Analysis of Feed Shoe Powder Deposition Method Using a Real-time Cumulative Mass Deposition Tester

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Abstract

A real-time cumulative mass deposition tester (MDT) was fabricated and tested to study the deposition profiles of powders in complex-shaped dies. The deposition behavior of two different powders (manganese zinc ferrite – MZF¹ and microcrystalline cellulose – MCC²) was studied in an “E” shaped die. The feed shoe deposition method was used to deposit the powders in the die via two different fill directions. The MDT was used to develop real-time fill trends, deposition profiles, contour plots and databases of spatial powder mass distribution in the die. From the results, it was ascertained that both fill direction and die shape affect a powder’s deposition behavior. It was observed that the average MCC powder masses deposited in both fill directions were roughly one-seventh the average MZF powder mass. Also, the average voids volume fraction of MCC was roughly double the average voids volume fraction of MZF. Due to its favorable particle characteristics (spherical-shaped particles and low cohesion), the MZF powder filled better compared to MCC. In the case of MZF, the coefficient of variation (COV) values for powder mass were mostly in the range of 5-20%, compared to 25-50% for MCC. Therefore, MCC is expected to be a more difficult powder to process due to its poor flowability and large variations in powder masses during deposition. Overall, the experimental results clearly show that the MDT is an effective and reliable tool that can be used for the real-time measurement of powder deposition profiles in a die.

Keywords: Mass Deposition Tester, spatial powder mass distribution, die filling, complex die shapes, feed shoe deposition method

1. Introduction

Powders play a major role in a variety of industries (such as ceramic, chemical, food, pharmaceutical, etc.) where they must be handled, stored, compacted or otherwise processed in large volumes. All phases of those operations require precise knowledge of the behavior of powder systems in order to improve the quality of the components produced. For example, in the powder compaction process, it is known that the quality of green compacts (unsintered, pressed particulate assemblies) is dependent upon factors such as intrinsic material properties, nature of applied load, die geometry, and a variety of operational parameters. Many compact-quality issues (such as cracking, low green strength, shrinkage or warpage) can be influenced by the anisotropic compaction of powder. This anisotropic mechanical response of powder during compaction is further attributable, in part, to non-uniform, pre-compaction fill-density of the powder within a die (Li and Puri, 1996). Localized weight or density gradients may arise from the die geometry, die-wall friction or even from the method used to deposit powder in the die. Since manufacturing processes have a tendency to magnify variation, ensuring a uniform pre-compaction particulate deposition will be an effective method of enhancing the quality of the green compacts (Mittal and Puri, 1999a, b).

Although the above facts are well documented in the literature, no effective tool that is capable of mea-

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suring the uniformity of powder deposition in complex-shaped dies is yet available. Therefore, the objective of this research was to fabricate and test a real-time cumulative mass deposition tester (MDT) for two different powders (with varied physical characteristics) in an “E” shaped die. The design of the MDT was based on the concept demonstrated by Puri and Dhanoa (2000). Puri and Dhanoa postulated that an anisotropic fill density distribution would result in an uneven vertical pressure distribution at the bottom surface of the die. This uneven vertical pressure distribution could then be detected and analyzed by placing multiple, sensitive and high precision load cells on the inside surface of the die-bottom.

2. Theory

2.1 Selected Literature Review

Dhanoa and Puri (1998) have summarized the results of much of the work done in the area of powder deposition. Some of the key studies mentioned, among others, were Molenda et al. (1994), Moyoey (1984), Moriyama and Genji (1985), Bocchini (1987) and Falkin et al. (1976). All the above-mentioned studies show that deposition methods are significant contributors to the variation observed in the bulk density of powder in a die. This variation is dependent on the rate of die fill, die-geometry and die-size. Therefore, in order to maintain homogeneity of a compact’s quality, a deposition method that gives the most uniform bulk density of powder should be used.

Dhanoa and Puri (1998) proposed a radical concept for quantifying the uniformity of powder fill in simple shaped dies. They developed a low-cost tester capable of acquiring real-time data for experimental analysis of the die-filling process. The underlying principle of their proof-of-concept tester was that an anisotropic fill density distribution would result in an uneven vertical pressure distribution at the bottom surface of the die. This uneven vertical pressure distribution could be detected and analyzed by placing multiple, sensitive and high precision load cells on the inside surface of the die-bottom. Using their tester, Dhanoa and Puri provided a qualitative data interpretation for the deposition of a spray-dried alumina powder in simple geometric cavities (i.e., circular, square and diamond-shaped in cross section). They studied two different die fill methods, namely funnel fill and sieve fill. The results indicated that their tester had the ability to quantify variations in spatial deposition of powder mass as a consequence of the differing fill methods.

2.2 Concept of Mass Deposition Tester (MDT)

The Mass Deposition Tester (MDT) was designed to acquire real-time data for complex die shapes using high precision semiconductor load cells that were sensitive enough to measure powder mass values in the range of 0 to 2.5 g (Figure 1). These load cells operate on a 10-volt DC excitation and the voltage changes (due to mass differences) are measured using a high precision data acquisition (DAQ) system. The signals acquired by the DAQ system are recorded using a program written in LabVIEW. This program displays the real-time spatial accumulation of powder mass in the die. The quantitative data obtained from the MDT can be used to develop iso-mass contours in a die.

3. Methodology

3.1 Experimental Materials

Two powders, a manganese zinc ferrite-based (MZF) and a microcrystalline cellulose-based (MCC), were selected as test materials in this research because of the contrasting nature of their characteristic properties (Table 1). The MZF powder used in this study was a cohesionless, spray-dried powder and is widely used for dry pressing magnetic components. On the other hand, microcrystalline cellulose (MCC) is a relatively cohesive powder that is widely used in the pharmaceutical industry and to a lesser extent in the food industry. The particle size distribution of the two test powders is shown in Figure 2 and the micrographs are shown in Figure 3.

The shape difference between the particles of the two powders is quite evident from Figure 3. The MZF powder particles are round, whereas, MCC particles are irregular and elongated (length to diameter ratio of 6). In this research, these two powders were
Table 1 Comparison of characteristic properties of the two test powders

|                  | Particle Shape | Median Size ($d_{50}$) | Density (g/cc) | Granule Strength | Cohesion (kPa) | Internal friction angle |
|------------------|----------------|------------------------|---------------|------------------|----------------|------------------------|
|                  |                |                        | Bulk          | Particle         |                |                        |
| MZF              | Spherical      | 150 μm                 | 1.45          | 5.03             | Rigid          | $\approx 0$            | 35°                    |
| MCC              | Needle-shaped  | 113 μm                 | 0.33          | 1.55             | Fragile        | $\approx 1.5$          | 46°                    |

Fig. 2 Particle size distribution of the two test powders

Fig. 3 Micrographs of the test powders (a) MZF powder (b) MCC powder

tested at environmental conditions of 22°C ± 2°C and 40% ± 5% RH.

3.2 Die Shape

An E-shaped die was instrumented as described in Figure 4. This particular shape was chosen because it represents a complex, yet, industrially relevant geometry that is being dry pressed in large quantities for ultimate use as a magnetic component. A nomenclature was developed for the E-shaped die, which is also explained in Figure 4.

The E-die was made of aluminum and had fourteen different hole locations where the load cell could be placed. The dimensions of the E-die were 5 (length) × 2.5 (width) × 1.8 cm (depth). Each of the holes was 0.5 cm in diameter. This was the smallest diameter hole that could be used, with load cell stem diameter of 0.3 cm. Smaller size holes would make the placement of multiple load cells, as originally planned, difficult to achieve due to the required precision in

Fig. 4 E-die with description of fill directions and selected hole locations

(PER = Perpendicular to Leg; PLB = Parallel to Leg from Back; PLF = Parallel to Leg from Front)
hole-to-hole alignment. The width of the top, middle and bottom legs of the "E" was 0.7, 1.4 and 0.7 cm, respectively. There were three practical directions from which the powder could be deposited into the E-die. These fill directions namely, perpendicular to leg from front (PLF), perpendicular to leg from back (PLB) and perpendicular to leg (PER), are also shown in Figure 4. Data were collected for all three fill directions, however, only the PLB and PLF fill directions were assumed to result in a symmetric fill with respect to the centerline of the middle leg of the "E". This assumption is not valid for PER fill direction; consideration of that data is therefore excluded from this paper.

Due to symmetry and time considerations, data were collected only for 8 different shaded locations (Figure 4). Also, based on prior experience with pressed parts, these eight measurement locations were identified as candidate regions of large powder mass variations. The results from these eight locations were then extrapolated to other locations due to symmetry of E-die. The nomenclature of these eight locations is given in Table 2.

| CM = Center Middle | LM = Left Middle |
| CT = Center Top | LML = Left Middle Lower |
| LB = Left Bottom | RMU = Right Middle Upper |
| RT = Right Top | WB = Web Bottom |

Five runs were done for each fill direction and for each of the shaded hole locations. Only one load cell was active during a given run due to instrument limitations and cost constraints. In total, 160 runs (2 powders * 8 hole locations * 5 replicates * 2 fill directions) were conducted. Results of these experiments are presented and discussed in this paper.

3.3 Powder Deposition Method

The feed shoe deposition method is widely used in powder processing industries to rapidly deposit powder into a die. Therefore, this powder deposition method was chosen in this research to simulate an industrial powder-processing situation. In this method, a feed shoe (made out of Plexiglas®) was manually moved forward and backward on guide rails (as shown in Figure 1). The guide rails had an opening that channeled the powder flow into the die cavity. During the forward stroke, due to the trajectories of particles moving at high velocity, powder tended to deposit on the die’s forward-end. This resulted in the partial filling of the die. Rearrangement of particles took place during the brief period of rest. During the backward stroke, trajectories of the particles were reversed resulting in deposition at die’s leeward-end, resulting in complete filling of the die. This deposition process schematic is shown in Figure 5.

![Fig. 5 Stages in feed shoe deposition method: (a) Forward stroke — partial die-filling (b) Rest period — particle rearrangement (c) Backward stroke — complete die filling](image)

The total time taken to deposit the powder into the die using the feed shoe method was in the order of 1.5-3 seconds (includes time to reach a steady value after the deposition process is completed). This also includes a period of rest of approximately 1 second. The dimensions of the feed shoe used were: outer diameter — 10 cm, inner diameter — 9.2 cm. The angle of feed shoe tube with respect to the base plate was 44.5 degrees.

4. Results and Discussion

The following subsections discuss the various applications of the mass deposition tester (MDT) based on the data collected on the E-die. Figure 6 summarizes some of the key benefits and applications of the MDT. A detailed explanation of each of the MDT’s applications is presented in the following subsections.

4.1 Generation of Fill Trends in Real-Time

The MDT load cells generate real-time fill trends as the feed shoe moves back-and-forth across the die-cavity. These fill trends quantify the mass of powder deposited at any location during the deposition process. This valuable information from the fill trends can be used to study the effect of die-shape, powder flowability, particle shape and fill-speed on the entire process of powder deposition. For example, in the case of feed shoe deposition, the effect of the forward and backward stroke can be studied independently using the fill trends. A typical real-time fill trend obtained for the feed shoe method is shown in Figure 7.
4.2 Qualitative Evaluation of Deposition Method

The deposition profiles obtained by pooling the different real-time fill trends can be used to study the effect of various operational procedures (such as fill-speed, direction of fill, die-material, etc.) on the powder deposition process. In this paper, only the effect of fill-direction on the spatial powder mass distribution in E-die was studied.

Manganese zinc ferrite (MZF) powder: The MZF powder's deposition profiles obtained for the PLB and PLF fill directions are compared in Figures 8 and 9. These figures clearly indicate that there is a significant difference in the way MZF powder deposits in E-
die for the two fill directions. Also, each fill direction has certain unique characteristics that are further examined.

In case of PLB fill direction, the observed maximum mass of MZF was concentrated at the right middle upper (RMU) location, followed by center middle (CM), left middle lower (LML) and left middle (LM) locations. This clearly indicates that the powder mass is concentrated in the middle leg of the E-die. This apparent mass concentration was expected because the middle leg was wider (1.4 cm) compared to the other two legs (0.7 cm). Therefore, the powder encountered less influence from die-walls during deposition in the middle leg. MZF powder’s final mass at various locations varied from 500-1700 mg. The average recorded powder mass in the PLB fill direction was 1017 mg. The voids volume fraction (volume of solids/total volume) values varied from 0.05 (in the middle leg) to 0.70 (in the outer legs). The average voids volume fraction was 0.42. Void fraction values were theoretically calculated for each measuring location. These values should be used qualitatively to study the distribution of the voids volume fraction in the entire die. The actual values are expected to be somewhat different from the calculated values. Although the absolute values are likely to differ, the ratios of any two values are expected to be nearly the same when using the numbers in this paper and those obtained using actual values. The void fraction analysis confirms that the powder was much tightly packed in the middle leg compared to the outer legs.

In case of PLF fill direction, it was observed that the fill-trends were quite different from those observed in the PLB fill direction. The maximum concentration of powder mass was again observed in the middle leg. However in PLF, the maximum mass was concentrated at center middle (CM), followed by right middle upper (RMU) and left middle (LM). The MZF powder mass at various locations varied from 500-1700 mg. The average recorded powder mass in PLF fill direction was 957 mg. The voids volume fraction varied from 0.04 (in the middle leg) to 0.71 (in the outer legs). The average voids volume fraction was 0.46. A thorough quantitative evaluation of the two fill directions is done in Table 3 (discussed further in section 4.3).

**Microcrystalline cellulose (MCC) powder:** Observations similar to the MZF powder were noted for the MCC powder. The MCC fill-trends obtained in PLB and PLF fill direction are shown in Figures 10 and 11. Nomenclature is shown in Figure 4 and summarized in Table 2.

![Fig. 8](image) Deposition profile of MZF powder in typical locations for PLB fill direction (Figure 4, Table 2)

![Fig. 9](image) Deposition profile of MZF powder in typical locations for PLF fill direction

![Fig. 10](image) Deposition profile of MCC powder in typical locations for PLB fill direction

![Fig. 11](image) Deposition profile of MCC powder in typical locations for PLF fill direction
It was observed that the fill trends of MCC in PLB and PLF fill direction are very different. In addition, the MCC powder's final mass varied from 50-330 mg in both cases. The average masses in the PLB and PLF fill directions were 150 and 143 mg, respectively. The quantitative results for MCC are tabulated in Table 4 (discussed further in section 4.3). The voids volume fraction varied from 0.40 (in the middle leg) to 0.90 (in the outer legs) for both fill directions. The average voids volume fraction was 0.71 in both PLB and PLF fill directions.

4.2.2 Effect of Powder Characteristics on Deposition Process: The mass deposition tester (MDT) can be used to study the deposition behavior of different powders and powder formulations. This information can be helpful in the development of quality control measures and prediction tools in an industrial powder-processing unit. For example, even before attempting to press a part, the MDT can give significant information regarding whether the powder will deposit uniformly into the die. Corrective measures (such as changing fill direction, tailoring particle shape, etc.) can then be applied to enhance the deposition. The data collected on the manganese zinc ferrite (MZF) and microcrystalline cellulose (MCC) powder highlight these salient features of the MDT.

Die filling: It was observed that in certain runs of the die collection process, the MCC powder was unable to completely fill the E-die cavity. This behavior of MCC was unlike that of MZF that completely filled the E-die cavity during every run. This effect can be attributed to the cohesive nature of MCC powder.

Fill trends: It can be observed from Figures 8 to 11 that the fill trends in both the powders are very different. These variations can be attributed to differing cohesion, angle of internal friction, particle shape, etc. The MZF particles are spherical in shape and flow readily. Therefore, the MZF powder was able to pack (or fill) better compared to MCC during deposition, thus leading to differences in the fill trends. It was also observed that the spatial powder mass distribution was markedly different for the two powders.

Amount of powder deposited: The average MCC powder mass deposited (for either fill directions) was roughly one-seventh that of the average MZF powder mass. The reason for such a variation in final masses can be attributed to the differences in bulk and particle densities of the two powders. Since MZF has a higher bulk and particle density, the average MZF powder mass was expected to be higher than that of MCC. However, the bulk and particle density ratios of the two powders (MZF:MCC) are only 4:1, which does not fully explain the observed mass ratio differences. The observed high ratio of 7:1 is clearly related to powder particle characteristics.

Voids volume fraction: In order to compare the deposition behavior of the two powders irrespective of the particle density, it was necessary to calculate the voids volume fraction (volume of solids/total volume) at various locations in the die. From the data it was observed that the voids volume fraction of MZF powder varied from 0.05-0.70. The volume voids fraction of MCC powder varied from 0.4-0.9. The average voids volume fraction for MZF and MCC was 0.42 and 0.71, respectively. Therefore, it is clear that the MZF powder packs more tightly compared to MCC. These differences in voids volume fraction can be attributed to the particle shape differences.

4.2.3 Development of Contour Plots for Given Die-Shape: The quantitative information from the MDT can be used to develop iso-mass contour plots of a particular die-shape at any given instant in time. These contour plots are helpful in ascertaining the regions of high and low mass. They are also useful in identifying certain locations that might lead to defects during powder pressing. These contour plots can be easily generated for any given die-shape using commercially available software such as Matlab® or SigmaPlot®. One such contour plot is developed for MZF in the PLF fill direction (Figure 12) based on the quantitative information tabulated in Table 3 of section 4.3.

Figure 12 strengthens the qualitative observations made in section 4.2. It is clear that the powder mass is concentrated in the middle leg and is roughly twice the mass in the other two legs. The contour plot also clearly demonstrates the anisotropy in spatial powder mass distribution in the E-die.

4.3 Quantitative Evaluation of Deposition Method

The mass deposition tester (MDT) can be used for the quantitative evaluation of a given deposition method and can be utilized to develop databases for practicing engineers. The quantitative information obtained from the deposition behavior of MZF and MCC in the E-die is tabulated in Tables 3 and 4.

From Table 3, it is observed that the high mass
zones are concentrated in the middle leg of the E-die (Figure 12). The middle leg roughly had twice the mass present in the outer legs. This trend was observed with both fill methods and in both powders. This clearly emphasizes that the presence of die-walls affects the spatial powder mass distribution in a die. These differences in spatial mass distribution will result in anisotropic powder compaction. From Table 3, the coefficient of variation (COV) values were mostly in the range of 5-20% for MZF powder.

From Table 4, the COV values for MCC generally ranged from 25-50%. This clearly emphasizes that MCC is much more difficult to process than MZF. It does not deposit as readily, i.e., its low flowability (compared with that of MZF) leads to large variations in deposited powder masses. This quantitative information supplements the observations made in section 4.2.2.

FromTables 3 and 4, it can be concluded that fill direction does not affect the average powder mass deposited in the E-die. For example, the average MZF powder mass deposited in the PLB and PLF fill directions was 1017 mg and 957 mg, respectively. On the other hand, the average MCC powder deposited in the PLB and PLF fill directions was 150 mg and 143 mg, respectively. The average voids volume fraction

![Fig. 12 MZF's spatial mass distribution at the end of fill process in PLF fill direction](image)

Table 3  Comparison of MZF powder's final mass and voids volume fraction values at various locations in E-die†

| Hole Locations^ | PLB Fill Direction | PLF Fill Direction |
|-----------------|---------------------|---------------------|
|                 | Average Mass (mg)   | Std. Dev. | COV* | Voids Volume Fraction** | Average Mass (mg) | Std. Dev. | COV | Voids Volume Fraction |
| Top Leg         |                     |           |      |                        |                    |           |     |                      |
| RT              | 528                 | 143       | 27   | 0.70                    | 503                 | 105       | 21  | 0.71                    |
| CT              | 752                 | 119       | 16   | 0.57                    | 851                 | 109       | 13  | 0.52                    |
| LM              | 1291                | 154       | 12   | 0.27                    | 1008                | 308       | 31  | 0.43                    |
| LML             | 1293                | 95        | 7    | 0.27                    | 963                 | 102       | 11  | 0.45                    |
| CM              | 1553                | 98        | 6    | 0.12                    | 1691                | 158       | 9   | 0.04                    |
| RMU             | 1671                | 343       | 21   | 0.05                    | 1559                | 84        | 5   | 0.11                    |
| Middle Leg      |                     |           |      |                        |                    |           |     |                      |
| Bottom Web      |                     |           |      |                        |                    |           |     |                      |
| WB              | 717                 | 123       | 17   | 0.59                    | 645                 | 132       | 29  | 0.63                    |
| Lower Leg       |                     |           |      |                        |                    |           |     |                      |
| LB              | 737                 | 132       | 18   | 0.58                    | 830                 | 177       | 21  | 0.53                    |
| Average**       | 1017                | 0.42      |      | 957                     |                    | 0.46      |     |                        |

† Five runs were done for each location. However, in certain locations, three or four out of five runs were acceptable.

^ Description of hole locations is given in Figure 4 and Table 2.

* COV% = (Average/Standard Deviation) * 100

** Voids volume fraction values were theoretically calculated for a given location. These values should be used qualitatively to study the distribution of the voids volume fraction in the entire die. The real values are expected to be higher than the quoted theoretical values.

++ Average values for mass and voids volume fraction were calculated using the values obtained for all 14 locations.
Table 4  Comparison of MCC powder’s final mass and voids volume fraction values at various locations in E-die

| Hole Locations^ | PLB Fill Direction | PLF Fill Direction |
|-----------------|--------------------|--------------------|
|                 | Average Mass (mg)  | Std. Dev. | COV* | Voids Volume Fraction** | Average Mass (mg) | Std. Dev. | COV | Voids Volume Fraction |
| Top Leg         |                    |           |      |                    |                    |           |      |                    |
| RT              | 54                 | 29        | 55   | 0.90               | ***                | ***       |      |                    |
| CT              | 64                 | 30        | 47   | 0.88               | 56                 | 28        | 49   | 0.90               |
| Middle Leg      |                    |           |      |                    |                    |           |      |                    |
| LM              | 123                | 71        | 58   | 0.77               | 173                | 57        | 33   | 0.68               |
| LML             | 317                | 106       | 33   | 0.42               | 120                | 68        | 56   | 0.78               |
| CM              | 302                | 111       | 37   | 0.44               | 308                | 73        | 24   | 0.43               |
| RMU             | 231                | 79        | 34   | 0.57               | 325                | 71        | 22   | 0.40               |
| Bottom Web      |                    |           |      |                    |                    |           |      |                    |
| WB              | 91                 | 26        | 28   | 0.83               | 93                 | 44        | 48   | 0.83               |
| Lower Leg       |                    |           |      |                    |                    |           |      |                    |
| LB              | 82                 | 41        | 50   | 0.85               | 115                | 34        | 29   | 0.79               |
| Average^**      | 150                |           | 0.72 | 143                | 0.71               |

^ Five runs were done for each location. However, in certain locations, three or four out of five runs were acceptable.

^ Description of hole locations is given in Figure 4 and Table 2.

* COV % = (Average/Standard Deviation)* 100

** Voids volume fraction values were theoretically calculated for a given location. These values should be used qualitatively to study the distribution of the voids volume fraction in the entire die. The real values are expected to be higher than the quoted theoretical values.

*** Data for this particular location did not turn out to be acceptable.

** Average values for mass and voids volume fraction were calculated using the values obtained for all 14 locations.

Values for MZF and MCC are roughly 0.43 and 0.71, respectively.

Also, there were a few locations where the localized powder masses deposited in the two fill directions were quite different. These differences in spatial powder mass distribution clearly indicate that the direction in which the feed shoe approaches the die-cavity can affect the deposition process. These differences in spatial mass distribution make it difficult to use final part weight or final part density as a quality criterion and would, instead, necessitate a measurement of "sectional weight or density". Therefore, it can be concluded that the MDT is an effective tool that is capable of quantifying the sectional differences that actually exist during filling of complex-shaped dies.

4.4 Assessment of a Deposition Method's Effectiveness

From the fill trends in Figures 8-11, the forward and backward strokes of the feed shoe can be readily delineated and quantified (Table 5). As the feed shoe moves forward, the die is filled partially. Some rearrangement of the particles takes place during the brief period of rest. Finally, the unfilled portions of the die are filled during the backward stroke (as shown in Figure 5).

A quantitative evaluation of how a die is filled during the forward and backward strokes of the feed shoe can help in ascertaining the effectiveness of the feed shoe fill method in a given processing situation. For example, it may be possible that if the die gets completely filled during the forward stroke, then there is no need for the backward stroke. On the other hand, if more uniform spatial powder mass distribution is obtained during forward stroke compared to the backward stroke, then a deposition method can be developed that incorporates two feed shoes with only forward strokes. Also, suitable adjustments in the fill-speed and the shoe design can result in a better spatial powder mass distribution. In Table 5, the MZF powder’s final mass values along with the masses obtained at the end of the forward stroke at the various hole locations are compared. Similar tables can also be developed for MCC.

From Table 5, it can be observed that average mass of powder deposited during the forward stroke of the feed shoe is less than average powder mass deposited after the completion of one cycle of feed shoe. Therefore, it can be concluded that the forward stroke only fills the die partially. The complete filling of the die takes place during the backward stroke. It can also be observed that even though the powder’s average final mass is the same in both fill directions, differences in spatial mass distribution are present even in the forward stroke. This analysis provides quantitative credence to the observations made in
Table 5: Comparison of MZF powder mass deposited during various strokes of feed shoe

| Hole Locations^ | PLB Fill Direction | MZF Powder Mass (in mg) | PLF Fill Direction | MZF Powder Mass (in mg) |
|----------------|--------------------|-------------------------|--------------------|-------------------------|
|                | FS*                 | FM**                    | Diff %***          | FS*                    | FM**                   | Diff %***           |
| Top Leg        | RT                  | 813                     | 528                | 659                    | 503                    | 131                 |
|                | CT                  | 460                     | 752                | 461                    | 851                    | 54                  |
| Middle Leg     | LM                  | 658                     | 1291               | 1022                   | 1008                   | 101                 |
|                | LML                 | 988                     | 102              | 583                    | 963                    | 60                  |
|                | CM                  | 1557                    | 1553               | 788                    | 1681                   | 47                  |
|                | RMU                 | 1892                    | 1671               | 113                    | 603                    | 1559                | 39                  |
| Bottom Web     | WB                  | 284                     | 717                | 621                    | 645                    | 96                  |
| Lower Leg      | LB                  | 627                     | 737                | 903                    | 830                    | 109                 |
| Average Mass (mg)** | **882 | **1017 | | **676 | **957 |

* The shaded portions indicate the locations where FS was greater than FM
^ Description of hole locations is given in Figure 4 and Table 2.
* FS = Powder mass deposited after completion of forward stroke
** FM = Powder mass deposited after completion of 1 complete cycle of feed shoe (forward + backward)
*** Diff % = 100 * FS/FM
** Average values for mass were calculated using the values obtained for all 14 locations.

section 4.1.1 where it was mentioned that fill directions lead to differences in the spatial powder mass distribution in E-die.

In Table 5, it was observed that there were certain locations where the mass deposited during forward stroke was greater than the total mass deposited. The reasoning behind such an effect is that during the forward stroke, the particles collide with the die-walls at high velocities. Due to the impact, the particles tend to pack more closely. However, during the brief period of rest, the MZF particles rearrange under the influence of gravity or vibrations and tend to slide over each other due to the low cohesion and angle of internal friction value. Due to this rearrangement of particles, the powder mass becomes more evenly distributed in the die. During the backward stroke, additional powder is deposited into the die. But since the trajectories of the particles in the backward stroke are different from those in the forward stroke, reduced packing of particles occurs. Hence, for certain locations it was observed that the mass deposited during forward stroke was greater than the total mass deposited.

5. Conclusions

From the data collected on the manganese zinc ferrite (MZF) and the microcrystalline cellulose (MCC) powder for E-die, it is concluded that the mass deposition tester (MDT) is an effective tool capable of generating a real-time deposition profile of a powder in a die. The die shape can either be complex or simple. The information obtained from the MDT is very helpful in comparing the deposition characteristics of different powders and powder formulations. Based on this study, the following conclusions were drawn:

1. Fill directions affect the deposition profiles. This was observed for both MZF and MCC powders. Also, each fill direction has certain unique characteristics.
2. The powder mass was highly concentrated in the middle leg of the E-die. This effect of high mass concentration in this leg was expected because the middle leg was wider (1.4 cm) compared to the other two legs (0.7 cm). Therefore, the powder experienced considerably less influence from die-walls during deposition in the middle leg.
3. The average MCC powder mass deposited in both fill directions was roughly one-seventh the average MZF powder mass. The reason for such a variation in final masses can be attributed partially to the differences in bulk and particle densities of the two powders. However, the bulk density ratio of the two powders (MZF:MCC) is only 4:1, which does not fully explain the observed mass ratio differences. The observed high ratio of 7:1 is clearly related to powder particle characteristics.
4. MZF powder was able to pack better compared to
MCC during deposition and hence the differences in the voids volume fraction values were observed.

5. From the quantitative evaluation of MDT results, it was observed that the coefficient of variation (COV) values were mostly in the range of 5-20% for MZF powder. On the other hand, the COV values for MCC generally ranged from 25-50%. This clearly demonstrates that MCC is a more difficult powder to process.

6. Assessment of MDT

From the data collected on the two powders, it is concluded that the mass deposition tester (MDT) is an effective tool capable of generating a real-time deposition profile of a powder in a die. The MDT can be used to develop fill trends, contour plots and databases for any powder's behavior during a given deposition process. The MDT is also very useful in comparing the effect of various operating parameters (such as feed shoe design, fill directions, etc.) on a powder's spatial mass distribution in complex-shaped dies. The MDT can be used to identify a deposition process that minimizes the localized density/weight differences even before attempting to press a part. In the long run, the MDT can lead to the development of quality control parameters and prediction tools for die-filling scenario during powder processing.

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