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Filling induced density variations in PM compacts

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Summary

Filling induced density variations is a problem that long has been overlooked by PM scientists. In this paper, density variations are addressed, both why they occur and what problems they may cause. A test method including a test rig is presented that is able to link several different factors to resulting powder densities. The relations are analysed and several density affecting mechanisms are suggested. These mechanisms could be used ether to minimise density differences within parts or to control density by direct powder to critical areas.

Introduction

The quality of a solid part produced by compressing and sintering a granular material is dependent on the homogenous density of the produced part. Inhomogeneous density will lead to distortion during sintering, resulting in inability to keep high demands on dimensional tolerances. Inhomogeneous density also means that the part will not live up to its potential regarding mechanical properties as low-density regions will remain as potentially weak areas. As demands for tolerances and mechanical properties are increasing, it becomes increasingly important to locate and eventually eliminate the sources for this variation. The sources may however be difficult to track. Inhomogeneous temperature gradients during sintering, or variations in compaction pressure or powder mix may lead to inhomogeneous density.

Comment [A1]: Om du inte har nåt emot det, kan vi här referera till mig, förslagsvis Bergquist B, Property variation in sintered steel: Design of experiments, INTERNATIONAL JOURNAL OF POWDER METALLURGY 33: (2) 30-& MAR 1997

The mechanical handling of the powder from the feed shoe and into a die has also been suspected as a source of density variations [1]. The subject has not been thoroughly investigated, presumably due to the lack of methods to make experimental data available. Recent investigations of the density distribution in large compressed rings has however indicated the presence of density variations of up to 3% that cannot be explained by other means then as a result from the filling operation [2]. The resulting density variations in this investigation were systematic, indicating that controlling or eventually eliminating this variation might be possible by modifying the filling procedure.

Establishing a relation between the mechanical handling of a powder and the resulting density is however a complicated issue. Attempts to identify and explain the underlying fundamental physical mechanisms of powder behaviour have been made since the 1960s [3]. This work has not yet generated any generally accepted phenomenological models. Many problems of a fundamental nature remains to be solved before the density of a powder arrangement can be modelled and predicted by its handling procedure [3, 4, 5, 6]. It is questionable if fundamental studies of powder behaviour will provide information detailed enough to be of use to a producer of powder metallurgy (P/M) compacts within the foreseeable future.

An alternative approach is direct studies of industrial filling systems in attempts to establish correlations between the density and different process variables. We believe this approach represents a more cost and time efficient alternative to improve the properties of P/M components.

In order to be able to find density variation sources, a method able to measure the density of sections within a cavity or a compressed P/M sample is required. Both measurements on compacted parts and on powder with a cavity can provide this information, they each have their own advantages and disadvantages.

Density measurements on compacted parts

Density measurements through Archimedes principle are an accurate way to study the density variations within a compact. The standardised method for studying the density of sintered materials (ISO 2738) can be used to study sections of green compacts. The advantage of this method is the high accuracy of the measurements. As it is insensitive to small changes in sample volume, small pieces falling of the parts during sectioning will not cause erroneous results. The disadvantage of this method is the need to compact the powder and use the density after compaction as an estimate of the density after filling. Depending on compact geometry and the direction of the studied density variations in relation to the compaction direction, the compaction process may introduce density variations on its own. The need for compaction will usually also limit the number of factors that can be analysed. Factors such as feed shoe geometry, feed shoe direction and speed may be hard to vary when the powder feeding system is integrated with a compaction press.

Density measurements on uncompacted powder

Measuring the powder density directly has the advantage of increased simplicity and flexibility when the compaction step can be avoided. The disadvantage is the loss of accuracy when the powder density is calculated through weighing alone, since the loss of powder particles during weighing often is unavoidable. This may to some extent be countered by increasing the size of the powder samples. Several methods that measure the powder density of an entire cavity by weighing are available today. The most common is the funnel method to estimate apparent density (ISO 3923-1). Other methods include the Arnold meter (ASTM B703) and Scott volumeter (ISO 3923-2). None of these methods offer the possibility to alter the filling operation but they can be valuable for characterising the bulk properties of a powder sample. They can however not be used to investigate powder filling behaviour as this is also affected by the handling of the powder during the filling.

To investigate powder behaviour during filling, other techniques have been introduced where feed shoe speed and cavity geometry can vary [Larsson, Vidarsson, Bocchini]. These methods are however still inadequate to study filling induced variation as they cannot measure density differences within a cavity. The filling behaviour of a thin, isolated rectangular cavity may also behave differently than the filling of a cavity where the rectangular section is a part of a larger geometry. In the latter case, powder may flow between sections, as opposed from an isolated cavity where all powder will arrive from above. In an isolated cavity, fluidising phenomena may affect the final density of the powder as air at the bottom of the cavity is forced to escape through the in-flowing powder.

Research advances within the field of powder packing

Particle packing is a complex area that has been studied by scientists for centuries. Despite the number of investigations that have been performed (over a thousand) [German PCC, Cumberland&Crawford] understanding of complex systems such as the filling operation commonly associated with the uniaxial compressing of free flowing powders is limited. At best, relations between different process parameters and the resulting powder density can be hinted at through various forms theoretical reasoning. Works intended for understanding

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filling primarily follow two different paths, fundamental studies of general powder behaviour and empirical studies of the filling operation.

The objective of the more fundamental studies have been to locate and identify the underlying physical mechanisms occurring on a microstructural level which, in turn, affect macroscopic powder behaviour. Insofar fundamental attempts are too crude to be useful for filling predictions [Rosato, Kestenbaum, Davis, Sundaresan, German PCC].

Empirical studies of the filling operation have been scarce but the field is receiving a growing interest. Today, several investigations where some form of feeding device mechanically transport a free flowing, metallic powder horizontally over a cavity where it falls down due to gravity have been published [Sawayama, Rice, Kondoh, Kondoh, Urata, Lindskog, Faikin, Larsson, Boccini, Vidarsson, Haskins, Itoh]. These studies do however, separately, only examine one or a few of the many factors affecting the density of the powder. Results might be valid for a specific experimental system but since the fundamental mechanisms of granular mechanics is not yet understood, great care should be taken when trying to compare results from different investigations or when drawing general conclusions on powder behaviour. In order to expand the knowledge of the powder filling operation it will therefore be necessary to compare the relative importance of different factors.

The origin of the density variation

Why can we find density differences in powder that has filled a defined space and how large can these differences become?

Even for simple powders such as those composed of monosized spherical particles, the density of the powder sample will vary between a minimum and a maximum level since interparticle friction will limit the ability of the powder to form regular packing arrangements. Several particles can together form arc or bridge like arrangement leaving large voids beneath. The amount of particle bridges in a sample will vary depending on to what extent the filling procedure can counteract interparticle friction and create denser packing arrangements.

Figure B1. A pile of particles with an increased volume due to the presence of two pores caused by particle bridging. [After German PCC]

At the minimum density level, the powder will contain a maximum amount of bridging particles and the entire powder sample will be at the brim of fluidisation, see Figure B1. By fluidising the powder and carefully lowering the flow rate of the fluidising medium below the fluidising velocity we can experimentally determine a good approximation of powder density in this theoretical state. The fractional powder *density at the onset of fluidisation* for a spherical, mono-sized powder has been determined to 0,53-0,54 [Haughey, German].

The minimum number of bridging particles and thus the maximum density will be achieved through an arrangement defined as *random dense packing.* The powder density at this is stage is the highest density that can be attained without disrupting the random particle arrangement. For spherical mono-sized particles this corresponds well to the experimentally determinable *tap density* and a fractional density of 0,637 has been reported [German, PCC]. If different parts of a cavity are subjected to considerable differences in handling, there is therefore a potential risk that a filled cavity that on the surface appears to have filled homogeneously might contain density differences of up to 18%.

Takahashi and Suzuki [##] have proposed a relation for the density of a powder subjected to small, well-defined vibrations. Their relation is illustrated in Figure B2 where the densification rate can be seen to decrease with the number of agitations.

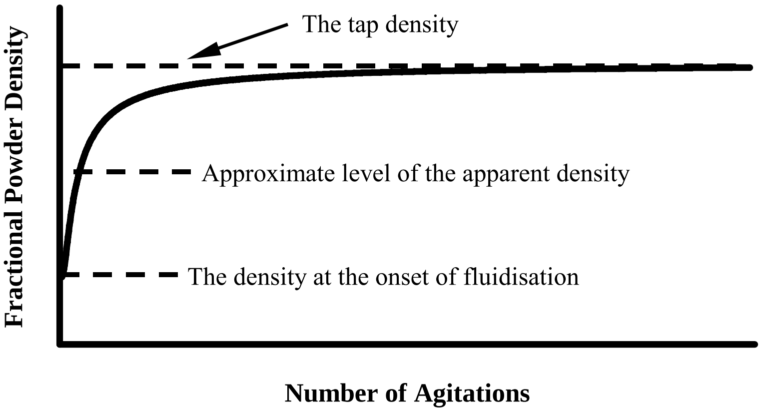

Figure B2. The densification of a spherical, monosized powder as a result of vibration (after Takahashi & Suzuki [##].

Figure B2 can be used as an indicator that the looser a powder arrangement is, the more sensitive to handling it becomes. After a filling operation has completed, the powder will usually have a density close to the apparent density of the powder. At this level, the density will be sensitive to handling and for complex cavity geometries, the differences in filling conditions for different parts of the cavity is sufficient to create density variations within the cavity. The density differences will be even higher in PM powders, since these contain size distributions and non-spherical particles. Particle surface irregularities will help formation of particle bridging and increase the difference between the powders maximum and minimum density [German PCC]. Particle size distributions may also increase this difference, since the effect of particle size segregation on the maximum density will be important (a mix of two monosized, spherical powders can increase the maximum density from 0,637 to 0,734) [German,PMSCI]. The effect on the minimum density on the other hand can be expected to be low or possibly negligible as the distribution of particles in this state is approximately random. A bimodal mixture of spherical particles will therefore increase the possible density differences from 18 to 32 percent.

As the surface area to weight ratio increases rapidly as powder sizes decrease, surface effects become increasingly important with small-size powder. As surface effects will be more pronounced, powder flow will decrease and the powder will pack more loosely [German, PM of Iron and Steel, p. 58]. Geometrical effects of tool cavities will also add variation, since bridging over thin sections may render the sections empty.

Terminology, Definition of powder density

The *apparent density* (or bulk density) of a powder sample is defined as its mass divided by the volume in a loose, non-agitated state [ASM Handbook Carson and Pittinger, German PMSci]. It cannot be considered a powder property since different experimental procedures, with different ways of assembling the powder sample will have a large influence over the result. Fractional densities ranging from 0,560 to 0,625 have been reported for monosized spherical particles [German, PPC].

With the development of the mentioned standardised methods to *estimate and quantify* apparent density this term has become synonymous with the experimental result of these methods. The result of these methods *can* be treated as a powder property since the mechanical contribution to the powder density can be controlled through a well-defined handling procedure. When differences between the different techniques are examined, it is however apparent that there is a mechanical contribution to the measured density [Peterson&Small]. Handling procedures not clearly defined in standards have also been reported to have systematic influence over the results [Dai&Lai, Alber].

Throughout this work the density of a powder arrangement have been termed by the more general 'powder density' to avoid confusion.

Problem description

Many different factors in a conventional filling system can be expected to introduce density variations in the filled powder. Today there is no viable method, simulation tool or test equipment, that may quantify these density variations in uncompressed powder and link the variations to influencing factors for practical applications. This may in turn limit the quality of PM parts.

Purpose

The purpose of this investigation is twofold:

- Establish a method to quantify density variations as results of a conventional filling
- Identify factors responsible for the systematic density variation

Empiric

Test rig

As the purpose of the investigation was both to create a method to quantify density variations as results of a conventional filling as well as to identify factors responsible for the systematic density variation. Discussions with colleagues within the solid mechanics department led us to the conclusion that computer simulations were currently ill fit to handle the complexities regarding filling with typical particle numbers. Simulation was therefore disregarded and we decided to use an experimental approach. Current test methods were studied, but considered inappropriate for seeking cause-effect relationships and therefore the investigation progressed by defining how we thought a proper experimental procedure and associated test equipment should be constructed.. As a first step, different factors suspected to influence filling was listed. These factors were then prioritised based on their likely effect on filled powder density, ease of control and ease of measurement (see Table 1). Since the list was used for the construction of a test rig, powder properties was not seen as interesting as those that had to be acknowledged prior to rig construction. The requirements for the rig based on the list, was that the rig had to be of a size comparable to or larger than production scale filling devices. The speed and position of the feed shoe needed to be adjustable within large ranges, possibly to larger speeds that what is currently used. The acceleration of the feed shoe should be controllable and the cavity and feed shoe geometry should be adjustable. Other requirements such as visibility proposed that plexi-glass should be used for most parts. Two types of cavities were developed, but only a ring shaped cavity is discussed here. A test rig was then developed that could satisfy the highest prioritised demands.

Table E1. Property selection table

Property	**Expected importance** 9 = high 3 = moderate 1 = low	**Measurability** 9 = high 3 = moderate 1. = low	**Adjustability** 9 = high 3 = moderate 1. = low	**Sum**	**Selected for test**	**Comment**
Feed shoe speed	9	9	9	729	Yes	
Number of additional filling cycles over a filled cavity	9	9	9	729	Yes	
Powder level of feed shoe	3	9	9	241	Yes	
The time the shoe spends stationary in the filling position	3	9	9	241	Yes	
Cavity geometry	9	3	9	241	No	
Feed shoe acceleration,	9	(9) 3	3	(241) 81	No	Was not tested due to measurement problems
Apparent density of powder	9	9	3	241	No*	
Powder flow	9	9	3	241	No*	
Suction or gravity filling	3	9	3	81	No	
Feed shoe vibration	9	3	9	81	No	
Cavity geometry	9	3	3	81	No	
Particle size distribution	3	9	1	27	No*	
Powder tap density	3	9	1	27	No	
Cavity vibrations	9	3	1	27	No	
Powder and machine temperature	1	9	3	27	No	
Fill table levelness	3	9	1	27	No	
Component density in powder mix	1	9	1	9*	No*	
Method to fill feed shoe	1	3	3	9	No	

Filling device

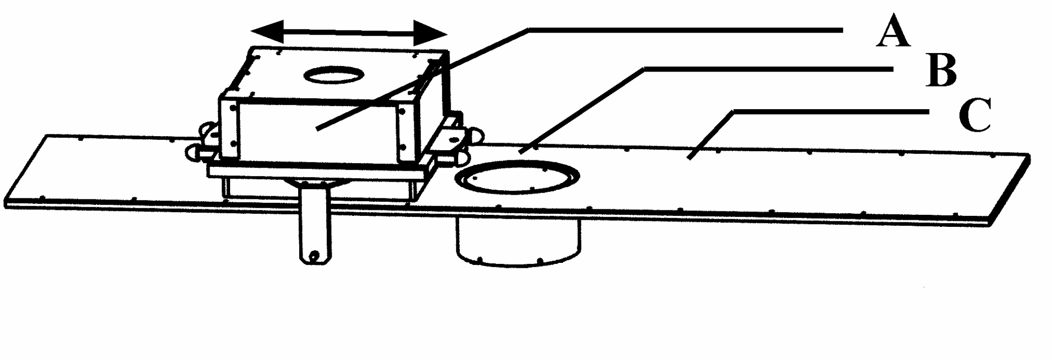

Figure E2. Detail of rig showing filling device. A = feed shoe, B = ring shaped cavity, C = feed shoe table. Arrow indicates the direction of the feed shoe motion. Hydraulics, electronics and foundation are not shown.

The main components of the filling device are illustrated in Figure 1. A hydraulically operated feed shoe (inner dimensions 320x320x160 mm) was filed with powder and used to perform a variety of movements to fill a ring shaped cavity (inner and outer diameter of 170 and 190 mm and a height of 20 mm). The maximum obtainable feed shoe speed was 1,6 m/s. Speeds below 0,2 m/s induced stick-slip vibrations and were therefore avoided during tests. Feed shoe position was recorded and fed back into the control and recording system. We were unable to accurately measure the limits in acceleration for the system, but rough calculations based on visual observations of the fill cycle estimate the maximum deceleration from 1,6 m/s to a full stop to 500 m/s^2. The feed shoe and the feed shoe table were constructed in PMMA (plexi-glass) to enable visual observations during the filling operation. The interchangeable cavity was constructed in aluminium to ensure higher measurement precision.

Density measurements

The cavity was divided into four 90° sections so that internal density differences could be measured. After each filling run four thin plates (0,3 mm thick) were inserted between them. An angle ϕ was introduced to correlate the position of the sections to the initial filling direction (see figure E3). The powder from each section was sucked out of the cavity and separated from the air stream with a 15-µm filter. The separated powder was weighted to yield the powder density. A small amount of the finest particles were lost in this operation. This had a negligible effect on the powder size distribution and will not influence the relative density variations between the different sections.

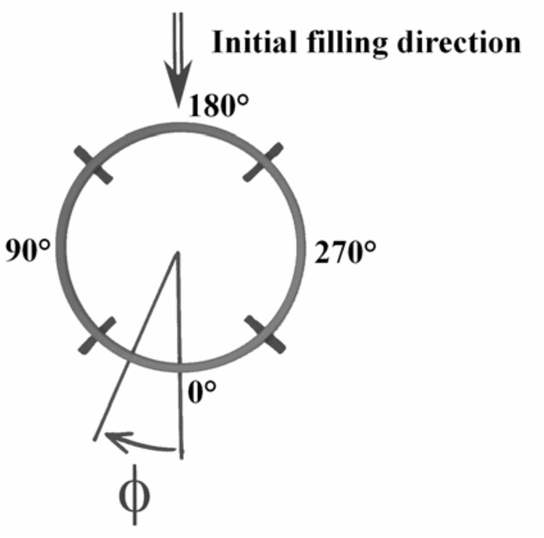

Figure E3. Section coordinates of the ring shaped cavity. The four sections were identified by their centre position (0,90,180 and 270 degrees)

Experimental strategy

Since there was a large number of identified factors that were considered interesting regarding their possible density variation effects, the first consideration was to perform a fractional factorial experimental design. A fractional factorial design has the benefit of reducing the number of performed runs to a minimum for a given experimental accuracy compared to a paired comparison test or a test with one factor at a time. A well-designed experiment also enables estimation of the effects of interactions between the tested experimental factors on the density. (It is not necessarily so that the effect on density of a fast powder delivery through high shoe speed is the same regardless of, say the feed shoe contains internal baffles)

A factorial design also has certain drawbacks. Experimental economy often limits the number of tested levels for each factor to two, which is fine if the effect is linear. With small differences between the levels, a linear approximation is often reasonable. Unfortunately, with many of the selected factors it was difficult to say how large a small difference should be. Factorial designs also require that all runs should be possible to arrange. If the process is as unknown as our test rig was to as, it is advisable to run a number of pilot runs.

To us, non-linear relations were considered as interesting as possible interactions. The simplicity and robustness of one factor at a time experiments was therefore favoured at the cost of a low experimental economy.

Experiments

Filling cycles

Three different types of filling cycles were used in this investigation. The position and speed of the feed shoe during these cycles are shown in Figure E4 and E5.

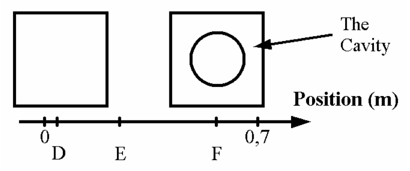

Figure E4. The relative positions of the centre of the feeding shoe, D = the starting and stopping position of the feed shoe, E= the turning position as the feed shoe is stopped before performing additional filling cycles, F = the filling position of the feed shoe.

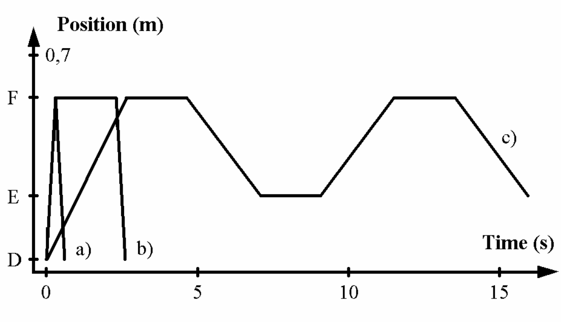

Figure E5. The three filling cycles were a) a cycle with constant speed and no pause in the filling position b) a cycle with constant speed and a 2 second pause in the filling position (F) c) as the previous cycle with additional filling cycles after the initial filling operation.

Powder

Pure iron powder (HÖGANÄS ASC 100.29) was used through the entire study. The feed shoe was filled with powder to a height of 8 cm prior to each performed experiment (equals roughly 25 kg).

Reliability and validity check

The described filling equipment resembles conventional filling equipment in most ways, but differs in some. One obvious difference is the lack of a powder hopper and powder feed tube attached to the feed shoe in favour of a manual filling.

Another concern is the manual labour needed during the analysis. Two critical steps included manual interference. The first interference was due to the larger tolerances needed since the feed shoe table, and feed shoe was produced from transparent plexi-glass sheets as compared to milled steel. The larger tolerances between feed shoe and feed shoe table resulted in a fine powder layer remaining on the surface of the feed shoe table after a completed fill cycle. The residual powder was scraped off in the direction of the feed shoe motion with a rubber scraper after each fill run.

The second manual interference occurred when the powder was sucked out of the cavity. Both these interferences will add variation to the measured result. Only one person was involved in the experimental labour and the associated error is therefore suspected to be fairly constant for all tests. As the conclusions are based on comparisons between different tests, the conclusions should be reasonably unaffected by human error.

Experiments

The most interesting, and most easily adjustable factors from Table 1 were selected for the experimental studies. Measurement difficulties ruled out direct tests of feed shoe acceleration. The selected tests were time of filling, measured as settling time of powder during filling, speed of filling shoe, number of shoe passages, powder level of feed shoe. Since the feed shoe was constructed with the possibility to add baffle inserts, this factor was also tested.

Powder density as a function of settling time

The reason for this experiment was to see if the filling was time dependent, that is, would a filling with a two second pause of the feed shoe above the filling position give the same density average and density profile as a filling sequence where the shoe immediately was retracted from the filling position. Shoe speed and acceleration was identical for both tests.

Powder density a function of shoe speed

Here, the purpose was to study the impact of the speed of the feed shoe upon the density. The shoe speed was varied between 0,2 up to 1,4 m/s, the feed shoe was stopped over the filling position where it was delayed for 2 seconds before returning with the initial speed to its starting position.

Powder density a function of number of shoe passages

Additional filling cycles over an already filled cavity were one of the factors expected to affect the density of the powder within the cavity. A fill cycle was selected with speed 0,2 m/s and a filling delay of 2 s. This cycle was repeated without emptying the cavity during multiple pass runs.

Powder density a function of shoe powder level

As increases in powder pressure might increase filled density, the powder pressure was varied by changing the amount of powder in the feed shoe from a height of 2,5 up to 15 cm. The fill cycle during these tests included a shoe speed of 0,2 m/s, a delay of 2 s.

Powder density as a function of shoe design

The feed shoe design used is an open-box type; there are not any baffles or other devices to direct the powder flow during filling. When the box is above a cavity, powder will flow unhindered to the bottom. A baffle insert was installed at the shoe bottom leaving a 1 cm slit opening in order to investigate the effect of a directed filling. The feed shoe speed during these tests was varied between 0,2 and 0,02 m/s. These experiments were performed with a simplified filling cycle where the feed shoe passed over the cavity with a constant speed, no delay was introduced and the feed shoe did not return to its original position but continued over the cavity to the other side.

Results

Density as a function of settling time

The introduction of a 2s delay of the feed shoe above the cavity raised the powder density in all compartments. On the average, this raise was of around 2 percent (see Figure R1). Without the pause, the 0° section remained partially unfilled. Figure R2 shows an example of such an incomplete filling from another test run.

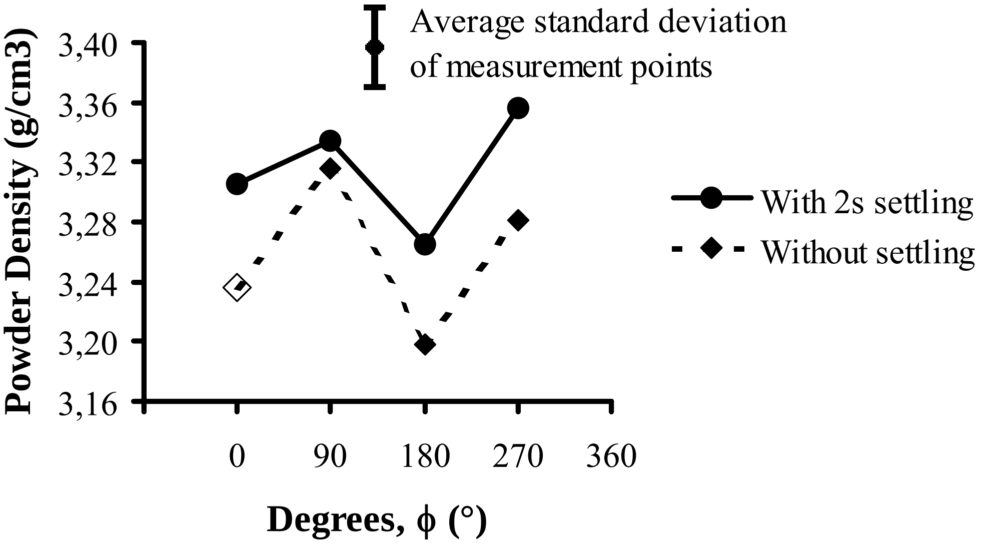

Figure R1. The powder density within the cavity after a filling operation performed with and without a two second pause at the filling position before the shoe starts to retract. Each point represents an average of 4 measurements. Without such a pause the powder density in the *entire cavity will be lower and the 0° section will remain partially unfilled (illustrated by the open measurement point).*

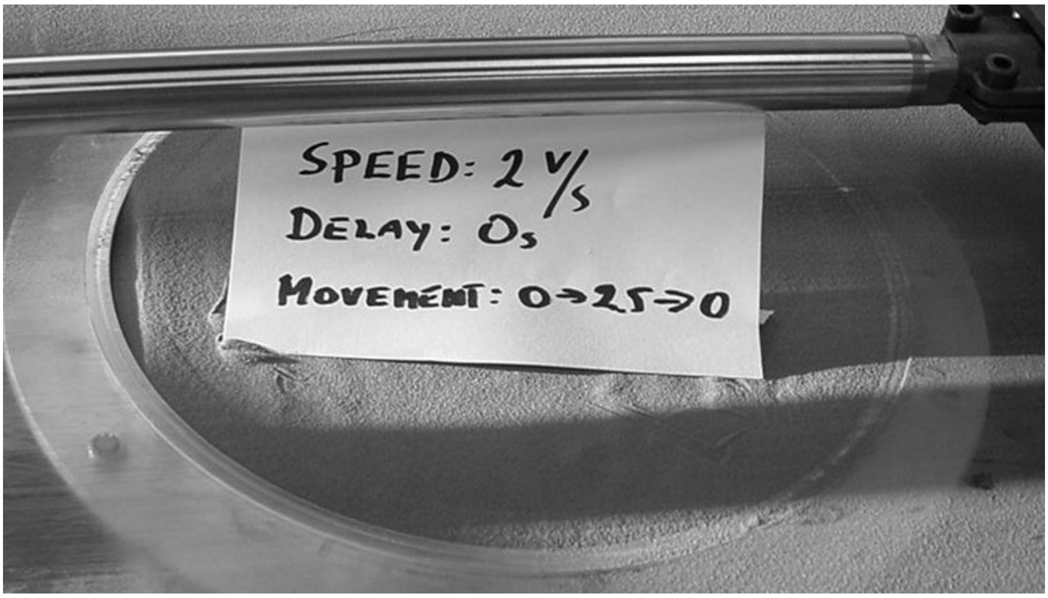

Figure R2. Photo of cavity after a pass without delay of feed shoe (photo taken after a run at 0,5 m/s shoe speed). Note how the 0° section (to the left in this figure) remains partially unfilled.

<u>Powder density a function of shoe speed</u>

The powder feed shoe speed was tested, with a low speed of 0,6 m/s and a high speed of 1,4 m/s. The cavity densities were around 2 percent higher after high-speed fillings, and the density increase was noted in all compartments, see Figure R3.

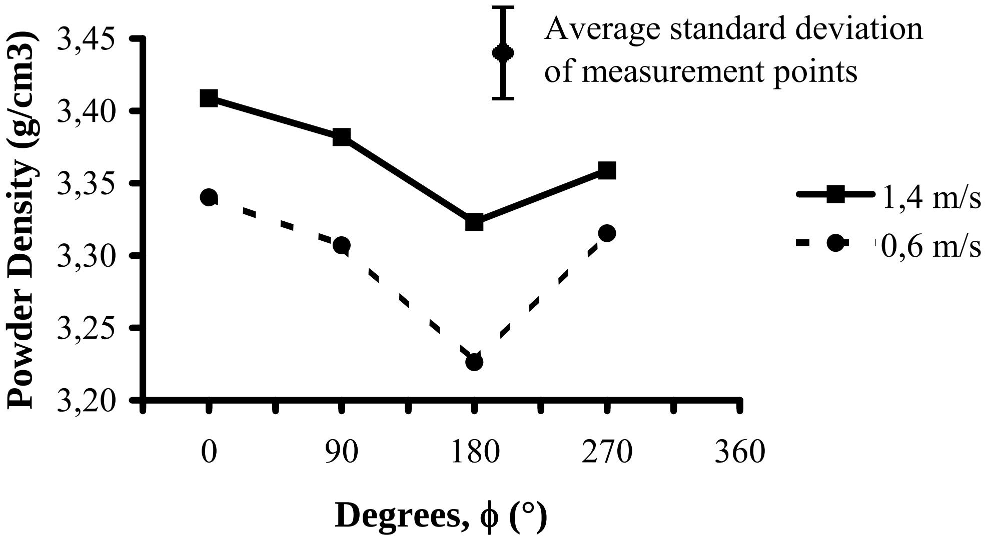

Figure R3. The powder densities of the four sections of the cavity after filling operations with three different filling shoe speeds. Each point represents an average of 4 measurements.

Shoe passage effects

During these tests the density within the cavity after a complete filling cycle was compared to the density within the cavity after several passes of the feed shoe without emptying the cavity. As suspected, the additional filling cycles increased the powder amount in the cavity, see Figure R4.

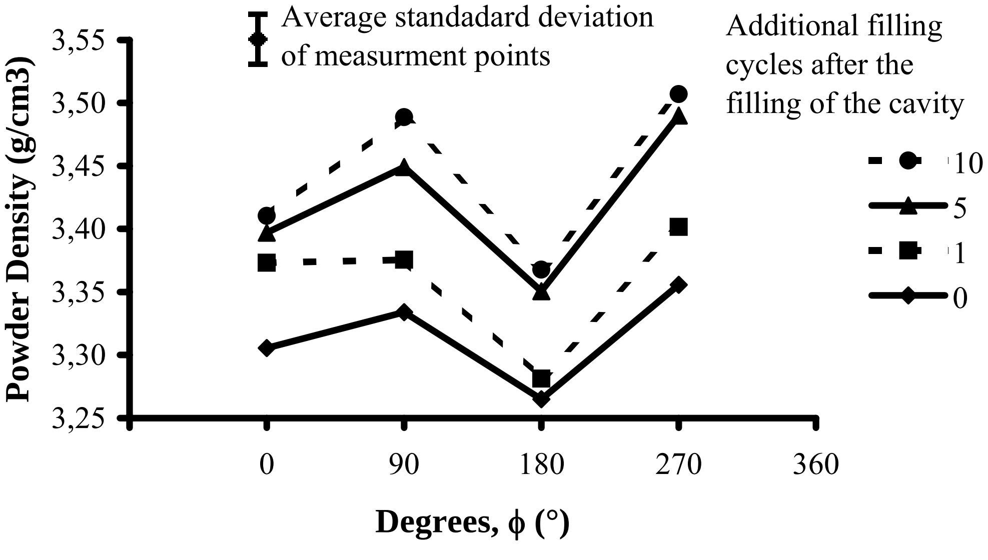

Figure R4. The powder density within the four cavity sections when an additional number of fill cycles (from zero to ten as the figure indicates) were performed after the initial fill cycle. Each point represents an average of 4 measurements.

Powder level in feed shoe

One presumption was that powder pressure resulting from different amounts of powder in the feed shoe might result in different filled densities in the cavity. This was not the case for the powder and geometry tested, see Figure R5. Except for a measurement taken with a powder level of 2,5 cm, the density was insensitive to the amount of powder within the feed shoe. With a powder height below 3 cm in the feed shoe, the powder could not reach the entire cavity and large sections remained partially unfilled.

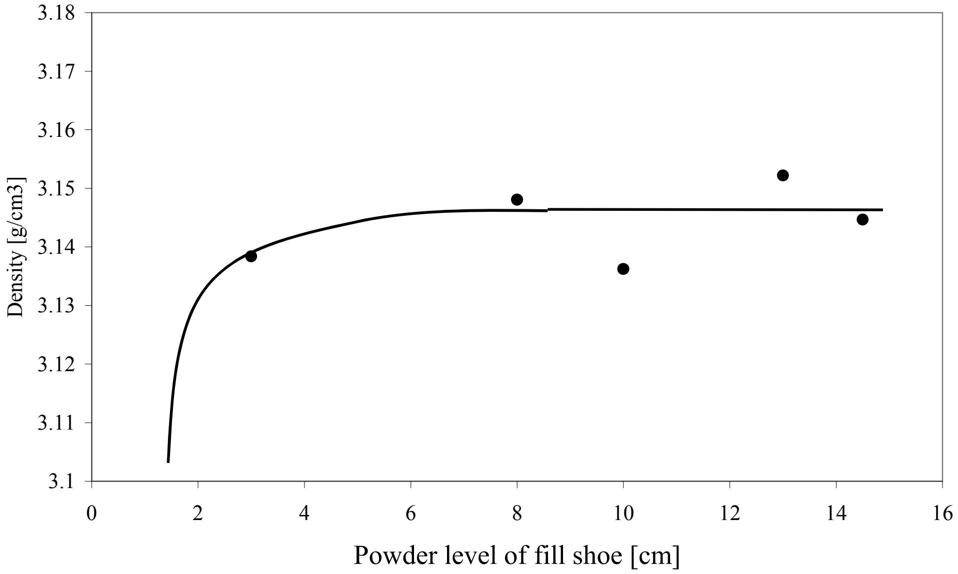

Figure R5. Cavity density as a function of powder level in feed shoe. Feed shoe speed 0,2 m/s, delay at filling position, 2 s. Each point represents an average of 4 measurements.

Filling with a slit opening in the feed shoe

With a slit opening in the feed shoe, the time to fill the cavity increased. In order to fill the cavity completely, a speed as low as 2 cm/s was necessary. At this speed, the test rig displayed serious stick-slip vibrations. Therefore, the slit-opening test gave inconclusive results.

Discussion

Mechanisms influencing filled density

Gravity

The first and most obvious density influencing mechanism is gravity; the filling sequence depends upon it. A particle unaffected by friction will drop from the bottom of the feed shoe to the bottom of the cavity in $t = \sqrt{\frac{h}{2g}}$ seconds. The test cavity had a depth of 2 cm, so the first particle, will reach the cavity floor in $t = \sqrt{\frac{0.02}{2 \cdot 9.81}} \approx 0.032s$. The filling rate will however be limited by the time it takes the feed shoe to pass over the cavity. Depending on the speed of the feed shoe this will take between 0,1 and 0,9 seconds for the feed shoe rates used in this investigation (0,2-1,4 m/s). As the time for the vertical transportation of the powder can be neglected, the filling rate will roughly correspond to feed shoe speed unless it is hindered or enhanced by other mechanisms.

Air resistance

Powder can easily pour down into the cavity as long as a part of the cavity still is open to the air. When the shoe covers the entire cavity, any remaining air in the cavity will be forced to pass through the incoming powder and up through the shoe. The amount of entrapped air will naturally depend upon cavity geometry and shoe speed. Kondoh et al. [#] have established that a 4 cm deep cavity will entrap air even at a shoe speed as low as 0,06 m/s. Since most filling operations within the PM industry employ higher speeds, air entrapment is a part of most filling operations.

If the feed shoe have started to retract and has left the cavity when the remaining air leaves the cavity, the volume occupied by the out-flowing air will not be replaced by new powder. Naturally, this will lower the powder mass of this section. The result of this can be seen in the filling operations illustrated in Figure R1. Here two different filling cycles were performed. One where the shoe has started to retract as soon as it reached the filling position and one where a two second stop was performed before the retraction of the filling shoe. Without a settling time, the period that the shoe covers the last centimetre of the cavity (approximately 0,7 seconds) is not enough to let the air be replaced by powder and the 0° section will therefore not fill completely (illustrated by the open measurement point in Figure R1 and by Figure R2).

The second effect is the change in filling behaviour when air is forced to pass through the pouring powder. In this investigation there are no signs indicating that this fluidising phenomenon affects the powder density. The previously described powder fluidisation will affect a larger part of the cavity at higher feed shoe speeds since the shoe will seal off the cavity earlier. and this would lead to a decrease of density in the exposed compartments. Instead, powder density increased with higher shoe speeds. If there is an effect on the density, it is either too small to be separated from the random variation in these investigations or localised to a too small volume (presumably just around the 0° position) to affect the average density of a 90° region. Still, air resistance must be considered as a potential source for variations in filled density.

Comment [BB3]: Hur ser vi och visar att effekten av fluidisering är så liten att den är obetydlig?

Comment [EHJ4]: Densitetsökningen som sker vid hastighetsökningen är homogent fördelad över hela kaviteten. Om fluidiseringen påverkade borde sektion 0° erhålla lägre densitet och skillnaden mellan 0° och resten av kaviteten borde öka med hastigheten.

Comment [A5]: Jag vill minnas att det inte är så självklart att en fluidisering alltid leder till lägre densitet. I vårt fall kanske fluidiseringseffekten snarare hjälper till att packa pulvret? I så fall är densitetsökningen kanske en fluidiseringseffekt?

Density increase with increased speed

As can be seen in Figure R2, there is a clear, homogenous increase in powder density through the entire cavity when the speed of the feed shoe is increased from 0,6 to 1,4 m/s. We believe that this increase in density is a result of the kinetic energy of the powder in the feed shoe that is partially transferred into the cavity where it causes a rearrangement of the particles and compaction. The acceleration rate during stopping of the feed shoe might be an influencing factor and the role of gravity during this movement isn't clear either, it may influence the process or might have be of negligible importance.

Comment [A6]: Alla möjliga samspel är väl möjliga; varför ta upp just detta samspel och varför först här? Om du vill ha kvar den brasklappen (som enligt min mening ger trovärdigheten av hela undersökningen en knäck) bör den inte komma först nu och dessutom motiveras tydligare. Nej mitt förslag är att brasklappen stryks helt och hållet (vi har väl inga belägg för att ett sånt samspel existerar?).

Mechanical packing through shear within the powder mass

If the fill cycle is repeated without emptying the cavity, additional powder will flow into the cavity and raise the density, as was seen in Figure R2.

This is also believed to be an effect of the kinetic energy of the powder in the feed shoe. Moving particles in the feed shoe will collide with stationary particles in the cavity and thereby partially transfer their kinetic energy to the powder inside the cavity. This movement causes a rearrangement of the particles and a denser packing arrangement. The degree of densification can be expected to vary with direction and size of the kinetic energy and interparticle friction.

The first particle collisions will start a chain reaction through the cavity where multiple particle collisions can reach far into the cavity (illustrated in figure D2). As the densification is the result of multiple particle collisions it can be expected to

- have a maximum depth. After a certain amount of particle collisions the kinetic energy will be lost because of the particle friction. Particles deep enough will therefore remain stationary.
- be less pronounced in the part of the cavity where the shoe starts to pass over the cavity. The cavity wall will hinder the transfer of kinetic energy from the powder in the shoe to the powder within the cavity.

Alt:

Moving particles in the feed shoe are pushed forward but will collide with stationary cavity particles in the shear zone. The stationary particles are pushed downward and forward in the motion direction of the feed shoe and will and thereby cause a rearrangement of the particles and a denser packing arrangement. The collision forces and rearrangements will transfer down through the powder mass until it is blocked off by normal forces from cavity walls (illustrated in figure D2) or overcomed by interparticle or wall-to-particle friction. The densification will:

- have a maximum depth. After a certain depth, the compacting action will be lost due to friction. Particles deep enough will therefore remain stationary.be less pronounced in the part of the cavity where the shoe starts to pass over the cavity.

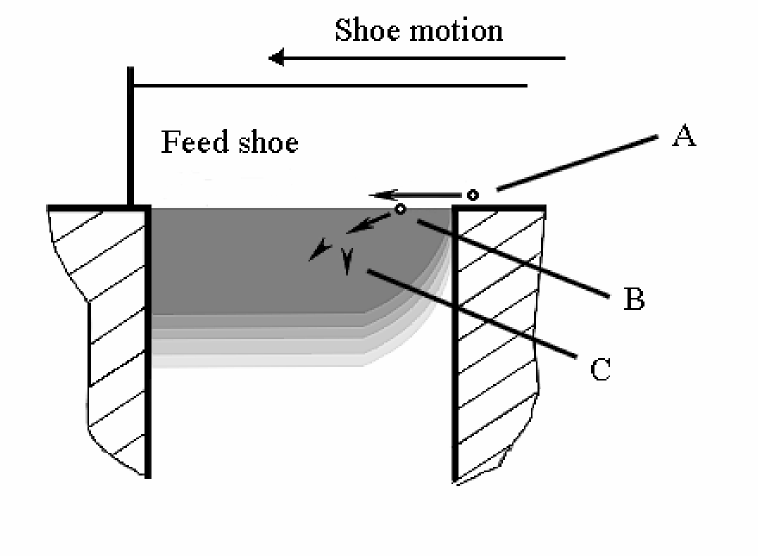

Figure D1. A schematic illustration of how the powder within the cavity is compacted as the feed shoe pass over the filled cavity. A – one of the particles in the feed shoe, B – one of the stationary particles put in motion by primary collisions, C – particles put in motion by secondary collisions. The grey area represents the area that will be affected by the compacting mechanism.

This proposed mechanism is in agreement with previous reports. Kondoh et al. [#], have analysed how powder particles in a vertical cross section of the cavity move as a result of the feed shoe movement. They found that powder particles in different parts of the cavity move in different directions when the feed shoe passes over the filled cavity. The parts close to the cavity walls perpendicular to the moving direction of the filling shoe did not appear to be affected by the passage of the filling shoe.

Relevance

How relevant is the powder density in the filled state as an indicator of the density variations the compacted part will have after compaction?

The powder filling experiments performed here indicates that the filling itself might induce a powder mass difference of 5% (see figure R2). Previous investigations have measured density differences in compacted rings filled under similar conditions (and compacted with 150 MPa pressure) to values of the same magnitude [Hjortsberg, Kyoto]. Previously unpublished experiments from that investigation also analysed the density distributions at compaction pressures up to 430 MPa (see figure D2). At all these compaction pressures the density variations within the parts remained at the same level. It is clear that horizontal powder transfer during compaction between 85 and 35% is of negligible importance. It is harder to determine if any powder transfer occurs at the earlier stages of the compaction. The fact that the density differences in the investigation performed here are of the same magnitude as those in compacted parts is however an indicator that powder transfer might not have a large effect on the density variation at this stage either.

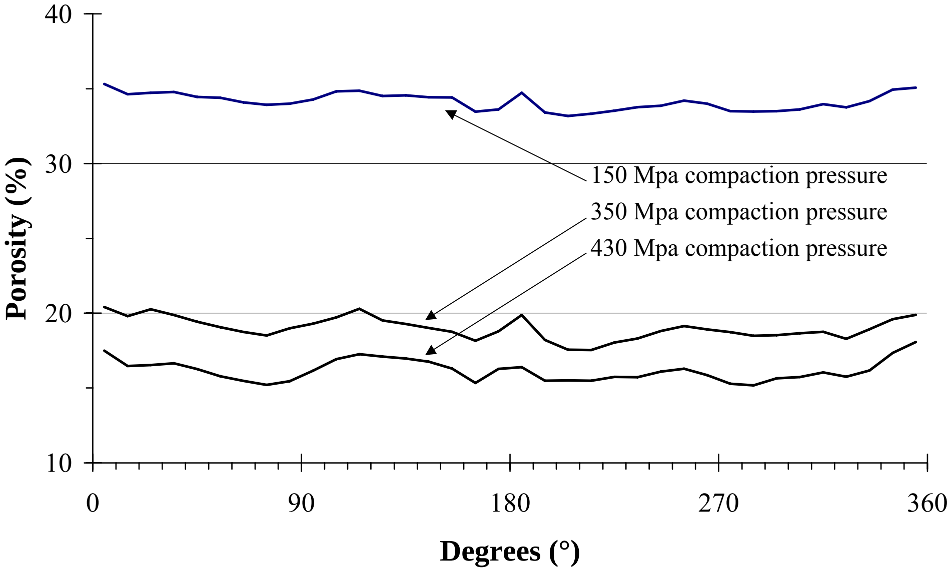

Figure D2. Porosity level of rings compacted at 150, 350 and 430 MPa respectively. Note how sections with low degree of porosity are found at the same location for all rings. Experimental procedures for these rings correspond to a previous investigation by Hjortsberg [Hjortsberg, Kyoto].

Conclusions

To fill a cavity with powder is easy, to fill a cavity evenly is a complex task that requires great effort. The next level of abstraction, the task to *understand* filling is an even greater challenge. We have in this paper tried to outline different routes to how current knowledge of filling could be expanded and have demonstrated a test device, constructed for the task. It has been demonstrated that test rig was successful in pinpointing the shoe fill cycle as a key element in the effort to achieve an even filling, whereas powder level of feed shoe had little importance.

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