, the powder used in this technology has spherical geometry and is dried beforehand. Figure 2-29 is an image of Ti6Al4V powder, obtained from a Scanning Electron Microscope (SEM). The powder is also usually sieved before and after use to decrease the fines and oversized particles. The most common particle size distribution used in PBF is 20 - 60 μm , but for LENS processes, it is 40 - 100 μm . LENS processes require even higher flowability than PBF processes and for this reason, smaller particles will not work.

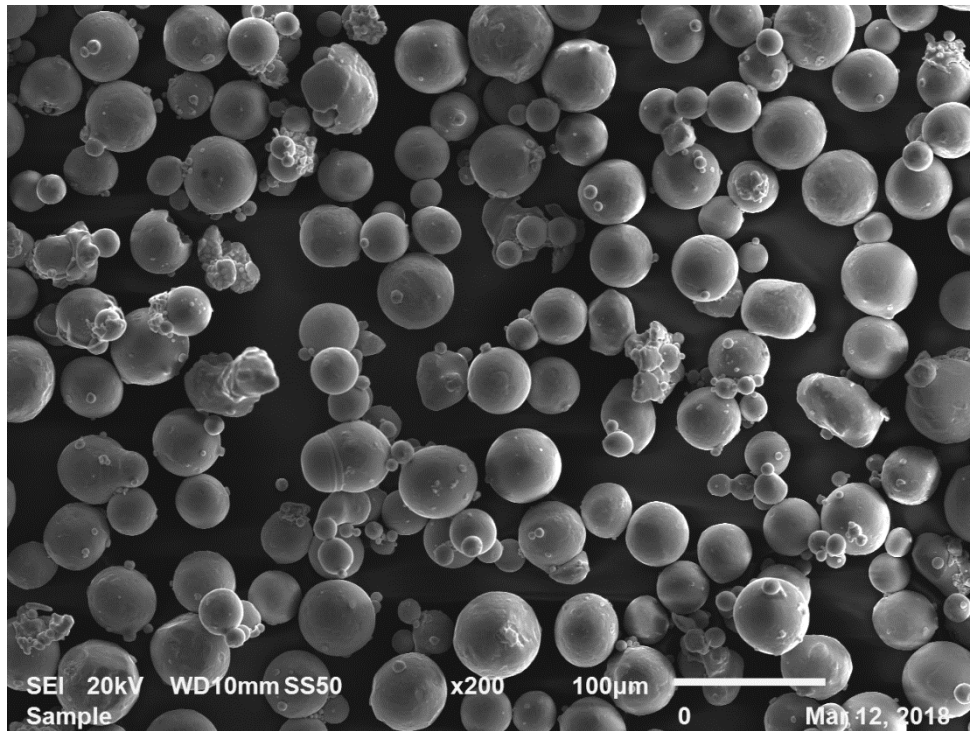


Figure 2-29: Typical Ti6Al4V powder

CHAPTER 3 EXPERIMENTAL PROCEDURE

3.1 Methodology

A literature study (Chapter 2) was conducted to investigate possible solutions to the first research objective. During this study, no literature could be found on the qualification of powder scrapers used in AM. However, only two viable solutions were identified: the first being that from the research done by Craeghs, et al. (2011), and the second being an LLS. After further investigation, it was determined that a LLS is the better option, as the camera and light method does not present the layer in a quantitative manner. Although, it was mentioned that it is possible to do this by combining the research of Craeghs, et al. (2011), Kleszczynski, et al. (2012) and Cooke & Moylan, (2011). However, this would not be as accurate as using LLS.

It was decided that five powder scrapers would be tested: three Aeroswift carbon fibre scrapers, a commercial carbon fibre powder scraper (produced by EOS for use in their machines) and a solid blade scraper manufactured from high speed steel (also commonly used in EOS machines). Three Aeroswift scrapers were used to show repeatability, as these scrapers are made by hand. The commercial carbon fibre scraper was used to compare the Aeroswift scraper to a carbon fibre brush scraper used in the industry, as they have been proven to work. The Aeroswift carbon fibre brush's dimensions are comparable to that of the commercially used one, except for its length, which is much longer, 640 mm as opposed to 256 mm. The commercial carbon fibre brush has a brush height of 1.5 mm and brush thickness of 0.5 mm, where the Aeroswift powder scraper has 2 mm and 0.5 mm



Figure 3-1: Tested powder scrapers

respectively. Figure 3-1 shows all three tested powder scraper and a commercial carbon fibre brush. From the top to bottom they are: the Aeroswift custom powder scraper, a single commercial carbon fibre brush scraper, three commercial carbon fibre brush scrapers in a scraper bracket for testing, and a solid blade scraper.

It is generally recognised that a solid blade scraper produces a near-perfect layer due to its edge being machined straight and sharpened. For this reason, it was decided to test a solid blade scraper, to show what a “perfect” layer would look like and to see how much a carbon fibre brush scraper’s layer quality differs. Thus, if the chosen method of quantification works, there will be a distinct difference between the performance of the carbon fibre powder scrapers and the solid blade scraper.

3.2 Experimental setup

An x-y welding table was utilised for the test set-up. The table was modified to incorporate the Aeroswift powder scrapers. The same brackets used for the Aeroswift scrapers was used to mount the commercial carbon fibre brush scraper as well as the solid blade. This made changing between powder scrapers easy. The LLS was mounted on a motorised translation stage, for linear movement in the x-direction, using a machined bracket. The bracket ensured that the LLS would be perpendicular to the powder layer. The motor used for the movement was controlled by drives connected to a laptop with the correct motion control software installed. The translation stage is part of a carriage on the welding table that runs on high precision rails with high precision linear motion bearings. This carriage was used for the y-direction travel of the powder scraper to scrape the layers of powder.

During preliminary tests, it was observed that there were many lines across the powder layer, consistent with vibrations from the drive motor. The carriage was thus disconnected from the motor to eliminate the vibrations caused by the motor and the scraping would instead be done by dragging the carriage by hand. Because the system runs on high precision linear bearings, human error would have no effect on the quality of the powder layer. Also, as this project does not investigate the effects of scraping speed, this would be sufficient. The same laptop used for the motion control of the translation stage, was used to run the LLS’s software, scanCONTROL. The tests were conducted at room temperature with no preheating (excluded drying of powder before the tests, refer to section). As mentioned in Chapter 1, durability and high temperature tests were not conducted in this project, however, those are important test for Aeroswift that will be conducted in the future.

The powder that was used in this project is Grade 5 Ti6Al4V powder, the same as what is used in the Aeroswift machine. A German-based company, TLS Technik, produces this powder by gas atomisation and the typical composition of the powder is shown in Table 3-1. The typical particle size distribution is 20 - 60 μm , with 5 % below size and 2 % above size. Appendix A.1 shows the full specification sheet for the powder, given by the supplier. Appendix A.2 gives the specification for Ti6Al4V, by ASM International, which shows that the composition range of TLS Technik, is in line with the accepted standard.

Table 3-1: Composition of typical Grade 5 Ti64 powder

Element (%)	Al	V	Fe	O	C	N	H
Ti6Al4V Grade 5 typical	5.9	3.9	0.19	0.12	0.01	0.01	0.004



Figure 3-4: Test setup

Two titanium plates were used as base plates for the powder scraping. Refer to Figure 3-4 to see the test setup. Figure 3-2 shows the high-precision linear bearings used on the high-precision rails for travel in the y-direction, referred to earlier.



Figure 3-2: High-precision linear bearing



Figure 3-3: Dovetail translation stage

Figure 3-3 is of the dovetail translation stage, to which the powder scraper are attached. Adjusting these translation stages is how the powder scrapers are aligned with the baseplates.

As mentioned in section 2.6.3, the ScanCONTROL 2960-50/BL model of Micro-Epsilon was used in the test and is displayed in Figure 3-5.



Figure 3-5: Micro-Epsilon's ScanCONTROL 2960-50/BL

3.3 Procedure

The powder used in the tests was dried at 120 °C to ensure optimum flowability for the tests. The scraper was aligned with the base plates and the scraping height set to scrape a layer more or less 0.5 mm thick. Powder was deposited in front of the scraper and scraped over the base plates by manually dragging the carriage. After a uniform layer of powder was scraped that covered most of the base plates, the carriage was positioned close to the start of the powder layer for the measurements to be done.

Nine line profiles (will be referred to as a line sections) were captured with the LLS, while the y-position remained unchanged, to cover a straight line with a total length of 540 mm. The LLS measures at a rate of about 5 Hz. Thus, because the measuring process was manually started and stopped, multiple datasets were given for each line section. The carriage was then moved to a new y-position to measure a different line across the powder layer. This was done for three separate lines in random y-positions. After all nine line sections were captured for each of the three lines, more powder was added in front of the powder scraper and a new layer was scraped. The new layer was then measured in the

same way, as well as for a third powder layer. The data obtained was transferred to Microsoft Excel to be processed. For each of the nine line sections the following was done:

- An Excel file was created with a name indicating the line section number, the line and the powder scrapers used to scrape the layer.
- The first three data sets of the line section was taken and averaged to give only one data set, which was transferred to the created Excel file.
- In Excel, a graph of the x- and z- coordinates was created to show the profile of the line section.
- A best-fit linear line, called a median line, was drawn on the graph and the equation for the line was acquired.
- The distance of each point on the graph to the median line was calculated using the median line equation and the x-coordinates.
- For each point, it was determined if that point was a peak. The process of determining if a point is a peak, is shown in an example below.
- The total number of peaks was calculated.
- The distribution of peaks given inside 25 μm intervals (0-25 μm , 25-50 μm , etc.) was then determined.

The following shows an example of how the line section data obtained was processed. The line section that will be used in the example is number 5 on line 1 for Aeroswift scraper 1. The Excel file name in this case was AS1_1_5. Each data set consists of 1280 x- and z-coordinates. Because of the large number of data points in the data sets, only the resultant graph will be shown, Figure 3-6.

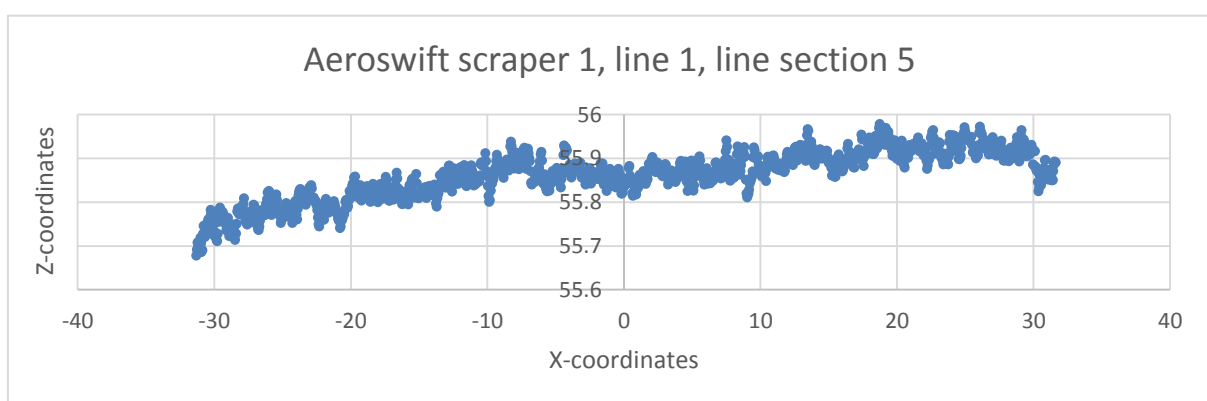


Figure 3-6: Graph of x- and z-coordinates for line section 5 of line 1

The graph in Figure 3-7 is obtained by selecting all the data points within the file and going to Insert > Charts > Scatter (X,Y) or Bubble Chart > Scatter.

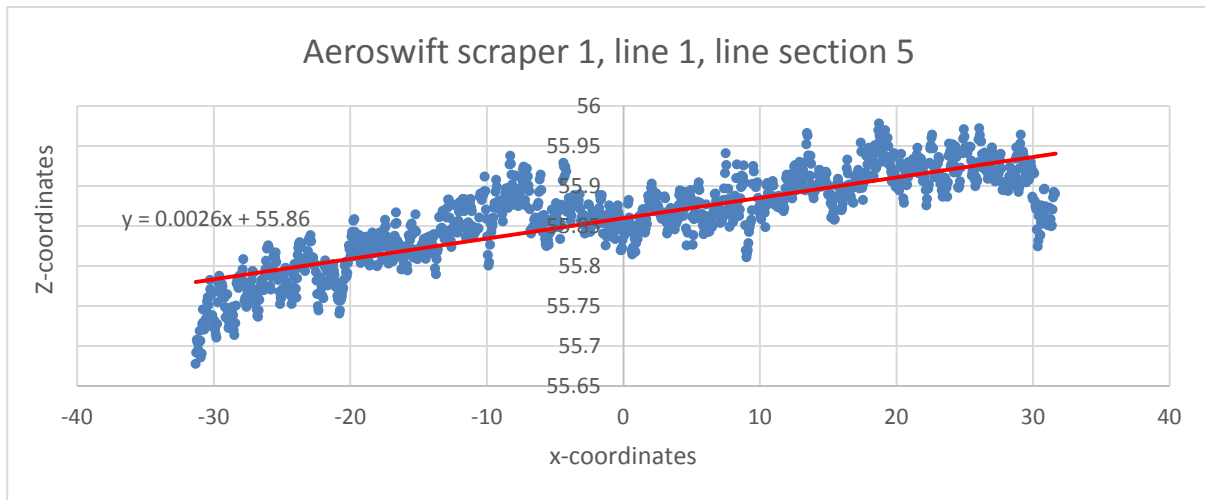


Figure 3-7: Graph with added median line and its equation

The median line and its equation on the graph in Figure 3-7 is displayed by doing the following: Right-click data point > Add Trendline > Trendline Options > Select Linear and check the “Display Equation on Chart” checkbox. Note from the median line that there is some misalignment of the LLS with the baseplate, however, it is only about 200 μm over the 60 mm line.

Next, the y-value for each point on the median line is calculated by using the median line equation and the x-coordinates. With these values calculated, the distance of each data point to the median line is determined. To determine if a data point is a peak, an IF-AND function was used within Excel.

Table 3-2: Data set sample

	A	B	C	D	E	F
	X-coordinate	Z-coordinate	Y-value of median line	Distance from median line	Peak	Peak height
1	29.390	55.930	55.93641	-0.0064	0	
2	29.347	55.937	55.93629	0.0010	0	
3	29.292	55.943	55.93616	0.0065	1	0.0065
4	29.246	55.932	55.93604	-0.0040	0	
5	29.196	55.942	55.93591	0.0060	0	
6	29.144	55.964	55.93577	0.0282	1	0.0282
7	29.098	55.953	55.93565	0.0170	0	

Table 3-2 is a sample taken from the Excel file. Column C is the y-value of the median line for each of the x-coordinates in Column A. Column D is obtained by subtracting Column C from B. Column E shows whether the data point is a peak or not (1 represents a peak). The IF-AND function was used in Column E. The example below shows what was entered into E3's cells to determine if data point A3 was a peak:

`"=IF(AND(D3-D2>0,D3-D4>0),"1","0")"`

The above is explained as follows: If cell D2, subtracted from D3, is less than zero and cell D4, subtracted from D3, is less than 0, then cell E3 will have a value of 1, else, E3 will have a value of 0. This formula, in essence, checks if the data point is higher than the ones on either side of it. Column F shows the value of column D if it was determined that the data point is a peak. Next, the number of peaks within the size ranges are determined. The formula used for this was as follows:

`"=COUNTIFS(E1:E7,">=0",E1:E7,"<0.025")"`

This formula counts the peaks found within the range of 0 to 25 μm for the entire column E. COUNTIFS was used, instead of COUNTIF, in order to have multiple criteria, which in this case was that the cell had to have a value of greater or equal to 0 and less than 0.025. In the example, it counts from row 1 to 7, but in the actual datasets, it counted from row 1 to row 1280. The resultant numbers were used for comparison of the powder scrapers.

3.4 Summary

- Five powder scrapers were tested on a test rig: three Aeroswift carbon fibre scrapers, a commercial carbon fibre powder scraper and a solid blade scraper manufactured from high speed steel.
- Nine line profiles were captured with the LLS, while the y-position remained unchanged, to cover a straight line with a total length of 540 mm. Three separate lines per layer were measure across three layers to show repeatability.
- Peaks were calculated by processing the obtained LLS data in Excel and the results analysed.
- High temperature resistance and durability were not considered during these tests.
- Main aim was to compare the carbon fibre brush scrapers with one another and then to compare them to a solid blade scraper, which would give a "perfect" layer when the blade is still new.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Powder analysis

The powder used in the tests was sent for particle size and composition analysis. The results from these analysis are shown in Appendix A.3 (last page of Appendix A.3 shows the particle size distribution results of the powder used). It can be seen that the actual particle size distribution falls within the distribution range given by the specification sheet of the supplier, shown in Appendix A.1. Figure 4-1 shows a magnified image of an un-sieved sample of the powder used. One can see the spherical geometry of the powder, but also some asymmetrical shapes. The smaller particles attached to the larger ones are called satellites. These satellites are smaller than the lower end of the specification and difficult to sieve out. They also influence the flowability of the powder negatively.

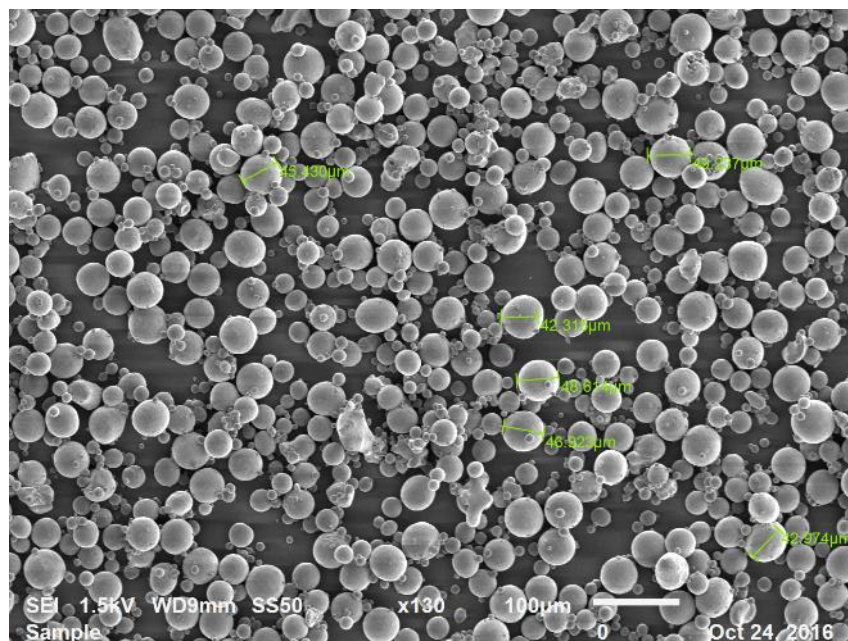


Figure 4-1: TLS Technik Grade 5 Ti64 powder – un-sieved

4.2 Powder scraper tests

Due to the way in which the LLS software exports the data, three data sets per line were obtained. These were averaged into one Excel file and then processed. The performance of the scrapers were given in the number of peaks that fell out of specification. In this case, the specification was that defects or peaks should be smaller than one-and-a-half times the thickness of one layer, which was 50 µm. The out-of-specification size distributions were thus 75-100 µm, 100-125 µm, and so on. Figure 4-2 shows a typical graph of the line profile, the best-fit line and its equation. Line section 7 of Aeroswift scraper 1 was chosen as it was a good representation of a typical line profile obtained.

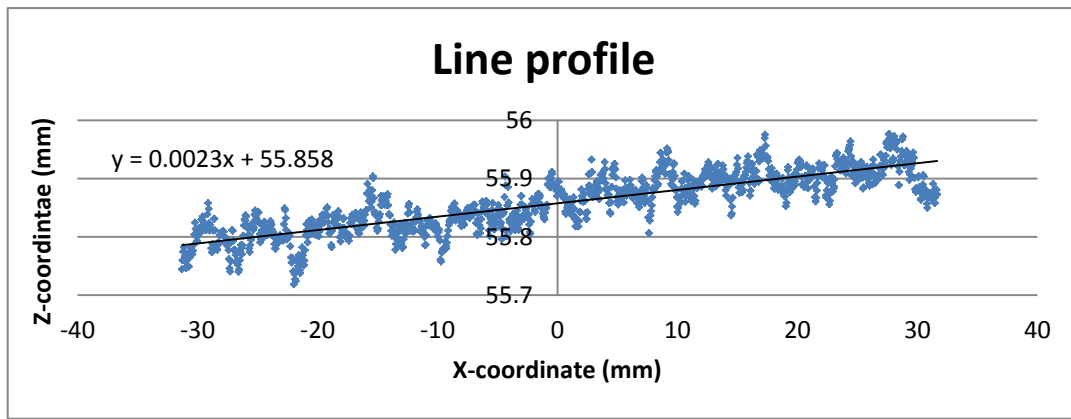


Figure 4-2: Line section profile of Aeroswift scraper

The reason for the slope of the median line is the misalignment of the LLS with the powder layer. Even though the LLS is mounted on a machined bracket to ensure alignment with the powder layer, it is incredibly difficult to achieve perfect alignment. However, the misalignment is negligibly small, only about 150 μm over 60 mm, and has no effect on the outcome of the tests.

Table 4-1 to Table 4-9 show all the peak distributions obtained, per line section, for Aeroswift scraper 2. The tables give a good comparison between the line sections and indicates that there are better performing line sections and worse performing line section.

Table 4-1: Aeroswift scraper 2 - line section 1

	Layer 1			Layer 2			Layer 3		
Peak size distribution (μm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	78	77	81	78	83	77	72	65	70
25-50	64	70	64	62	66	62	67	68	65
50-75	11	10	12	17	10	13	16	18	19
75-100	1	1	2	1	1	2	4	1	4
100-125	0	0	0	0	0	0	0	0	0
125-150	0	0	0	0	0	0	0	0	0

Table 4-2: Aeroswift scraper 2 - line section 2

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	60	69	72	66	78	52	69	67	57
25-50	63	76	65	63	62	73	66	74	70
50-75	28	13	30	32	24	18	21	20	24
75-100	1	2	3	1	1	3	1	1	3
100-125	0	0	0	0	0	0	0	0	0
125-150	0	0	0	0	0	0	0	0	0

Table 4-3: Aeroswift scraper 2 - line section 3

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	68	62	62	70	61	66	56	65	62
25-50	57	77	76	63	78	71	74	62	68
50-75	29	27	22	26	19	23	29	21	28
75-100	5	1	3	5	5	2	2	5	4
100-125	0	0	1	0	0	0	0	0	0
125-150	0	0	0	0	0	0	0	0	0

Table 4-4: Aeroswift scraper 2 - line section 4

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	81	101	94	88	88	80	96	87	93
25-50	68	63	66	75	60	73	58	69	76
50-75	8	14	10	10	15	10	14	12	9
75-100	2	2	0	0	0	1	0	0	1
100-125	0	0	0	0	0	0	0	0	0
125-150	0	0	0	0	0	0	0	0	0

Table 4-5: Aeroswift scraper 2 - line section 5

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	56	41	53	67	53	53	52	50	60
25-50	45	59	46	50	57	54	49	52	43
50-75	28	30	32	37	24	33	39	33	42
75-100	9	10	9	7	11	9	7	10	6
100-125	1	0	0	0	1	0	0	1	0
125-150	1	0	0	0	0	0	0	0	0

Table 4-6: Aeroswift scraper 2 - line section 6

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	71	70	58	61	85	76	61	59	61
25-50	65	72	72	64	54	59	71	74	64
50-75	16	15	14	21	19	16	19	11	12
75-100	4	0	0	1	2	4	3	2	4
100-125	0	0	0	0	0	0	0	0	0
125-150	0	0	0	0	0	0	0	0	0

Table 4-7: Aeroswift scraper 2 - line section 7

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	79	86	89	75	77	86	80	89	94
25-50	72	55	65	68	77	72	68	59	66
50-75	11	16	8	9	12	14	11	8	8
75-100	0	0	0	1	0	1	1	0	1
100-125	0	0	0	0	0	0	0	0	0
125-150	0	0	0	0	0	0	0	0	0

Table 4-8: Aeroswift scraper 2 - line section 8

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	89	62	67	78	82	69	75	70	72
25-50	64	70	66	61	69	66	70	60	65
50-75	10	17	20	14	13	19	13	20	17
75-100	1	5	2	1	1	3	3	0	2
100-125	1	0	1	0	0	0	0	0	0
125-150	0	0	0	0	0	0	0	0	0

Table 4-9: Aeroswift scraper 2 - line section 9

	Layer 1			Layer 2			Layer 3		
Peak size distribution (µm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	81	69	76	70	55	72	83	80	79
25-50	53	49	35	46	55	59	45	47	56
50-75	17	25	26	28	23	27	25	16	22
75-100	3	5	5	3	6	2	4	5	3
100-125	0	0	0	0	0	0	1	0	0
125-150	0	0	0	0	0	0	0	0	0

From these tables one can see that there is a trend, which is that a line section will perform more or less consistent across all three lines, for all three layers. There are deviations, but not in the sense that, if a line section performed well (has a low number of peaks above 75 µm), it would suddenly perform poorly in the following lines or layers. If the number of peaks in an out-of-specification size range differ by a significant amount, it could be traced back to peaks in lower size ranges, rolling over to a higher size range in different measurements. One should also take into account that the LLS uses the reflection of laser light off an object and its results is influence by the reflectiveness of the object. If an object is very reflective, its results might be inconsistent and incorrect. Thus, when looking at a sudden peak appearing inconsistently, it might be addressed to an object in the powder layer, which is much more reflective than the surrounding powder.

From these results, it can be observed that line section 5 performed the worst with an average number of peaks in the 75 – 100 µm range of 8.7, a few peaks in the 100 – 125 µm

range and one in the 125 – 150 μm range. Line section 4 and 7 performed the best, with an average of 0.7 and 0.4 in the 75 – 100 μm range and no peaks in the higher ranges. The rest of the line sections performed similarly, and was quite good, with almost no peaks above 100 μm and averages in the 75 – 100 μm range of 1.9, 1.8, 3.6, 2.2, 2 and 4.

The differences in the results of each line section could be due to the deviations in the bottom surface of the brush. As mentioned, these brushes are made by hand and to get the bottom surface perfectly consistent and flat is near impossible. This has the effect that some parts of the brush is flatter than others and that some line sections perform much better.

Another possible reason for the differences in results, and once again caused by the method of manufacturing, is that the brush could have an inconsistent thickness. These inconsistencies are caused by the winding of the carbon fibre tow (the unidirectional, resin-free, carbon fibre rope used to manufacture the brush) around a flat bar and rod. The tow sometimes feeds with varying thicknesses and has the effect that the brush has section where it is thinner. A thinner brush has lower stiffness than a thicker one and will deflect more under load when scraping powder. As these thinner parts are only 1 mm broad, it could cause one to see the deviations in the line sections of the powder layer. The more thinner parts in a section, the more the results will deviate from other sections.

Table B-1-1 to Table B-1-15 in Appendix B show the average number of peaks across all three lines for each powder layer. It also shows the average of all the line sections. From these tables, the difference between line sections can be seen. The powder layer quality of all the Aeroswift scrapers are very comparable to that of the commercial scraper, but neither of them come close to the powder layer quality of the solid blade scraper, as anticipated. The average number of peaks in the 75 – 100 μm range is in the region of 20 for all the carbon fibre brush scrapers and less than 1 for the solid blade.

Both the Aeroswift scrapers and the commercial scraper has some bad and good line sections, which indicates that there are some inconsistencies with the carbon fibre brush scrapers in general. This could be adhered to the method of manufacturing or damage before use. Aeroswift scraper 2 performed the best of the Aeroswift scrapers, with averages in the 75 – 100 μm range of less than 3 and 0.1 in the 100 – 125 μm range. Aeroswift scraper 3 performed slightly worse with averages in the 75 – 100 μm range of 2.4 - 3.4, still close to that of Aeroswift scraper 2, but with slightly higher average of 0.2 in the 100 – 125 μm range. Aeroswift scraper 1 performed the worst with averages between 5 and 6 in the 75 – 100 μm range, about 1 in 100 – 125 μm and even greater-than-zero averages in 125 – 150 and 150 – 175 μm ranges.

The commercial carbon fibre brush's performance was in between the Aeroswift scrapers' performances, it had averages of about 4 to 4.5 in the 75 – 100 μm range, 0.5 in 100 – 125 μm and 0.1 in 125 – 150 μm . Thus, all the carbon fibre powder scrapers had similar or comparable performances. However, the commercial carbon fibre brush scraper had variances in the average number of peaks in the 75 – 100 μm range of 0 - 14.3 across its line sections. This confirms the inconsistencies with the carbon fibre powder scrapers.

The graphs in Figure 4-3 to Figure 4- gives a comparison of the average number of peaks within the size ranges for all three the measured powder layers, for each of the tested powder scrapers.

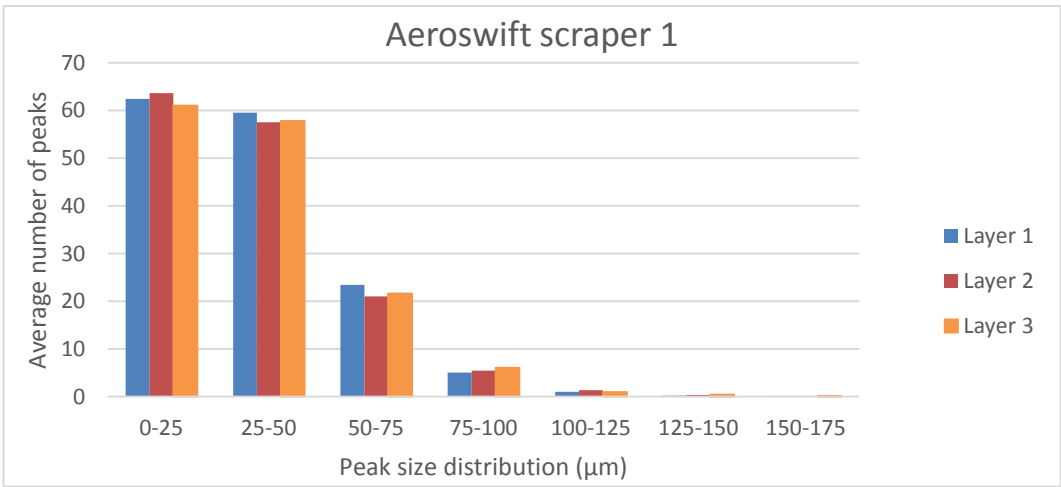


Figure 4-3: Layer comparison for Aeroswift scraper 1

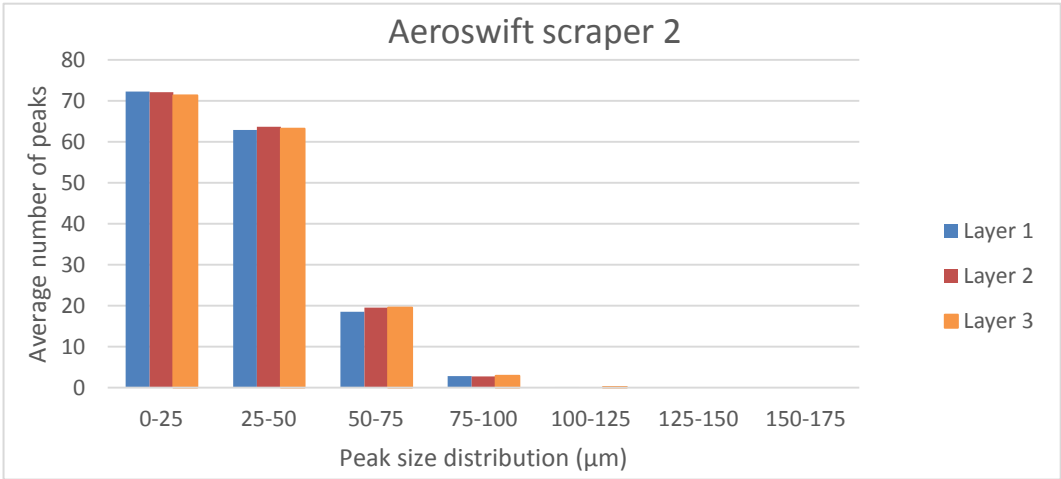


Figure 4-4: Layer comparison for Aeroswift scraper 2

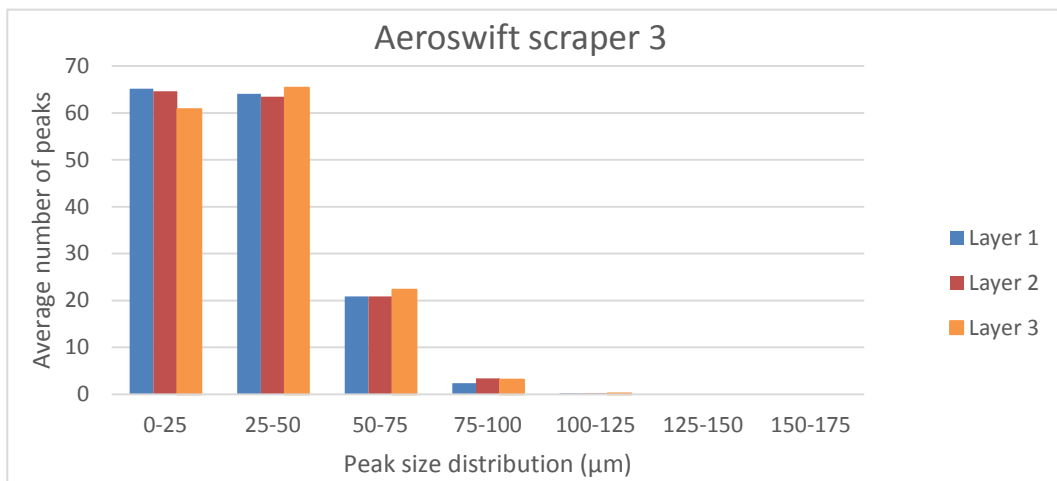


Figure 4-5: Layer comparison for Aeroswift scraper 3

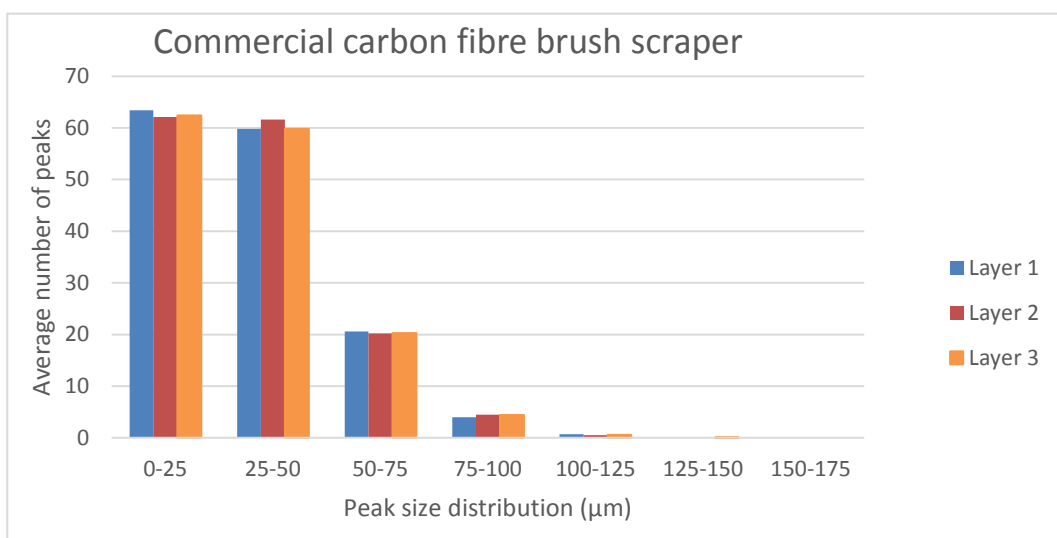


Figure 4-6: Layer comparison for commercial carbon fibre brush scraper

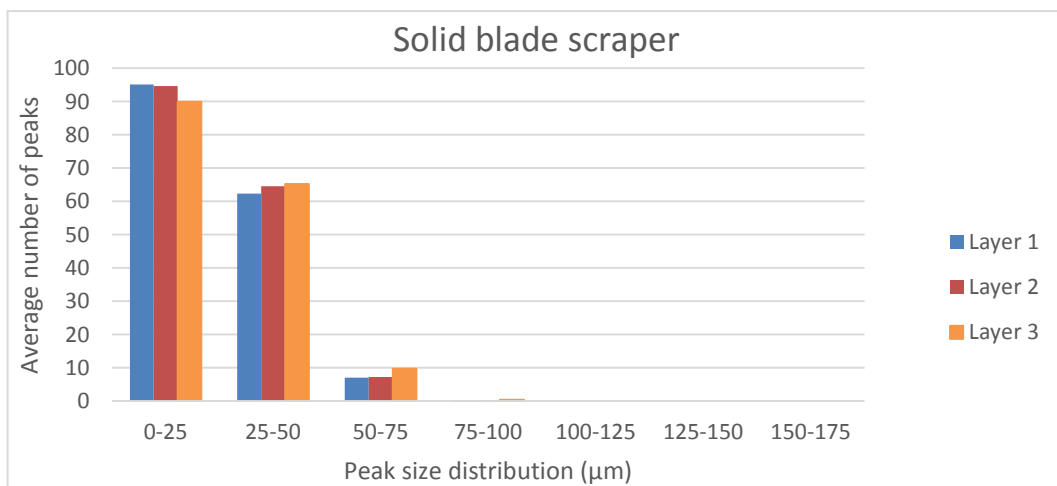


Figure 4-7: Layer comparison for solid blade scraper

From these graphs, one is able to see the clear difference between the quality of the

powder layer produced by the solid blade scraper and that of both the carbon fibre brush scrapers. Also, in each of the graphs, it can be observed that the averages across the three layers are very similar. Because the averages are so similar, one can average across the three layers to obtain a comparison graph of all the tested powder scrapers. The resultant graph is shown in Figure 4-, once again shows the large difference between the powder layer quality of the solid blade scraper versus that of the carbon fibre brush scrapers. It also shows that the performance of the carbon fibre brush scrapers are comparable.

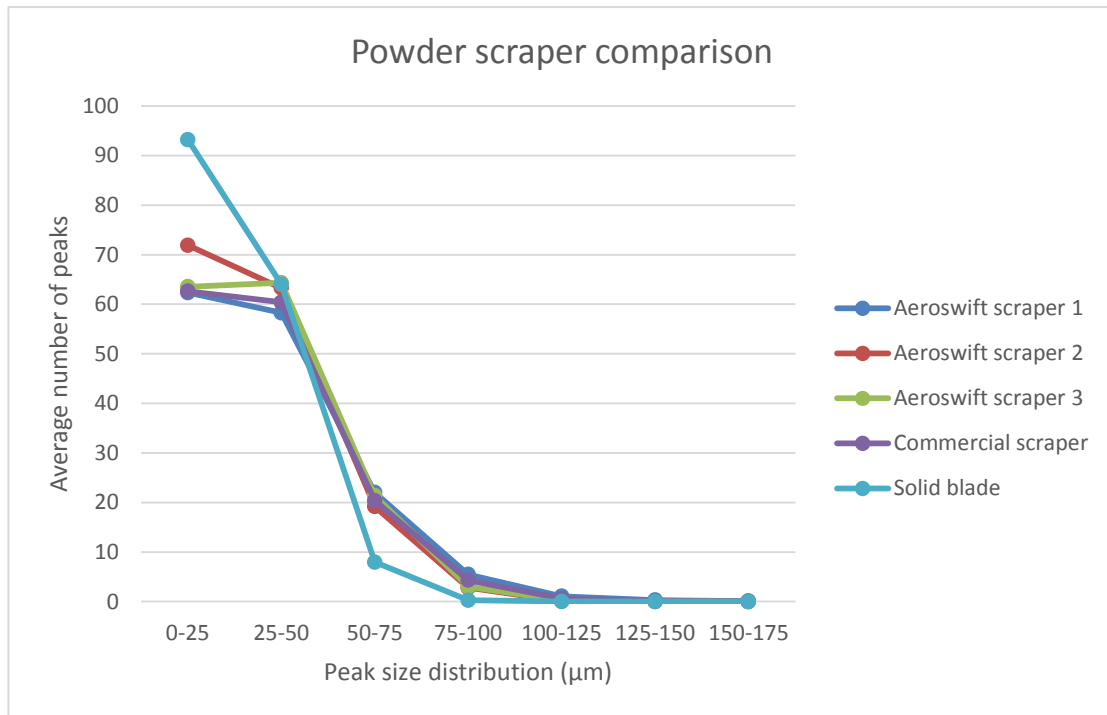


Figure 4-8: Average number of peaks comparison

4.3 Other analysis

To use the R^2 value for a comparison was also investigated, but turned out to not be suitable in this case. R^2 refers to a percentage of how well the observed data fits the fitted data, or how measured data is scattered about the median line. Results for line section 1 to 4 of layer 1 for Aeroswift scraper 1 was 28%, 8%, 25% and 68%, respectively, from which no conclusion could be drawn. Normally, an R^2 closer to 100% shows that the measured data is on the median line, but not in every case. However, because the R^2 values are both close to 0% and also higher than 50%, it would not be a good indication of the quality of the powder layer. The R^2 values for the three corresponding line sections of one layer was also calculated, but resulted in 29.1%, 22.4% and 22.1% for line section 1 of layer 1 for Aeroswift scraper 1, and 3.6%, 12.3% and 35.8% for the same line section and layer of the solid blade. For the R^2 value to be eligible as a comparison tool, these values would need to be close together.

Appendix B.2 contains 45 tables. These tables show all the line results for each of the powder scrapers. The averages across all the line sections are also shown, along with the maximum and minimum value, as well as the standard deviation. One can see that the averages in the 75-100 μm and 100-125 μm regions, for all three lines on each of the layers, remain consistent. The largest difference observed, was 2. Even the line averages across the three layers show to be more or less consistent. This proves repeatability when using the LLS to quantitatively evaluate a produced powder layer.

Standard deviation is explained as being the average value of which all the values in a data set differs from the average of that data set. When analysing the standard deviation given in the above mentioned tables, it can also be used, along with the average, for a comparison. For instance, when looking at Aeroswift scraper 1's first layer, it has an average and standard deviation of 3 (for both), in the 75 – 100 μm region, and 0 (for both), in the 100 – 125 μm region, across all three lines. When compared to the commercial carbon fibre brush's first layer, which has an average and standard deviation of 20 and 6, and, 3 and 3, for the same regions, one is able to say that Aeroswift scraper 1 performed much better than the commercial carbon fibre brush. Perhaps the standard deviation of the line section data could be used for a comparison.

This was investigated and the standard deviation for each line section is shown in Table 4-10. Because repeatability has already been proven, only the results for the first line of the first layer, for each powder scraper, is shown and will be discussed.

Table 4-10: Standard deviation of line 1 on layer 1

	Line section number									
	1	2	3	4	5	6	7	8	9	Average
AS 1	35.6	27.4	28.1	27.8	30.3	36.0	27	51.3	41.4	33.9
AS 2	25.1	32.2	36.1	27.9	36.7	31.0	24.7	26.6	27.4	29.7
AS 3	26.6	29.1	35.1	32.2	30.6	32.4	30.8	28.5	27.4	30.3
CCFB	31.1	27.5	30.7	27.1	26.1	36.2	39.8	35.0	33.4	31.9
Solid blade	22.8	24.3	24.3	25.5	23.7	24.0	21.1	25.5		23.9

Table 4-10 also proves what was previously discussed. It shows that Aeroswift scraper 2 performed the best out of the carbon fibre brush scrapers, which had an average standard deviation of 29.7, with Aeroswift scraper 3 close behind it at 30.3. The commercial carbon fibre brush scraper, also as previously discussed, falls between Aeroswift scraper 1 and 3, with 31.9. The worst performing carbon fibre brush scraper was Aeroswift scraper 3, with

33.9 as an average standard deviation. Once again, a clear difference between the solid blade scraper and the carbon fibre brush scrapers can be seen, which had a 23.9 average. A lot can also be said when looking at each individual line section's standard deviation. With the carbon fibre brush scrapers, an inconsistency between the line sections can be observed, especially with Aeroswift scraper one, which had two very poor line sections, with standard deviations of 51.3 and 41.4. This is much higher than its average of 33.9. The solid blade's line sections look to be more consistent and none of the values deviates from the average by more than three.

Because the standard deviation of the total data set of a line section takes into account not just the peaks, but all the points in the line profile, it is a better quantitative indication of the quality of a powder layer.

CHAPTER 5 CONCLUSION

From the results, it can be concluded that that an LLS can be used to quantitatively evaluate the performance of a powder scraper, and can thus be used to compare and evaluate powder scrapers. The reason is that the results show a clear, quantitative, difference in the quality of the powder layer produced by the solid blade scraper as opposed to that produced by all the carbon fibre powder scrapers. This is what was expected, that if an LLS is a viable method of evaluation, it would show a significant difference between powder layer quality of the two different types of scrapers. The best method to quantitatively evaluate the performance a powder scraper was determined to be the standard deviation of the line profile obtained by the LLS.

It is also concluded that this method was used to evaluate the custom carbon fibre brush powder scraper used in the Aeroswift system. In addition, the results showed this scraper meets the powder layer quality requirements for the system, as it achieved comparable performance to a commercially used carbon fibre brush scraper; in some instances, it even performed better. However, there were some inconsistencies across the line sections for all the carbon fibre brush scrapers. For the commercial carbon fibre scraper, it could be due to damage before use or misalignment at the overlapping parts during assembly, as three overlapping scrapers were used. For the Aeroswift scraper, the inconsistencies could be due to the method of manufacturing. These scrapers are manufactured by hand, which makes it near impossible to manufacture each powder scraper to have the same performance. It is thus suggested that the manufacturing process be changed to improve the performance consistency of the Aeroswift scrapers.

This project did not take into account the durability of the powder scraper and it is suggested that this be investigated in future work. Even though the durability of the Aeroswift scrapers have not formally been tested, these scrapers have successfully been used in a few builds with more than 6000 layers. The durability tests should also be done at high temperatures to investigate the performance of the Aeroswift scrapers in the case of high preheating temperatures are used. Once the durability and high temperature tests have been conducted, the custom carbon fibre brush scraper can be fully signed off as sufficient. However, for now they are the best choice. For durability reasons, the solid blade scraper was not a potential solution for the Aeroswift system.

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Appendix A.1

Spezifikation

Specification

Titanpulver, kugelig
Titanium powder, spherical

PS Ti 642060 V1

Date: 15.05.2012

Material: **Ti6Al4V ASTM Grade 5 ELI**

Abmessung: **20 - 60 µm**
Dimension:

Particle Size Distribution:

Particle Size Analysis, CILAS 920 Naß

Particle Size (µm)	%	%
> 60	2,0	max.
< 20	5,0	max.
d10	22,0-27,0 µm	
d50	35,0-40,0 µm	
d90	51,0-56,0 µm	



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Spezialpulver KG
Postfach 1328
D-05733 Bitterfeld
PO-Strasse
D-05749 Bitterfeld
Telefon: +49-(0)3493-72306
Fax: +49-(0)3493-72470
E-Mail: info@tis-technik.de
Internet: www.tis-technik.de



Chemical Analysis:

Elem.	%
Al	5,5 - 6,75
V	3,5 - 4,5
C	0,1
Fe	0,4
N2 max.	0,03
H max.	0,004
O2 max.	0,13
Ti	bal.
All other impurities	<= 0,4

Appendix A.2

Ti-6Al-4V

(Age Hardenable Titanium Alloy)

Ti-6Al-4V and its modification Ti-6Al-4V ELI are moderately age-hardenable titanium alloys, the latter containing extra low interstitials to impart additional toughness at sub-zero temperature. This alloy is the most widely used of all titanium alloys and a great wealth of data exists. Ti-6Al-4V is characterized as an alpha rich alpha-beta titanium alloy.

Composition:⁽¹⁾

	Ti-6Al-4V	Ti-6Al-4V ELI
Aluminum	5.50-6.75	5.50-6.50
Vanadium	3.50-4.50	3.50-4.50
Carbon	0.08 max.	0.08 max.
Nitrogen	0.05 max.	0.05 max.
Hydrogen	0.015 max.*	0.0125 max.
Oxygen	0.20 max.	0.13 max.
Iron	0.30 max.	0.25 max.
Yttrium	0.005 max.	—
Residual Elements:		
each	0.10 max.	0.10 max.
total	0.40 max.	0.30 max.
Titanium	Remainder	Remainder

*Bar, 0.0125 max; billet, 0.0100 max.

(1) To AMS 4911D

Physical Constants:

Density, lb/cu in.	0.160
gm/cu cm.	4.43
Thermal coef. expansion/°F	
(32 to 212°F)	4.9×10^{-6}
(32 to 600°F)	5.1×10^{-6}
(32 to 1000°F)	5.3×10^{-6}
Thermal conductivity, Btu/sq ft/hr°F/ft	4
Electrical resistivity, microhm-cm	170
Specific heat, Btu/lb°F	0.13
Modulus of elasticity	See Table 1
Beta Transus,	
°F	1825±25
°C	996±14
ELI	
°F	1805±25
°C	985±14

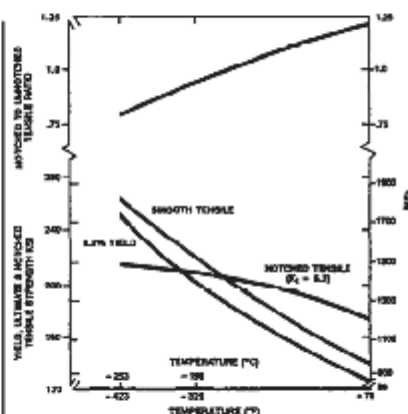
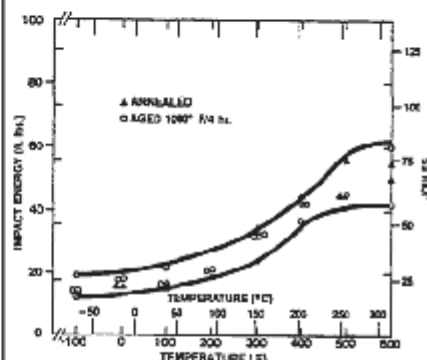
Table 2 - GUARANTEED MINIMUM MECHANICAL PROPERTIES

	Ti-6Al-4V	Ti-6Al-4V ELI
Tensile strength, psi	130000	130000
Yield strength (0.2% offset), psi	120000	120000
Elongation (2 in.), %	10	10
Reduction of area, %	20	—
Charpy impact (V-notch), ft-lb	18	19
Rockwell hardness*	C30	C30

*Typical.

Table 3 - TYPICAL TENSILE PROPERTIES OF Ti-6Al-4V SHEET
 (Thicknesses up to 0.187 in.)

Condition	Tensile Strength psi	Yield Strength (0.2% Offset) psi	Elongation (2 in.) %
Annealed	144000	136000	14
Solution treated	152000	132000	12
Aged	168000	154000	8


Fig. 1 - Effects of temperature on the cryogenic behavior of Ti-6Al-4V ELI sheet.

Fig. 2 - Effect of temperature on the Charpy V-notched impact energy absorption of annealed and STA sheet and bar.
Table 1 - MODULUS OF ELASTICITY

Temperature °F	Dynamic Modulus, psi	
	Annealed	Condition STA*
70	16×10^6	16.8×10^6
200	15.5	16.0
400	14.2	15.0
600	13.5	14.0
800	12.0	13.0
1000	9.0	9.0

*STA - solution treated, aged.

Table 4 – SHORT-TIME ELEVATED-TEMPERATURE TENSILE PROPERTIES OF ANNEALED Ti-6Al-4V

Form	Test Temperature °F	Tensile Strength psi	Yield Strength (0.2% Offset) psi	Elongation (2 in.) %	Reduction of Area %
Sheet	Room	144000	136000	18	—
	400	118000	100000	17	—
	800	98000	82000	18	—
	1000	78000	60000	36	—
Bar	Room	114000	130000	18	41
	400	118000	100000	19	50
	800	100000	85000	20	55
	1000	78000	60000	48	64

Table 5 – SHORT-TIME ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-4V (STA* CONDITION)

Form	Test Temperature °F	Tensile Strength psi	Yield Strength (0.2% Offset) psi	Elongation (2 in.) %	Reduction of Area %
Sheet	Room	178000	164000	5	—
	400	145000	120000	5	—
	800	120000	92000	8	—
	1000	90000	70000	19	—
Bar	Room	168000	155000	18	55
	400	135000	110000	19	58
	800	112000	90000	18	70
	1000	98000	72000	28	82

Table 6 – STRESS-RUPTURE PROPERTIES OF Ti-6Al-4V

Condition	Test Temperature °F	Stress (psi) for Rupture in 100 hr
Annealed	800	83000
	900	50000
STA (Solution treated, aged)	800	90000
	900	58000

Table 7 – LOW-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-4V ELI

Test Temperature °F	Tensile Strength psi	Yield Strength (0.2% Offset) psi	Elongation (2 in.) %
Room	130000*	120000*	10*
-320	218000	202000	13.5
-423	263000	248000	6

*Minimum.

Heat Treatment:

Annealing: 1325 to 1375°F, 1/2 to 4 hrs, furnace cool to 1050°F, air cool.
 Stress relieving: 1000 to 1200°F, 1 to 8 hrs, air cool.
 Solution treatment: 1660 to 1775°F, 5 to 10 min. for sheet, 1/2 hr. for plate over 1/4 in., 1-2 hours for bars and forgings, water quench.
 Age: 1000°F, 4 hours, air cool.
 Note: Solution treatment and aging not applicable to Ti-6Al-4V ELI.

Machinability:

Ti-6Al-4V is machinable by most conventional techniques. Generally, drilling, milling, shaping, and similar operations can be performed by using rigid tool setups with tool-steel tooling. Slow speeds, heavy feeds, sharp tools and adequate coolant are required. Can be readily cut with saw or abrasive wheel.

Workability:

The alloy can be alpha-beta forged in the range 1700-1810°F, finishing no lower than the former temperature. The alloy is formable at room temperature, but hot forming is recommended for complex structures. All standard sheetmetal forming techniques can be used for forming in the annealed or solution-treated conditions. Only parts that require very gentle forming should be made from aged sheet.

Weldability:

Sound moderately ductile welds can be made by using the inert gas shielded tungsten or metal arc processes on material in the annealed, solution-treated or aged condition. Welds in Ti-6Al-4V ELI are more ductile than those produced in Ti-6Al-4V. The back of the weld area and the heat-affected zone must be adequately shielded by the shielding gas. Filler metal of the same composition as the parent metal may be used. Where maximum joint ductility is desired, commercially-pure titanium filler wire is often used and the weld zone is built up to compensate for any loss in joint efficiency.

Corrosion Resistance:

This alloy is resistant to corrosion in chlorine-containing atmospheres, sea water, wet chlorine gas and oxidizing acids. It has good resistance to oxidation at temperatures up to 800°F for short-time exposure and up to 600°F for long-time service.

Specification Equivalents:

AMS 4906, 4907, 4911, 4928, 4930, 4934, 4935, 4954, 4956, 4965, 4967.
 ASTM B265, 348, 367, 381, 382 and F136.
 MIL-T-9046, 9047, 46077, 81556
 MIL-F-89142
 British T.A. 10, 11, 12, 13, 28, 56
 French A1R 9183, 9184
 German W1.3.7104 (Rust 1 and 2)
 European AECMA Ti P 63

General Characteristics:

Ti-6Al-4V is an alpha-beta titanium alloy with total alloy content controlled to produce an attractive annealed strength. It can be heat treated to yield a material having mechanical properties in the range of those of many of the high-strength steels. It has good stress rupture properties at temperatures up to 800°F, can be formed by conventional procedures and welded by shielded arc techniques. Ti-6Al-4V ELI is produced with extremely low interstitials and, as a result, has excellent toughness down to liquid hydrogen temperatures.

Forms Available:

Sheet, plate, bar, billet, and ingot.

Applications:

Tanks, pressure vessels, cryogenic storage vessels (Ti-6Al-4V ELI), aircraft forgings, fasteners, jet engine components.

Manufacturer:

Titanium, Denver, CO 80202; (303) 996-6600

Appendix A.3

Certificate of Analysis

Customer: CSIR Pretoria

Material: Ti6Al4V - Powder
Gd 5

Particle Size: 20-60 µm

Lot No.: 1354/3

Date of Delivery: 28.09.2012
Delivery Note 8004837

Our reference No.: 10/9003431
Your Purchase No.: 406355
dated: 09.07.2012

Particle Size Distribution:

Particle Analysis, CILAS 920 NASS

ATTACHED NO.: 3492 (3445)

Chemical Analysis:

Elem.	%
Ti	bal.
Al	6,38
V	3,96
C	0,006
Fe	0,161
O	0,087
N	0,008
H	0,0020
Y	< 0,01
Zn	<0,002
Mg	<0,002
Sn	0,004

Bitterfeld; 28.09.2012

Unterschrift / Signatur

Report No.: 13801
 Date: 29.06.2012
 Contact: GB

Task:

Application field: Geology / Metallurgy
 Material: Ti6Al4V
 Feed size: 0 - 60 µm
 Feed quantity: 7 g per sieve
 Material specification(s): dry
 Customer requirements(s): sieving on 20 / 32 / 45 / 63 µm
 Subsequent analysis: Particle size analysis

Solution

Selected Instrument(s): Air Jet Sieving Machine AS 200 jet
 EasySieve Evaluation Software

Configuration(s)	1 x AS 200 jet, 100-240 V, 50/60 Hz	300270001
Item nos.:	1 x Industrial vacuum cleaner GM 80, 230 V, 50/60 Hz (other electrical versions available)	327480004
	1 x Test Sieve, ASTM E 11, 8"x1", 25µm, 500Mesh, stainless steel, with compliance certificate acc. EN 10204 2.1	60141000025
	1 x Test Sieve, ASTM E 11, 8"x1", 32µm, 450Mesh, stainless steel, with compliance certificate acc. EN 10204 2.1	60141000032
	1 x Test Sieve, ASTM E 11, 8"x1", 45µm, 325Mesh, stainless steel, with compliance certificate acc. EN 10204 2.1	60141000045
	1 x Test Sieve, ASTM E 11, 8"x1", 63µm, 230Mesh, stainless steel, with compliance certificate acc. EN 10204 2.1	60141000063
	1 x EasySieve, for Windows 2000/XP/Vista/7, English/German, Single-user-licence, -SR-incl. adapter RS232-USB	326450028

Parameter(s): Revolution speed 55 rpm, negative pressure about 40 mbar
 Time: 1 min for each sieve (about 10 min for a whole sieve analysis)

Achieved result(s): see test report EasySieve

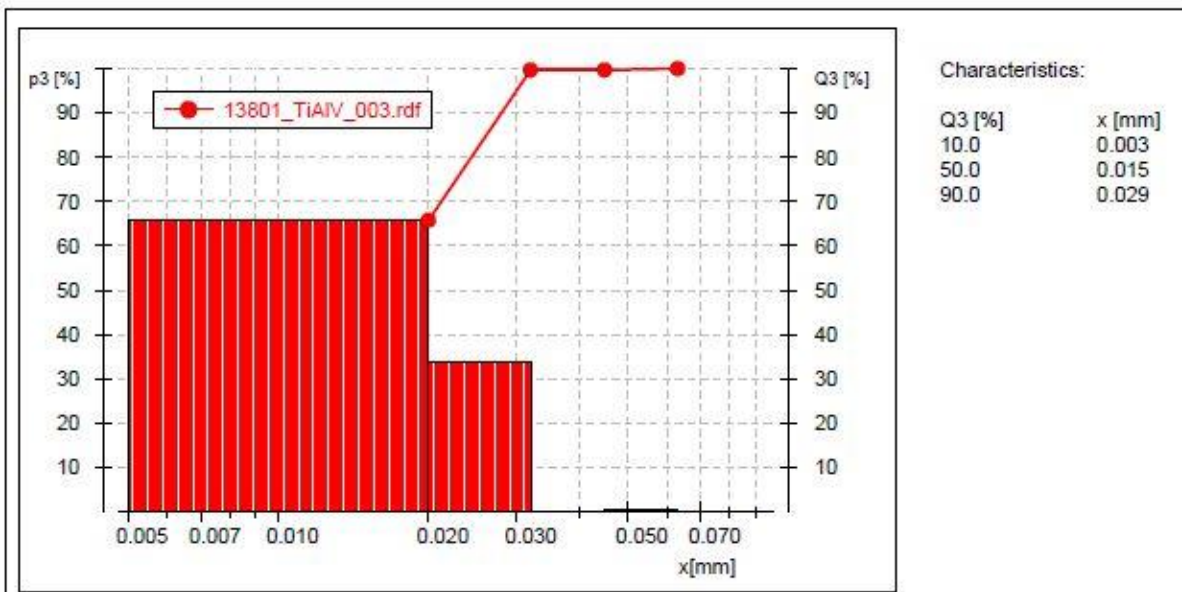
Remark(s):

Recommendation: The Air Jet Sieving Machine AS 200 jet is suitable to analyse the sample material under the above mentioned conditions.

Retsch Sieve Analysis

Company:	Aerosud ITC		
User:	GBE		
Result file:	...II Users\Anwendungsdaten\EasySieve\SIEVEDAT\13801_TiAlV\13801_TiAlV_003.rdf		
Task file:	13801_TiAlV.afq	Size classes file:	13801_TiAlV.gkl
Date:	29. 6.2012 13:46	Sieving duration [mm:ss]:	01:00
Sieve machine:	AS 200 jet	Number of revolutions [1/min]:	55.0
Material:	Ti6Al4V		
Sample quantity [g]:	7.01	Sum loaded sieve weights [g]: 7.01	
Sieve loss [%]:	-0.00		
Sampling:	J.	Sample preparation:	No sample preparation
Sieve method:	air jet sieving AS 200 jet	Sieve diameter:	8" x 1"
Sieves according to standard:	DIN ISO 3310-1	Sieving aids:	No sieving aids
Comment:	Sample < 25 µm 1 min. sieving		

Size class [mm]	p3 [%]	Q3 [%]
< 0.020	65.8	65.8
0.020 - 0.032	34.0	99.7
0.032 - 0.045	0.0	99.7
0.045 - 0.063	0.3	100.0
> 0.063	0.0	100.0

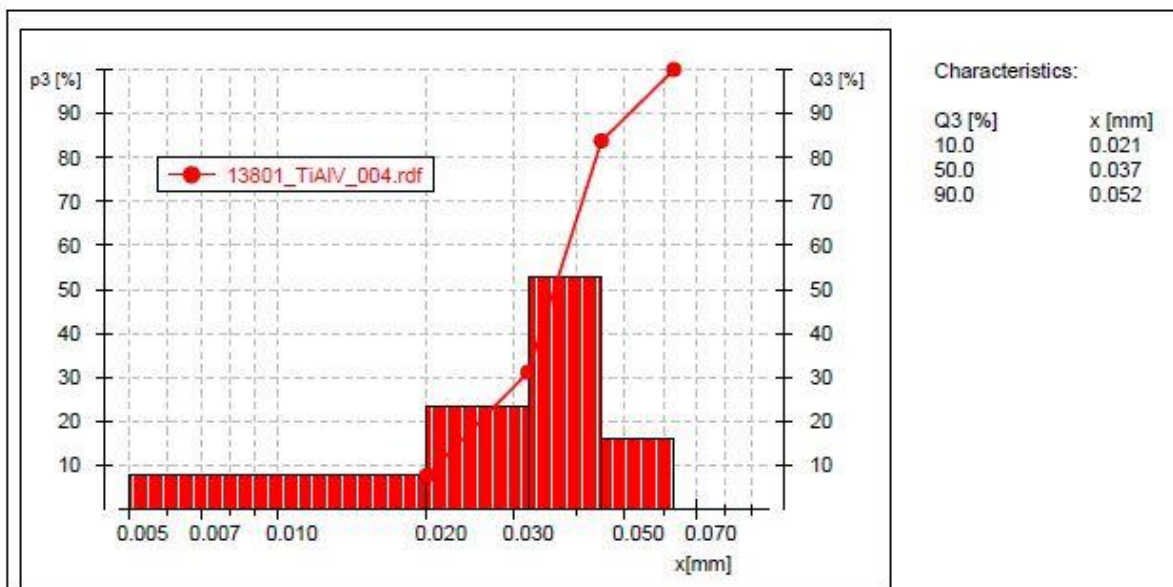


User: _____

Retsch Sieve Analysis

Company:	Aerosud ITC		
User:	GBE		
Result file:	...\\Users\\Anwendungsdaten\\EasySieve\\SIEVEDAT\\13801_TiAlV\\13801_TiAlV_004.rdf		
Task file:	13801_TiAlV.afq	Size classes file:	13801_TiAlV.gkl
Date:	29. 6.2012 14:04	Sieving duration [mm:ss]:	01:00
Sieve machine:	AS 200 jet	Number of revolutions [1/min]:	55.0
Material:	Ti6Al4V		
Sample quantity [g]:	7.02	Sum loaded sieve weights [g]: 7.03	
Sieve loss [%]:	-0.14		
Sampling:	/.	Sample preparation:	No sample preparation
Sieve method:	air jet sieving AS 200 jet	Sieve diameter:	8" x 1"
Sieves according to standard:	DIN ISO 3310-1	Sieving aids:	No sieving aids
Comment:	Sample 10- 60 µm 1 min. sieving		

Size class [mm]	p3 [%]	Q3 [%]
< 0.020	7.7	7.7
0.020 - 0.032	23.5	31.2
0.032 - 0.045	52.6	83.8
0.045 - 0.063	16.2	100.0
> 0.063	0.0	100.0



User: _____

Appendix B.1

Appendix B.2

Table B-2-30: Aeroswift scraper 1 - layer 2, line 2

	Number of peaks per line section												
	1	2	3	4	5	6	7	8	9	Average	Max.	Min.	Std. deviation
0-25	47	88	86	66	72	48	74	26	52	62	88	26	19
25-50	60	65	57	52	71	56	70	38	58	59	71	38	9
50-75	31	13	12	10	17	29	12	36	21	20	36	10	9
75-100	2	3	3	6	2	6	0	19	10	6	19	0	5
100-125	0	0	1	0	0	0	0	6	4	1	6	0	2
125-150	0	0	0	0	0	0	0	2	0	0	2	0	1
150-175	0	0	0	0	0	0	0	2	0	0	2	0	1

Table B-2-31: Aeroswift scraper 1 - layer 2, line 3

	Number of peaks per line section												
	1	2	3	4	5	6	7	8	9	Average	Max.	Min.	Std. deviation
0-25	52	77	72	87	87	56	75	20	65	66	87	20	20
25-50	56	67	46	47	55	56	61	33	56	53	67	33	9
50-75	30	17	21	13	16	30	19	42	18	23	42	13	9
75-100	3	0	2	3	4	9	2	17	6	5	17	0	5
100-125	0	0	2	0	0	0	0	7	4	1	7	0	2
125-150	0	0	0	0	0	0	0	4	0	0	4	0	1
150-175	0	0	0	0	0	0	0	0	0	0	0	0	0

Table B-2-32: Aeroswift scraper 1 - layer 3, line 1

	Number of peaks per line section												
	1	2	3	4	5	6	7	8	9	Average	Max.	Min.	Std. deviation
0-25	60	86	84	72	77	52	62	40	41	64	86	40	16
25-50	63	62	52	65	60	72	52	37	55	58	72	37	9
50-75	28	11	14	11	12	24	22	40	27	21	40	11	9
75-100	1	0	3	3	5	6	6	16	14	6	16	0	5
100-125	0	0	1	0	0	0	0	10	0	1	10	0	3
125-150	0	0	0	0	0	0	0	3	0	0	3	0	1
150-175	0	0	0	0	0	0	0	0	0	0	0	0	0

Table B-2-33: Aeroswift scraper 1 - layer 3, line 2

	Number of peaks per line section												
	1	2	3	4	5	6	7	8	9	Average	Max.	Min.	Std. deviation
0-25	50	77	54	78	69	45	68	36	54	59	78	36	14
25-50	76	72	63	39	61	54	71	28	64	59	76	28	15
50-75	20	13	21	16	21	32	15	30	26	22	32	13	6
75-100	0	1	4	5	3	5	1	24	8	6	24	0	7
100-125	1	0	0	0	0	1	0	3	0	1	3	0	1
125-150	0	0	0	0	0	0	0	6	0	1	6	0	2
150-175	0	0	0	0	0	0	0	1	0	0	1	0	0

[illegible]

Table B-2-70: Solid blade - layer 3, line 3

[illegible]

Appendix C

Paper presented at the 2017 RAPDASA Conference

EVALUATION OF A CARBON FIBRE POWDER SCRAPER USED IN METAL ADDITIVE MANUFACTURING

(i) D. Bester^{1*}, H. Wichers², H. Moller¹

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Council for Scientific and Industrial Research, South Africa
DBester@csir.co.za, HMoller@csir.co.za

²North-West University, Department of Mechanical Engineering, Potchefstroom Campus, 0001, South Africa
Harry.Wichers@nwu.ac.za

ABSTRACT

Powder Bed Fusion (PBF) is an Additive Manufacturing process which builds parts, layer by layer, by melting the cross-section of the part onto a powder layer. Aeroswift is a PBF machine, designed and built in South Africa. A powder scraper was designed which would be flexible, work for extended periods of time and have the ability to operate at high temperatures. In this study, the process of development toward carbon fibre scrapers and the evaluation for comparison to commercially available scrapers is explained. Results showed that the carbon fibre powder scraper is comparable to commercially available scrapers and is a viable solution for Aeroswift.

[1] INTRODUCTION:

Powder Bed Fusion (PBF) is an Additive Manufacturing (AM) process that produces a part by building it layer by layer. This is done by melting the cross-section of the part onto a powder layer, using an energy source and scanning method. The energy source is either a laser called Selective Laser Melting (SLM), or an electron beam named Electron Beam Melting (EBM). The build platform moves down by one layer thickness (typically between 20 and 50 μm), a new powder layer is added and the next cross-section is scanned. This process is repeated until all the cross-sections of the part are scanned and a completed component printed. The cross-sections are obtained by running the CAD model through slicing software, Chua [1].

Aeroswift is an SLM machine, designed and built in South Africa by the NLC and Aerosud ITC, which has a build volume of 2000 x 600 x 600 mm^3 , which is much larger than current commercially available machines. Due to the large width of the build platform and other factors, such as preheating to 600°C, a custom powder scraper was designed. The quality of a powder layer is very important in PBF processes and influences the surface roughness of a built part and, to a certain extent, its dimensional accuracy and density. This powder scraper had to fulfil the following specification:

6. High operating temperature: the machine has a preheat temperature of up to 600°C.
7. Flexible: due to known defects in PBF, such as warpage, Vorsa et al. [2] and balling, Kruth et al. [3]), a flexible powder scraper is required that would be able to deal with these defects without failing.
8. Durable: the powder scraper should be able to operate for extended periods, as at full capacity, a build could be as many as 12 000 layers.
9. Consistent powder layers: consecutive powder layers should not differ much from the previous layer.
10. Smooth surface: the powder layers produced should have a good surface roughness and should be uniform throughout.

A carbon fibre brush powder scraper was designed and manufactured and after its implementation, test builds were conducted for parameterisation. Excessive roughness of consolidated layers caused premature failure of the powder scraper. It was uncertain whether the failure was due to unsatisfactory powder layers or due to the lack of optimised process parameters. Thus, a quantitative method was needed to determine the quality of the powder layer, to show if the layer produced by the powder scraper was sufficient or not. The quality of the powder layer refers to the flatness (surface roughness) of the layer.

Therefore, the research objectives are:

1. Devise a method for a quantitative evaluation of the performance of a powder scraper.
2. Use the devised method to evaluate the carbon fibre powder scraper developed for the Aeroswift system.

[2] LITERATURE

a. Powder layer monitoring

A literature survey revealed only one method that addresses the monitoring of a powder layer. This was done by Craeghs et al. [4] and is used in many commercial machines today. The method uses a camera and lighting from different sides of the powder bed. Photographs are taken of every layer for each individual light, while the others are off. The lights illuminate the powder bed from a side and cause defects to cast shadows on the powder bed. The photographs are converted to grey scale images and each layer's images are analysed. Five lines are taken across the images (in the direction of the light) and averaged. Each point in the line has a grey scale value and a graph of the grey scale values is plotted with a set threshold. If a grey scale value exceeds the threshold, the system either re-scrapes the layer or calls for user intervention. A schematic of this method is shown in Figure 1.

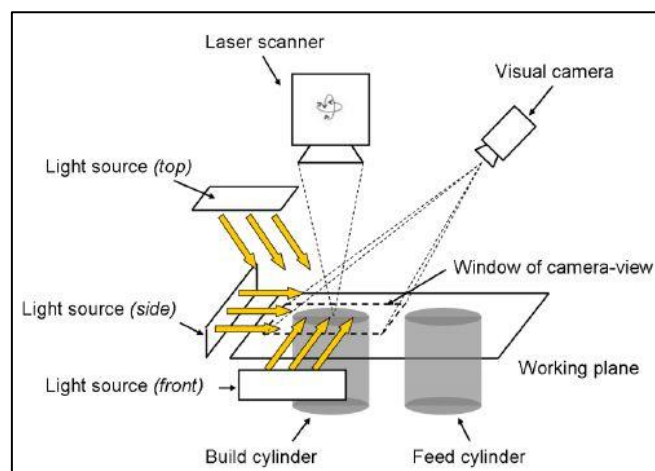


Figure 1: Visual inspection of powder layer, Craeghs [2]

This method, however, does not analyse the powder layer in a quantitative way. It only shows if a layer falls within a certain specification or not. By calibrating the size of a shadow of an object with a known height, it is possible to calculate the height of the defects in a powder layer using the same set-up, by measuring the size of the shadow cast.

However, the resolution achievable this way is only about 100 $\mu\text{m}/\text{pixel}$, due to the resolution of the cameras and the width of the powder bed. This means that shadows of different-sized defects will possibly be represented by the same number of pixels in an image.

b. Laser Line Scanner

A Laser Line Scanner (LLS) is a device that measures the profile of a line on a surface and gives the x- and z-coordinates as an output. The z-coordinates are calculated by using triangulation of the laser light reflected off a surface onto a highly sensitive sensor matrix, Micro Epsilon [5]. The one used in the project is a Micro-Epsilon's ScanCONTROL 2960-50/BL, which has an x- and z-resolution of 40- and 4 μm respectively, Micro Epsilon [6]. The only downside of the device is that it can only measure a 60 mm line per instance.

[3] METHODOLOGY

A literature study was conducted to investigate possible solutions to the first research objective. In the study, no literature could be found on the qualification of powder scrapers used in AM. However, two viable solutions were identified: the first being that from the research done by Craeghs et al.[3], and the second being an LLS. After further investigation it was determined that LLS is the better option, as the camera and light method is not as accurate.

It was decided that five powder scrapers would be tested: three Aeroswift carbon fibre scrapers, a commercial carbon fibre powder scraper and a solid blade scraper manufactured from high speed steel. Three Aeroswift scrapers were tested to show repeatability. The commercial carbon fibre scraper was tested to compare the Aeroswift scraper to a carbon fibre scraper used in the industry, as they have been proven to work. The commercial carbon fibre brush's dimensions are comparable to that of the Aeroswift carbon fibre brush scraper, except for its length, which is much shorter. It is generally recognised that a solid blade scraper produces a near-perfect layer due to its edge being machined straight and sharpened. The solid blade was tested to show what a "perfect" layer would look like and to see how much a carbon fibre scraper's performance differs. Thus, if the chosen method of quantification works, there will be a distinct difference between the performance of the carbon fibre powder scrapers and the solid blade scraper.

a. Experimental set-up

An x-y welding table was utilised for the test set-up. The table was modified to incorporate the Aeroswift powder scraper. The same type of brackets used on the Aeroswift scrapers was used to mount the commercial carbon fibre scraper as well as the solid blade. This made changing between powder scrapers easy. The LLS was mounted on a motorised translation stage, for linear movement in the x-direction, and a carriage was used for the y-direction travel of the powder scraper to scrape the layers of powder. The carriage runs on high-precision rails and was disconnected from the motor to reduce the vibrations caused by the motor. The scraping was thus done by dragging the carriage by hand. A laptop was used to run the LLS's software and motion control software for operating the motor of the translation stage. Spherical titanium (Ti6Al4V) powder was used with a particle size distribution of 20-60 μm . Two titanium plates were used as base plates for the powder scraping. Refer to figure 2 to see the test set-up.



Figure 2: Test set-up

b. Experimental procedure

The powder used in the tests was dried at 120 $^{\circ}\text{C}$ to ensure optimum flowability for the tests. The scraper was aligned with the base plates and the scraping height set to scrape a layer more or less 0.5 mm thick. The LLS was mounted on a bracket that was machined in a way so that the laser line was parallel to the powder scraper and level with the build plate. Powder was dropped in front of the scraper and scraped over the base plates by dragging the carriage by hand. Nine line profiles were captured, while the y-position remained unchanged, with the LLS to cover a straight line with a total length of 540 mm. The carriage was then moved by hand to a new y-position to measure a different line across the powder layer. This was done for three separate lines in random y-positions. After all nine measurements were captured for each of the three lines, more powder was added in front of the powder scraper and a new layer was scraped. The new layer was then measured in the same way and repeated for a third layer. The data obtained was processed in Microsoft Excel. For each of the nine line measurements the following was done in Excel:

3. A graph of the x- and z- coordinates was created to show the line profile.

4. A best-fit linear line, called a median line, was drawn on the graph and the equation for the line was acquired.
5. The distance for each point in the line profile to the median line was calculated using the equation and the x-coordinates.
6. For each point it was determined if that point was a peak or a valley.
7. The total number of peaks and valleys was calculated.
8. The distribution of peaks given inside 25 μm intervals (0-25 μm , 25-50 μm , etc.) was then determined.

[4] RESULTS AND DISCUSSION

Due to the way in which the LLS software exports the data, three data sets per line were obtained. These were averaged into one Excel file and then processed. The performance of the scrapers were given in the number of peaks that fell out of specification. In this case, the specification was that defects or peaks should be smaller than one-and-a-half times the thickness of one layer, which was 50 μm . The out-of-specification size distributions were thus 75-100 μm , 100-125 μm , etc. Figure 3 shows a typical graph of the line profile, the best-fit line and its equation. Line section 7 was chosen as it was a good representation.

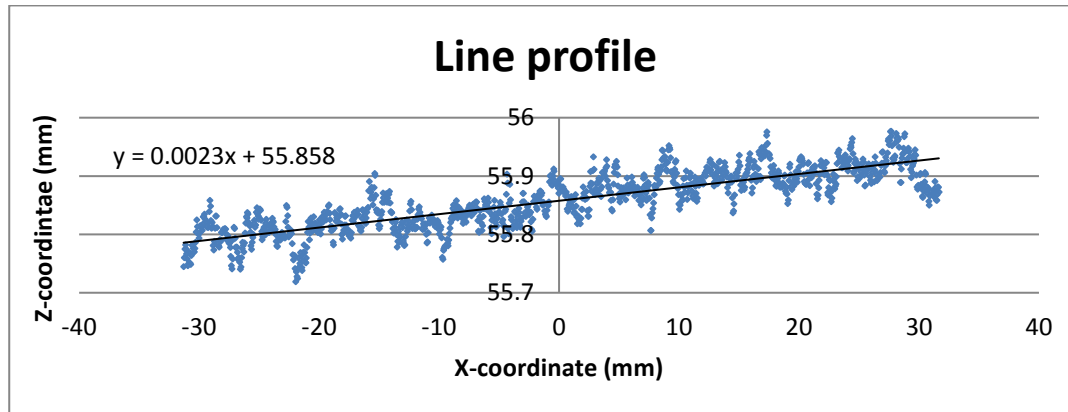


Figure 3: Line section profile of an Aeroswift scraper

Tables 1 and 2 show the number of peaks within a size range for all three corresponding line sections across all three layers.

Table 1: Aeroswift scraper 2 - all data for line section 7

	Layer 1			Layer 2			Layer 3		
Peak size distribution (μm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	79	86	89	75	77	86	80	89	94
25-50	72	55	65	68	77	72	68	59	66
50-76	11	16	8	9	12	14	11	8	8
75-100	0	0	0	1	0	1	1	0	1

Table 2: Aeroswift scraper 2 - all data for line section 5

	Layer 1			Layer 2			Layer 3		
Peak size distribution (μm)	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
0-25	56	41	53	67	53	53	52	50	60
25-50	45	59	46	50	57	54	49	52	43
50-75	28	30	32	37	24	33	39	33	42
75-100	9	10	9	7	11	9	7	10	6
100-125	1	0	0	0	1	0	0	1	0
125-150	1	0	0	0	0	0	0	0	0

Tables 3 to 7 show the results of the powder scraping tests. The tables show the line that had the least number of out-of-specification peaks, the line that had the most out-of-specification peaks and the average between all nine line sections. The range 0-25 and 25-50 μm is ignored, but still added to show the comparison of in-specification peaks.

Table 3: Aeroswift scraper 1

Peak size distribution (μm)	Best-performing line (number of peaks)	Worst-performing line (number of peaks)	Average (number of peaks)
0-25	74	35	65.3
25-50	64	38	57.6
50-75	16	37	22.8
75-100	0	14	5.2
100-125	0	8	1.2
125-150	0	0	0
150-175	0	2	0.2

Table 4: Aeroswift scraper 2

Peak size distribution (μm)	Best-performing line (number of peaks)	Worst-performing line (number of peaks)	Average (number of peaks)
0-25	79	56	73.7
25-50	72	45	61.2
50-75	11	28	17.6
75-100	0	9	2.9
100-125	0	1	0.2
125-150	0	1	0.1
150-175	0	0	0

Table 5: Aeroswift scraper 3

Peak size distribution (μm)	Best-performing line (number of peaks)	Worst-performing line (number of peaks)	Average (number of peaks)
0-25	80	52	71.6
25-50	68	49	63.1
50-75	11	39	20.8
75-100	1	7	2.8
100-125	0	0	0.1
125-150	0	0	0
150-175	0	0	0

Table 6: Commercial carbon fibre scraper

Peak size distribution (μm)	Best-performing line (number of peaks)	Worst-performing line (number of peaks)	Average (number of peaks)
0-25	79	37	61.4
25-50	66	67	59.1
50-75	13	35	20.4
75-100	0	3	3.3
100-125	0	1	0.8
125-150	0	0	0.2
150-175	0	0	0

Table 7: Solid blade scraper

Peak size distribution (µm)	Best-performing line (number of peaks)	Worst-performing line (number of peaks)	Average (number of peaks)
0-25	82	96	97.4
25-50	67	56	60.3
50-75	3	12	7.6
75-100	0	0	0.1
100-125	0	0	0
125-150	0	0	0
150-175	0	0	0

From the results it can be seen that the solid blade powder scraper performed much better than the Aeroswift and the commercial carbon fibre powder scraper. It had no peaks above 100 µm and in the 75 - 100 µm range there was only one (79 µm) peak. This confirms that the method of qualification is suitable. A solid blade scraper could, however, not be considered for use in Aeroswift as it is inflexible and any misalignment of the build platform or defects in a build would damage the blade or cause it to jam.

Another observation made was that the data obtained for each corresponding line section did not vary by much. For instance, if the data for line section 7 showed good results, it would do the same for all line section 7's across all three layers. The numbers of peaks do vary between datasets, but not in a significant way. A line section that gave good results did not change between different layers or lines.

The Aeroswift scrapers performed comparably to the commercial carbon fibre scraper if the average number of peaks within certain size distributions is compared: For the commercial carbon fibre scraper, 20.4 in the 50 - 75 µm range and 3.3 in the 75 - 100 µm range, compared to 22.8 and 5.2 for Aeroswift scraper 1, 17.6 and 2.9 for Aeroswift scraper 2 and, 20.8 and 2.8 for Aeroswift scraper 3. If the best-performing lines of the two scrapers are compared, they also perform similarly (13 and 0 vs. 16 and 0, 11 and 0 and, 11 and 1). However, when considering the worst-performing line, the commercial carbon fibre scraper performed better. This could be due to the manufacturing method of the scrapers. The Aeroswift scrapers are made by hand in a non-automated way. The commercial carbon fibre scrapers, however, are produced in higher volumes and possibly manufactured in an automated process, which would be more consistent.

[5] CONCLUSION

It is thus concluded that an LLS can be used to quantitatively evaluate the performance of a powder scraper and that this method can be used to evaluate the custom carbon fibre brush powder scraper used in the Aeroswift system. This scraper achieved comparable performance to a commercially used carbon fibre brush scraper. However, there were some inconsistencies across the line sections and it is suggested that the manufacturing process be changed to improve the performance of the Aeroswift scrapers even more.

This project did not take into account the durability of the powder scraper and it is suggested that this be investigated in future work. Even though the durability of the Aeroswift scrapers have not formally been tested, these scrapers have successfully been used in a few builds with more than 2000 layers. The durability tests should also be done at high temperatures to investigate the performance of the Aeroswift scrapers if high preheat temperatures are used. For durability reasons, the solid blade scraper was not a potential solution for the Aeroswift system.

[6] ACKNOWLEDGEMENTS

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