Hopper design for metallic powders used in additive manufacturing processes

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SYNOPSIS

The influence of hopper geometry on the flow behaviour of typical metallic powders used in additive manufacturing processes is investigated. Bulk hopper theory provides a method of determining critical hopper parameters for bulk amounts of particulate solids to be stored and discharged out of hoppers. Bulk hopper theory proves to be unsuitable for the additive manufacturing process. The discharge rate of powder out of the hopper is as important as the flow / no-flow criteria used for bulk hopper theory. Additive manufacturing requires the controlled delivery of small amounts of powder onto a bed in a homogenous layer that is usually less than 100 µm thick.   Powder flow behaviour of different metal alloys with particle diameters in the range of 20 – 90 µm is investigated. Powder volumetric flow rates as a function of hopper outlet width is determined. The results obtained through experimentation are presented in the form of empirical equations.

KEYWORDS: additive manufacturing, powder, powder flow, hopper design

1. INTRODUCTION

Hoppers are used in many industries where solid particles need to be transported to a feeding device continuously. Hoppers are also used for the storage of particulate solids. The theory of hopper design for bulk amounts of solids has been investigated by Jenike and has been used since the 1960's (Chase, *sa*). A limited amount of literature is available for smaller, non-bulk hoppers, such as the hoppers used in additive manufacturing processes. Additive manufacturing is the process of building a part by consolidating layers of material progressively onto the substrate. The layers of material can be a powder which is melted by a laser beam to fuse it onto the underlying substrate. The hopper is used to discharge powder onto a powder bed which is subsequently scraped to a very thin and flat layer.

The amount of powder needed for a layer to be placed on top of the substrate is in most cases in the order of a few grams and cannot be classified as bulk powder flow. For this reason bulk hopper theory cannot be applied when designing the critical hopper dimensions.

The objectives of this investigation are to:

- Quantify the critical hopper design dimensions for hoppers needing to discharge only 50 – 100 grams of powder per layer placement.
- Investigate whether different powder alloys influence the design dimensions of hoppers.
- Compare experimental hopper design dimensions to hopper dimensions as determined by the standard Jenike method.

The materials included in this study were spherical Ti6Al4V, stainless steel 410, Inconel 718 and a Haynes 31 powder alloy. The flow-ability of powders in atmospheric conditions was tested. A successful hopper design would be one where rat-holing and arching problems were eliminated and a constant volumetric flow rate could be achieved.

2. THEORY OF BULK HOPPER DESIGN

Hoppers are used to store and discharge powders. A well designed hopper will provide predictable gravity discharge of particulate solids. The following factors are important when designing a hopper:

- whether the hopper will have a mass flow or a core flow discharge characteristic
- the material properties of the powder
- the interaction between the powder and the hopper wall
- the influence of ambient conditions on particle behaviour.

Two flow patterns may develop in a hopper namely core flow and mass flow. The mass flow pattern allows all of the powder in the hopper to be in motion. In core flow only a core of powder in the centre of the hopper outlet is in motion with stagnant powder next to the walls.
Figure 1 a-b illustrates the difference between the two different modes of flow achievable in hoppers.

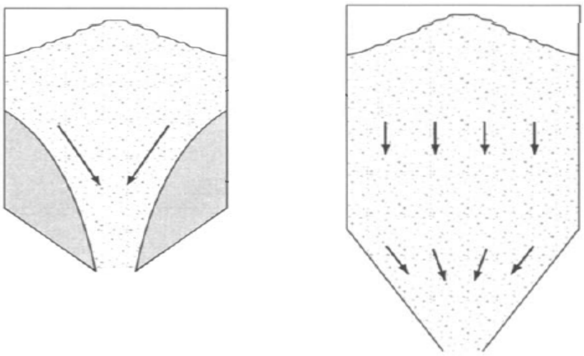

(a) (b)

Figure 1: Flow modes of hoppers (a) core flow and (b) mass flow

The design of hoppers for specific flow regimes is a function of the powder properties and the interaction of the powder with the hopper wall material. This means a specific hopper design could yield mass flow for particulate material A and core flow for particulate material B. To design for mass flow the following powder properties should be determined, according to Prescott & Barnum (2000):

- Coefficient of internal friction (δ) (degrees)
- Coefficient of wall friction (δ_W) (degrees)
- Powder permeability and bulk density
- Effect of temperature on the powder

The coefficient for internal friction is an indication of friction forces between flowing particles. It is often expressed as an angle. This is an indication of the angle at which a powder particle will slip over another particle of the same powder. According to Carson & Pittenger (1999) the values of the friction coefficients are a function of consolidating pressure, particle size and shape, moisture content, the wall surface and other specific process conditions. The internal friction varies with different powders and different reasons can be given for the different flow-ability that each different powder possesses.

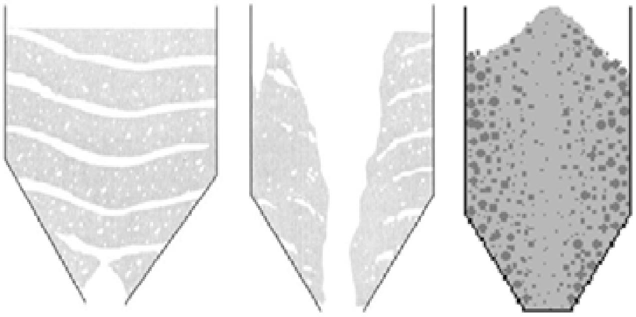
The coefficient of wall friction (external friction) is the amount of friction developed between the wall of the hopper and the solid particles in contact with it. The coefficient of wall friction is measured using a shear cell test. Although not always true, in general smoother surfaces in contact with flowing powder have lower values of friction (Carson & Pittenger).

Permeability is a measure of the resistance to flow when a fluid passes through a powder body. The flow rate out of the hopper may be influenced by the permeability. Permeability is a function of the bulk density of the powder and is measured across a circular vessel filled with the powder.

The bulk density of powder is a property which varies and is dependent on the applied consolidating pressure. When the bulk density is known, hopper storage capacity can be determined. The bulk density is measured before a shear test starts by measuring the weight of powder present on a ring of known volume and determined by the ratio of mass to volume.

The standard method for determining hopper design parameters is known as the Jenike method and is described in ASTM standard D6128. Powder is tested in a shear cell tester to determine friction coefficients which are used in a mathematic and graphic model to determine hopper design parameters.

The problems normally encountered with hoppers are arching, rat-holing and segregation. These three problems are illustrated in Figure 2 a-c.



(a) (b) (c)

Figure 2: Problems encountered in hoppers (a) arching (b) rat-holing and (c) segregation

Arching will typically occur when the outlet diameter of the hopper is sufficiently small for a stable arch to form just above the outlet of the hopper when gravity cannot overcome the frictional forces in the powder. Rat-holing will usually occur when the angles of the hopper wall are too shallow. Any slight disturbance to the hopper can cause the frictional forces to be overcome and the powder to come flooding out of the hopper. This irregular flow behaviour is highly unfavourable as it cannot be predicted and can therefore cause problems further down the processing line. Segregation normally occurs when the powder in the hopper has a large particle size distribution or when different types of powder are present in the hopper.

3. EXPERIMENTAL

This investigation employed the following strategy for hopper design:
For a hopper to be successfully designed the hopper walls need to be steep enough to avoid rat-holing and the outlet dimension needs to be large enough to avoid arching.

Four different types of powders were used in this investigation. Table 1 indicates the general chemical composition (mass percentage) of the powder alloys used.

Table 1: Chemical composition of powder alloys

SS 410	Ti6Al4V	IN 718	Haynes 31
84.5 – 86.5 % Fe	90 % Ti	50 – 55 % Ni	55 % Co
11.5 – 13.5 % Cr	6 % Al	17 – 21 % Cr	26 % Cr
0.15 % C	4 % V	16 – 25 % Fe	11 % Ni
		5 % Nb	8 % W
		3 % Mo	

Figure 3 shows the particle size distribution of the different powders used.

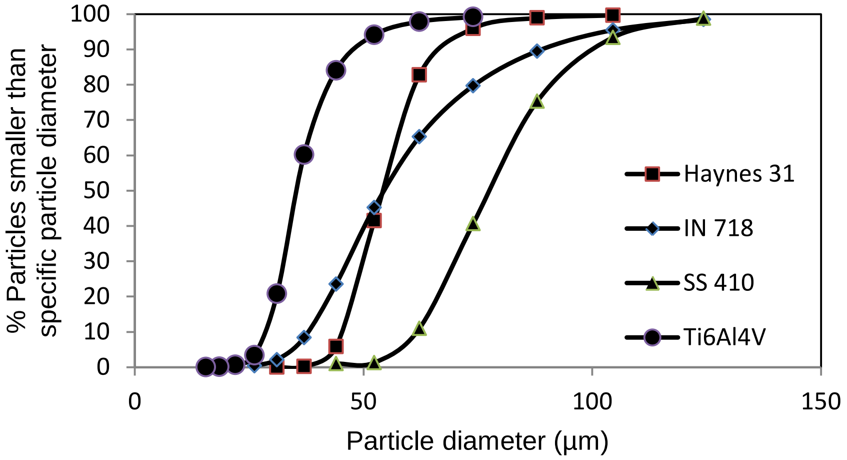
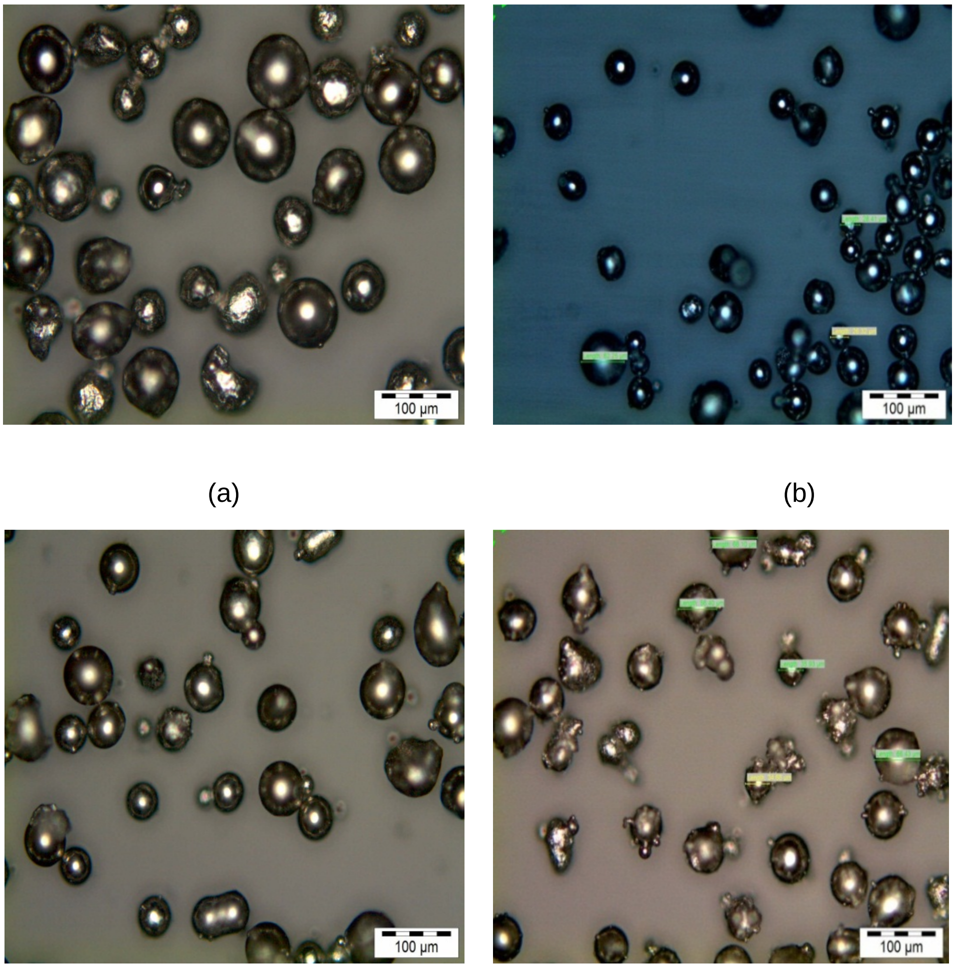


Figure 3: Particle size distribution of the powders used

SS 410 is a low carbon martensitic stainless steel that is found in applications ranging from coal shoots and mining machinery to jet engine parts. It is also well suited for refurbishment build-up on pump and shaft components. Ti6Al4V is a Ti base alpha/beta alloy with great commercial importance. It finds wide application in the aerospace industry due to an attractive strength to weight ratio. Traditionally components were forged, but the low heat input from additive manufacturing processes has opened up new applications for welded components.

Inconel 718 is a heat treatable Ni base super alloy that has found numerous applications in the high temperature areas of aerospace engines over the past 50 years. Repair build up on turbine vane edges is common practice. Haynes 31 is a Co base super alloy that is primarily used for the repair of aircraft engine components made from Co base alloys.

All the powders used in this investigation were of spherical morphology with particle sizes ranging from 20 to 90 µm. Figures 4 a-d show micrographs of the particles of each individual powder.

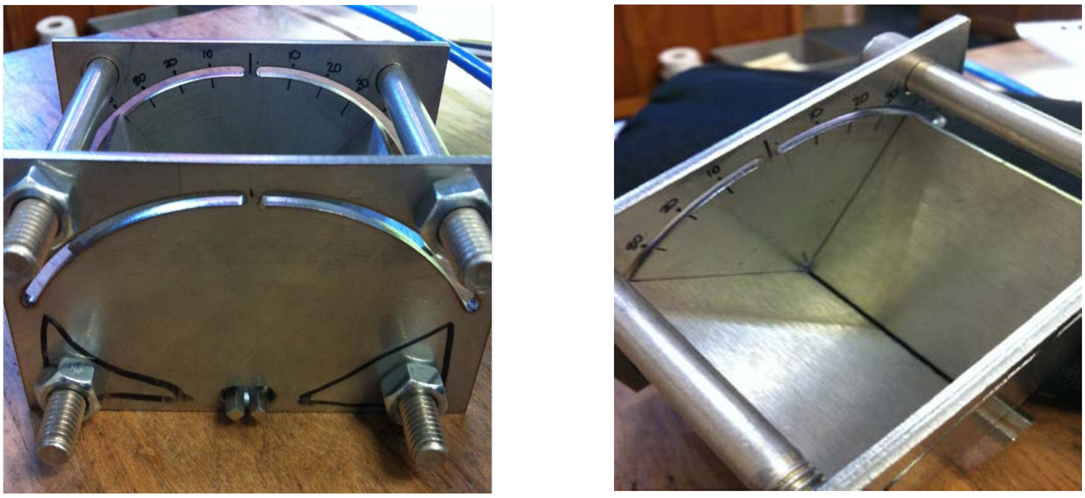


(a) (b)

(c) (d)

Figure 4: Microscopic view of (a) SS 410 (b) Ti6Al4V (c) IN 718 and (d) Haynes 31

A small wedge shaped hopper of cold rolled stainless steel was constructed. The hopper walls were manufactured such that they were adjustable to ensure that a variable hopper wall angle and a variable hopper outlet dimension could be achieved. Figure 5 a-b illustrates the hopper used.

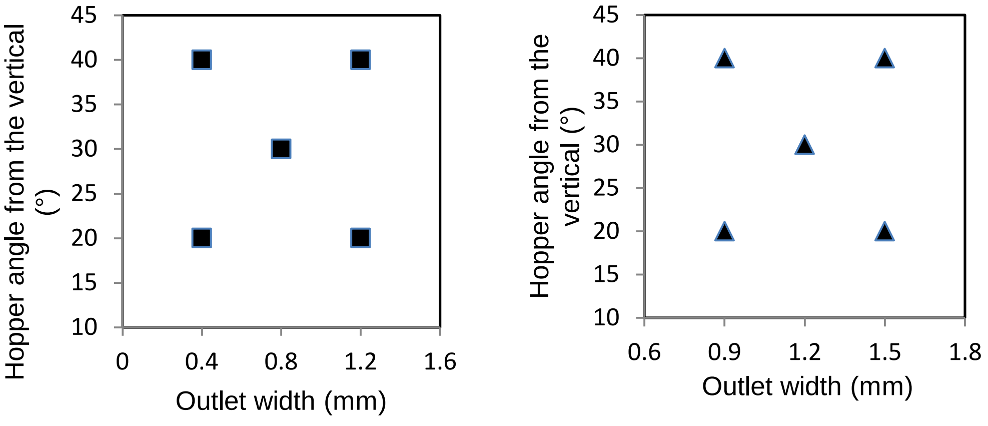


(a) (b)

Figure 5: Experimental hopper (a) front view (b) top view

After assembly, the hopper walls were set at the required half angles and outlet dimension. The plates were cleaned with acetone and methanol before performing a run followed by two repeat runs to establish the repeatability of the system and to determine the variance within the system. The mass of the powder of interest was measured. The hopper stand was checked and the experiment started when the powder was poured into the hopper while simultaneously starting a stopwatch. The change in mass and change in time was recorded on video for quality data capturing. After all the powder was discharged due to gravity, the hopper was cleaned from any residual powder by tapping the hopper or using compressed air. The mass measurements were converted to volumetric values as the powders had differing densities. This process was repeated twice for each run.

All the powder used except the Ti6Al4V powder could be run at the same experimental parameters in atmospheric conditions. The Ti6Al4V powder would only start flowing freely under gravity when the hopper outlet width was 0.9 mm. A possible reason for why the Ti6Al4V powder seemed to be less free flowing than the other powders tested is discussed in the results and discussion section. The Ti6Al4V powder was dried by placing it in an oven at 130°C for an hour and a half as the moisture content was proven to affect the powder flow-ability in the laboratory. The dried titanium powder flowed out of the hopper under gravity force alone with a 0.4 mm outlet width like the other powders. Figure 6 a-b represent the experimental parameters used.



(a) (b)

Figure 6: Design of experiments (a) SS 410, IN 718 and Haynes 31 and dry Ti6Al4V and (b) humid Ti6Al4V

A FT4 powder rheometer was used to determine the bulk hopper design parameters for Ti6Al4V powder using the methodology described in the ASTM D6128 standard for hopper design. The test was run four times where the simulated hopper wall material was stainless steel with a surface roughness of 0.28 µm.

4. RESULTS AND DISCUSSION

Table 2 summarises the properties of the powders used in this investigation. The powder density was determined in the laboratory and the d_{50} value was read from Figure 3.

Table 2: Powder properties

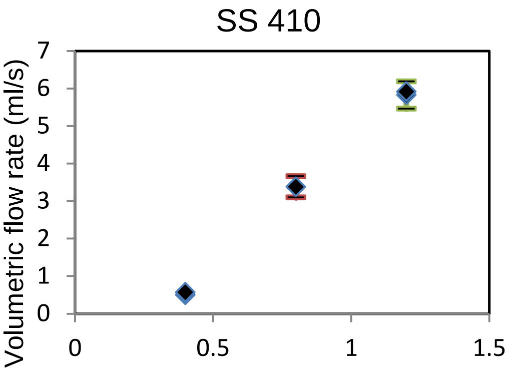
	Powder density (g/ml)	Particle size* range (µm)	Particle d_{50} (µm)
SS 410	4.50	45 - 90	77
Ti6Al4V humid	2.47	20 – 60	35
Ti6Al4V dry	2.65	20 - -60	35
IN 718	4.96	45 - 75	53
Haynes 31	4.45	20 - 80	53

*Particle size range as provided by the manufacturer

The particle size range was within the same order of magnitude for all the powders under investigation. The density of all the powders was in the same range except for the titanium which had the lowest density. The volumetric flow rate was used instead of the mass flow rate to be able to compare the flow-ability of the powders with differing densities. The volumetric flow rate of each individual powder was determined and is shown in Figure 7 a-c. The powder with the highest flow rate was the powder with the highest density. The powder that flowed with most difficulty was Ti6Al4V, which has the smallest d_{50} value as well as the lowest density as shown in Table 2.

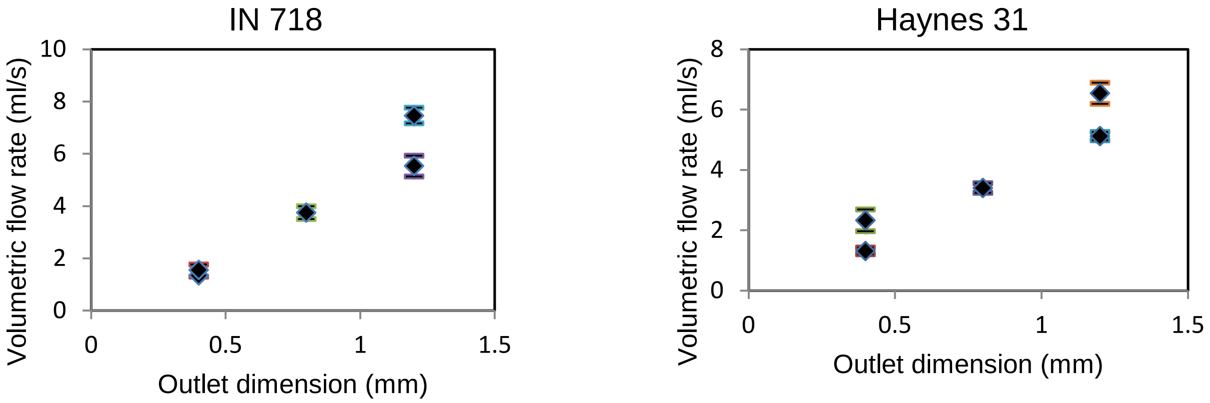
The experimental parameters for the powders were the same except in the case of the titanium alloy. The titanium alloy did not flow freely in atmospheric conditions under the force of gravity alone until the outlet width of the hopper was increased to 0.9 mm. The titanium alloy particles proved to be more cohesive compared to the particles in the other powders. Cohesion, which is a binding mechanism, is mainly due to solid bridges that form, interlocking forces, attraction forces or interfacial forces. These are all factors which contribute to the poor flow-ability of the powder, which is a function of many factors such as powder morphology, humidity, consolidating pressure and the history of the powder and other specific process conditions. In the case of Ti6Al4V powder the poor flow-ability experienced by the powder can be due to humidity causing an increase in the moisture content of the powder. This assumption was proven in our laboratory when dried powder would flow freely from a specific hopper outlet width through which the non-dried powder would not flow. The specific dependence of powder flow-ability on the moisture content of the powder still needs to be numerically quantified.

The results from the experiments are depicted in the figures below. Figure 7 illustrates the volumetric flow rate dependence on hopper outlet width for all the powders investigated except for the titanium alloy powder which is discussed in more detail and is illustrated by Figure 8. The linear trends observed for each different powder alloy are shown below each graph where y is the volumetric flow rate in ml/s and x is the outlet dimension in mm. These equations are valid for outlet widths within the range of 0.4 to 1.2 mm in the case of SS 410, IN 718, and Haynes 31 alloy and dry Ti6Al4V and 0.9 to 1.2 mm in the case of humid Ti6Al4V and when the hopper material is stainless steel with a surface finish of between 0.2 and 1 µm (Outokumpu).



y = 6.6x – 2.1

(a)



y = 6.3x – 1.1

(b)

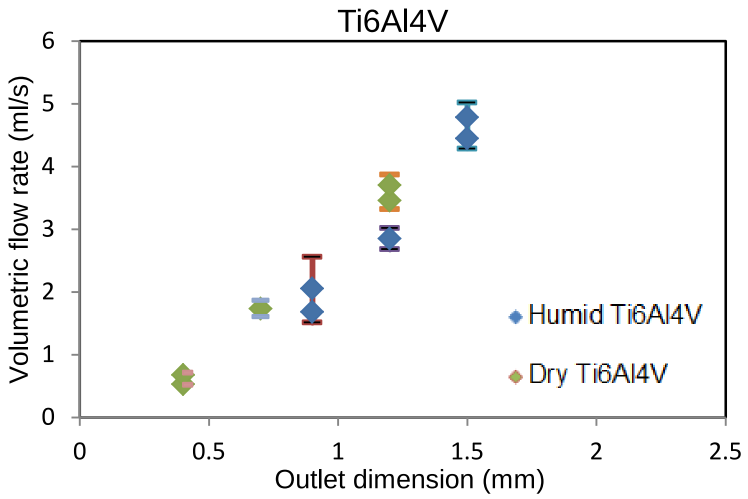
y = 5.0x – 0.3

(c)

Figure 7: Volumetric flow rate dependence on hopper outlet width for (a) SS 410 (b) Inconel 718 and (c) Haynes 31 (▬ indicates error bars)

As can be seen from Figure 7 the volumetric flow rate dependence on hopper outlet width followed a linear trend for small outlet sizes. The linear trend indicates that the volumetric flow rate is a stronger function of outlet dimension than wall friction when the outlet dimension is small enough. In the additive manufacturing process a specific, and in many cases a low, powder delivery rate is required, not only a flow - no flow criteria like in bulk hopper design. This means that smaller outlet dimensions will most likely be the more favoured parameter and a linear trend will be a good prediction of the volumetric flow rate for the powder used in additive manufacturing.

Figure 8 illustrates the powder delivery rate for Ti6Al4V powder when in the dried and non-dried conditions. The powder delivery rate is close to the same for both conditions and followed a linear trend in both cases.



HUMID: y = 4.6x – 2.3 DRY: y = 3.7x – 0.9

Figure 8: Volumetric flow rate of dried and humid Ti6Al4V powder (▬ indicates error bars)

The big difference between the dried and humid powder was the outlet dimension at which powder would flow out of the hopper under gravity force only. The dried powder would flow out of the hopper freely at a smaller outlet width than the powder that wasn't dried. The minimum outlet width for flow to occur took place at 0.4 mm dried and at 0.9 mm when not dried. The moisture content in the Ti6Al4V powder caused the powder to create a stable arch that could only be overcome when the hopper outlet width reached 0.9 mm.

The hopper wall angle did not have the same influence on powder delivery rate as the hopper outlet dimension, but it can be seen from Figure 7 a-c that at larger outlet widths, a deviation from the observed linear trend starts to occur. As the outlet size is increased, the mechanisms causing powder to flow out is still only gravity and the mechanisms preventing powder to flow is still only the friction between particles and particles and the hopper wall, and a physical barrier in the form of hopper walls. As the outlet width is increased, the physical barrier blocking flow decreases but frictional forces are still present and are noticeable at this stage of flow. The dependence of the volumetric flow rate on the hopper wall angle is a function of the surface finish of the inside walls of the hopper. The hopper wall material used was cold rolled stainless steel of which the typical surface finish is between 0.2 and 1 µm (Outokumpu). In this investigation a hopper with only one surface finish was used. Further studies to determine the dependence of volumetric flow rate on the surface finish of the hopper material should be a suitable extension for the current investigation.

The Jenike method was used and a hopper outlet width of 31.25 mm was reported from the results. The Jenike overestimates the outlet width of the hopper for mass flow with a factor of 26 (based on the results for the maximum volumetric flow rate obtained). The Jenike method is based on quasi-steady state conditions where the material is assumed to be a rigid plastic frictional continuum (Kruyt, 1993) and the forces applied to the powder need to reach a yield criterion in order to flow. Other literature on methods of hopper design is not readily available and the Jenike method is a good starting point. This method is however not very suitable once the hopper needs to be designed like specifically in this case where the hopper will be used in additive manufacturing. As hopper design is very dependent on the type of powder to be used and the powder flow-ability in turn is dependent on the process conditions it is used in, experimental runs to determine optimum hopper design dimensions for a specific application yields much faster and tangible results.

5. CONCLUSIONS AND RECOMMENDATIONS

Four different types of powder were investigated for hopper design in additive manufacturing processes. The four powders differed in terms of density, particle size distribution and chemical composition. The volumetric flow rate as a function of hopper wall angle and hopper outlet width was determined for the four different types of powder. The physical property most influencing the powder volumetric flow rate was the particle density, as the Inconel 718 with the highest density also had the highest flow rate. In terms of non-measurable flow-ability such as cohesion of the powder to the walls of the hopper as well as fluidity in movement, the particle size distribution played a role as the powder flowing with the most difficulty was the powder with the lowest d_{50} value.

The critical dimension for hopper design in additive manufacturing was found to be the outlet width. Linear trends were determined to predict the volumetric flow rate when the outlet dimension and surface finish of the hopper wall material is known. The volumetric flow rates for the different alloy powders were comparable except for the titanium alloy which had a lower flow rate. The Ti6Al4V powder used in this investigation was found to flow differently when dried, indicating that the humidity of the atmosphere in which the powder is handled has an effect on the flow-ability of the Ti6Al4V.

Bulk hopper design methods were found to be unsuitable for additive manufacturing hoppers that need to feed powder to the powder bed as the suggested values were much higher than experimentally observed values.

6. REFERENCES

Carson, JW, Pittenger, BH (1999) “Bulk properties of powders” in ASTM Handbook – Powder metal technologies and applications, ASM International, 287-301

Chase, GG (sa) “Solids notes 10”, Course Notes, Department of Engineering, University of Akron

Kruyt, N (1993) “Results of Jenike’s (1987) radial stress field theory for the flow of granular materials in conical hoppers: flow regimes and flow factors” *Powder Technology*, (76), 109 - 112

Prescott, JK and Barnum, RA (2000) “On powder flowability” *Pharmaceutical Technology*, October issue, 60 - 85

Outokumpu (*sa*) “What surface finishes are available for stainless steel?” http://www.outokumpu.com/en/stainless-steel/about-stainless/stainless-steel-surface-finishes/Pages/default.aspx 17 July 2013