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Packing behavior of metal powders used in a new rapid tooling process

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The requirements for faster product development cycles, lower product cost and environmental sustainability are ever increasing in today's globally competitive market. Tooling is a very important phase in the product manufacturing cycle. Conventional tooling processes, however, can be expensive and time consuming. New tooling methods with shorter lead-time and lower cost are needed. The new rapid tooling processes considered in this study uses a metal shell filled with packed metal powders to form an injection mould. The feasibility of this new rapid tooling method depends mainly on the mechanical behaviors of the metal powders and metal shells under working loads. In this paper, the factors affecting powder packing behaviors such as powder shape, size, and size distributions are presented.

1. Introduction

Due to the globalization of consumer markets and the consequent increase in competition, it is more important than ever for manufacturers to be the first into the market with their products. This has lead to an ever-increasing demand for manufacturers to shorten their product manufacturing cycles. Tooling is a very important phase in the product manufacturing process. Great effort has been made to develop new rapid tooling that combines the recently emerged rapid prototyping (RP) processes with one or more subsequent processes.

RP refers to the physical modeling of a design using a special fabrication technology. A RP system quickly generates physical models and prototype parts from three-dimensional (3D) graphical computer data. Using an additive approach to building shapes, a RP system can use liquid, powder, or sheet materials to form physical objects. Generally, RP machines use plastic, wood, ceramic, metal powder, and paper to fabricate the parts layer by layer. The RP method allows designers to verify their product design at an early stage and to use 3D representations for design review with sales, marketing and production departments. Another important function of RP is that it can be used as a medium for the part shape transfer in freeform fabrication. Along with the RP process used in industry, processes for rapid tooling (RT) have been developed [1]. As an emerging technology, RT is the natural extension of RP technology that adopts rapid prototyping techniques and applies them to tool and die making.

Almost all products developed in the manufacturing industry start from the creation of a 3D computer model using a computer added design (CAD) system. At this stage, the product geometry is defined. Its aesthetic and dimensional characteristics are verified. Converting the CAD model into a prototype model by using a RP process is easily realized [2]. However, creating tooling for a prototype represents one of the most time consuming and costly phases in the development of new products. The current market requires faster product development and reduced production time, along with higher quality, greater efficiencies, lower cost, and an ability to meet environmental and recycling objectives. Such demands have driven the development of rapid tooling (RT) technologies. Whether the application is prototype, bridge, short-run, or production tooling, RT represents an opportunity to decrease both time and expense.

The aim of this work is to evaluate the feasibility of a new RT process using packed metal powders to back support a metal shell to form a mould, so that to ensure the combination of the metal shell and packed metal powder can support the working load of the tool and limit the deformation within the tolerances. The feasibility of this new RT process depends mainly on the mechanical behaviors of the metal powders and metal shells. This study is focused on the powder packing behavior of the metal powder used to support the metal shells. Powder packing experiments are conducted in this work. The results are presented and discussed. Based on the results, an optimal packing model is suggested for the new RT process.

2. THE NEW RT PROCESS

The new RT process is shown schematically in Fig. 1. For convenience, the figure only illustrates the fabrication of half mould. The proposed new RT process involves the following major steps:

Step 1: A three-dimensional computer model of the mould is designed on a computer.

Step 2: A plastic pattern complementary in shape to the mould is fabricated using a RP process, such as Stereolithography.

Step 3: A metal layer is formed onto the cavity side of the plastic pattern using an electro-chemical process to form a metal shell. The metal shell is then separated from the plastic pattern. Alternatively, the plastic pattern can be removed after Step 6 is completed.

Step 4: Metallic ribs with appropriate properties and dimensions are added to the back of the metal shell to reinforce the metal shell.

Step 5: Metal powders are packed into the metal shell to provide mechanical support to the metal shell.

Step 6: The backside of the mould is sealed to prevent leakage of the metal powder. The tool is finished by adding required features.

It is expected that this new RT process will be fast and inexpensive. In addition, because the metal powders used in backing are fully recyclable, the process is also expected to be environmentally friendly.

STEP 1
CAD model of mould Design

STEP 2
Fabricating a RP Pattern

STEP 3
Forming a metal shell

STEP 4
Adding reinforcing ribs

STEP5
Backing with metal powders

STEP6
Sealing and finishing

Figure 1: *The new rapid tooling process.*

3. EXPERIMENT PROCEDURE

Powder packing can be divided into single component packing, binary packing as well as multiple component packing. In single component packing, all packing particles used are of the same size and geometry. In binary or multiple components packing, two or more packing components are involved. Packing density is affected by the size and proportion of each packing component. The voids formed by large particles can be filled by small particles. The voids created by small particles can be further filled by even smaller particles.

Eleven kinds of metal powders with different shapes, sizes, and materials chemistry are used for the powder packing test. The materials and characteristics of the powders used are given in Table 1.

For single component powder packing, the powder is first weighed and placed into a scaled cylinder or beaker. The powder in the container is vibrated for 15 minutes on a vibration machine with the topside of the powder being lightly pressed by a flat plate. After vibration, the volume of the powder is measured. The packing density is determined based on the measured data for the weight and volume of the powder.

For binary or multiple component powder packing, the coarse metal powder is weighed and placed into a scaled cylinder. The cylinder is vibrated on a vibrating machine for 15 minutes while the topside of the powder being lightly pressed by a flat plate. After the volume of the coarse powder is measured, an appropriate amount of fine powder is added to the container while the cylinder is vibrated. The volume of the mixed powders is measured and the packing density of the mixed powders is calculated. For a three-component mixture, the finer powder is added to the previous mixture while the cylinder is vibrated. The final volume is measured and the packing density of the mixed powders is calculated.

For binary component powder packing involving low fluidity powders, the weighed coarse and fine powders are placed into a scaled cylinder or a beaker. The mixture is stirred so that the powders are mixed evenly. It is then vibrated. The volume of the mixed powders is measured after the vibration. The packing density is calculated.

The packing density of a powder compact is defined as the ratio of the volume occupied by the powder to the total volume, i.e.,

$$f = \frac{V_{POWDER}}{V_{TOTAL}} = \frac{\sum W_i / \rho_i}{V_{TOTAL}} \qquad (1)$$

where V_{TOTAL} is the total volume of the packed powder and the porosity, W_i is the weight of the powder component i, and ρ_i is the theoretical density of the powder material for component i.

4. RESULTS AND DISCUSSION

4. 1 Single Component Packing

The packing density of powder compacts depends on the characteristics of the particles. Generally, for single component packing, the density of the particle material has no significant influence on its packing density. Particles of the same size and shape will have the same packing density despite the difference in theoretical density of the materials [3]. The main factors affecting the packing density for single component powder packing are particle size, particle shape, and the ratio of the diameters of the container to the particle.

4.1.1 Effect of the ratio of the diameters of the container to the particles

Table 2 shows the effect of the ratio of D/*d* on packing density (D is the diameter of the cylindrical containers used in the experiments, and *d* is the diameter of the particles). For *D/d* varying from 3.5 to 39.4, carbon steel balls (Sample #1) with 3175 μm (1/8-inch) in diameter were used along with cylindrical containers with different diameters. For *D/d* of 57.6, copper shorts with a diameter of 850 μm (Sample #2) were used. It can be observed from Table 2 that at low D/*d* ratios, packing density increases relatively rapidly with the increase in D/*d* ratio. The packing density become almost constant when the *D/d* ratio is greater than 7.66. This is consistent with McGary's previous work [4], in which the author has also concluded that maximum packing density will be realized if the *D/d* ratio is greater than 50.

***Table 1** Characteristics of selected powders*

Sample Number	Materials name	Material	Material density (g/ml)	Geometry	Average particle size (μm)
1	Carbon Steel Ball	Carbon Steel	7.85	Spherical	3175
2	12 HP Copper Shot	Copper	8.91	Round	850
3	34 HP Bronze	Bronze	8.65	Round	450
4	Fe Powder	Iron	7.85	Spherical	22~53
5	T-15 Powder	Tool Steel	8.19	Spherical	>150
6	T-15 Powder	Tool Steel	8.19	Spherical	80~150
7	T-15 Powder	Tool Steel	8.19	Spherical	<22
8	ATOMET 1001	Low Carbon Steel	7.85	Irregular	>150
9	ATOMET 1001 Powder	Low Carbon Steel	7.85	Irregular	<22
10	DISTALOY 4600A	Low Carbon Steel	7.9	Irregular	>150
11	DISTALOY 4600A	Low Carbon Steel	7.9	Irregular	<22

***Table 2** Single component packing density for different D/d*

Sample number	2	1	1	1	1	1	1
D/d	57.6	39.4	15.1	10.9	7.66	4.93	3.50
Packing Density	0.65	0.63	0.61	0.62	0.62	0.58	0.55

4.1.2 Effect of particle shape and size

The particle shape can vary significantly depending on the manufacturing process used and influences the particle packing, flow, and compaction properties. The greater the particle surface roughness or the more irregular the particle shapes, the lower the packing density [5]. For a gas atomized metal powder, the shape is almost spherical and for water atomized metal powder, the shape is more irregular [6]. Some of the selected powder shapes used in this study are shown in Fig. 2.

Figure 2: Optical micrographs of powders with different shapes.

Table 3 gives the comparison of the packing densities for particles with different shapes. The irregular shape DISTALOY 4600A (Samples #10 and #11) and ATOMET 1001 (Samples #8 and 9) powders have a lower packing density, which is 0.49, as compared with the packing density of the powders of the spherical shape with the same size (Powders # 5 and #7), which is 0.63. Therefore, the packing density of the powders with irregular shapes is 22% lower than that of the powders with the spherical shape.

On the other hand, particle size has little effect on packing density in the size range investigated for both spherical/round particles and for irregular shaped particles. The packing density varies between 0.60 and 0.63 for spherical or round shape particles, and it is 0.49 for the powders with irregular shapes.

4.2. Binary and Tertiary Packing

4.2.1 Effect of particle size ratio

The results of single-component powder packing experiments indicate that the maximum packing density is about 0.65. For the new RT process considered in the current study, a higher packing density is required to achieve sufficient load transfer ability. Adding certain amount of smaller particles into a packing structure consisted of large particles can greatly improve the packing density. Small particles are used to fit into the interstices between large particles, and smaller particles can be used to fit into the next level of pores. Continue this exercise will gradually improve the packing density of the powder compact. The size ratio and the mixing ratio of the packing components are two dominant factors that affect the final packing density of the binary or multi-component systems, in addition to the factors discussed in the single-component system in the previous section. The mixing ratio is defined as the ratio of the weight of the large particle to the total weight of the powder mixture. The particle size ratio is defined as the ratio of the size of the large particle to that of the small particle. In the case of spherical particles, the size ratio can be conveniently expressed as the diameter ratio.

To exam the effect of the particle size ratio of the packing components on the packing behaviour of binary and tertiary mixtures, the experiments are conducted for different particle size ratios at a mixing ratio of 0.74 for binary mixtures, and 0.63 for the large size particles in the tertiary

Table 3. Single component packing density for different particle shapes and sizes

Sample number	1	2	3	4	5	6
Shape	Spherical	Round	Round	Spherical	Spherical	Spherical
Size (μm)	3175	850	450	22~53	>150	80~150
Packing density	0.63	0.65	0.63	0.63	0.63	0.60
	7	8	9	10	11	
Shape	Spherical	Irregular	Irregular	Irregular	Irregular	
Size	<22	>150	<22	>150	<22	
Packing density	0.63	0.49	0.49	0.49	0.49	

mixture and 0.23 for the middle size particles in the tertiary mixture. Table 4 gives the packing densities of binary and tertiary mixtures at different particle size ratios. The results show that adding small particles into a packing structure of large particles can greatly increase the packing density. The packing density of the binary or tertiary mixture increases between 9% and 44% as compared with the single component packing density. The increase in the packing density for the binary mixture with a low particle size ratio (Cases 4-6) is in the range of 9% ~ 14% and it is 32% ~ 33% for the binary mixture with a high particle size ratio (Cases 2 and 3). The increase in the packing density for the tertiary mixture is 44%.

The basic requirement for improved packing density in multiple component packing is that small particles can freely pass through the voids between large particles. For spherical component packing, the minimum size ratio that satisfies this requirement can be determine using the packing models shown in Fig. 3. There are two extreme packing conditions in the ordered single component packing. The simple cubic packing, as shown in Fig. 3 (a), produces the largest interstice between particles. The close packing, such as in the face-centred cubic structure shown in Fig. 3 (b), on the other hand, produces the smallest interstice between particles. The size of the fine particles should be smaller than the throat gate dimension of large particles so that the fine particles can freely pass through the throat gate between large particles.

In Fig. 3, R is the radius of the large sphere, and r is the radius of the small sphere. For the face-centered packing model, the relation between R and r can be expressed as:

$$\frac{R}{R+r} = \cos 30^\circ \qquad (2)$$

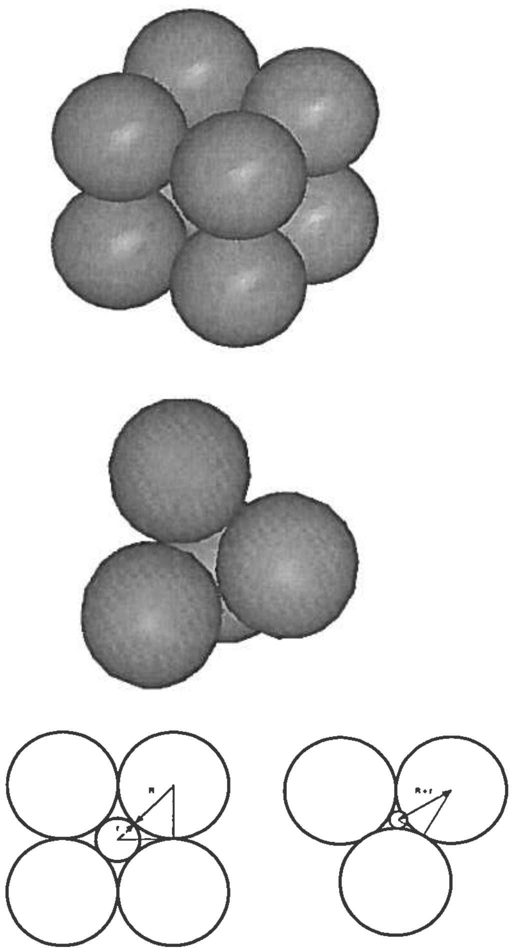
$$R/r = 6.46 \qquad (3)$$

For the simple cubic packing, the relation becomes

$$\frac{R}{R+r} = \cos 45^\circ \qquad (4)$$

$$R/r = 2.41 \qquad (5)$$

It can be concluded that the minimum particle size ratio, R/r, for small particles to fill the voids between large particles without pushing them apart is 2.41. When the ratio R/r is greater than 6.46, all of the small particles can pass the throat gates and enter the interstices between large particles. In order to obtain a higher packing density, the particle size ratio should be greater than 6.46.



(a) (b)

Figure 3: *Throat gate structures between particles*

(a) Simple cubic packing
(b) Face-centred cubic packing

The experimental results on the effect of particle size ratio are shown in Table 4. The particle size ratios in Cases 1 to 3 are much higher than 6.46. Thus, the packing densities in these cases are higher than those in Cases 4 to 6. In Case 6, the particle size ratio is lower than 6.46, but higher than 2.41. So, the small particles can only partially fill the voids between the large particles. The packing density increases compared with the single component packing density, but is lower than the system with high particle size ratio. In Case 5, the size ratio varies from 5.67 to 10.6 and it does not totally satisfy the particle size ratio requirement for good binary packing, which leads to a lower packing density. The particle size ratio in Case 4 is 6.82 and it is greater than the minimum particle size ratio requirement for good binary packing. However, the packing density is also low. This is due to the fact that the actual powder packing is not ordered packing. The result suggests that the minimum particle size ratio for actual powder packing to achieve a good binary packing should be higher than 6.82. As expected, the highest packing density is obtained from tertiary powder packing, Case 1, which is 0.91.

It is observed that the binary packing density for the mixture of Sample #2 and Sample #4 (Case 3) is slightly higher than that for the mixture of Sample #1 and Sample #4 (Case 2). This may attribute to the fact that the single component packing density for Sample #1 is lower than that for Powder #2 as shown in Table 3. It is also noticed that the binary packing density is between 0.71 and 0.72 when the particle size ratio is lower than the minimum particle size ratio requirement for good binary packing and it is 0.84 to 0.86 when the particle size ratio is higher than the minimum particle size ratio requirement. Therefore, the particle size ratio has little effect on the binary packing density once the size ratio is lower or higher than the minimum particle size ratio requirement for good binary packing.

4.2.2 Effect of mixing ratio

Table 5 and Fig. 4 show the packing densities of four different binary mixtures with different mixing ratios. The packing density varies from 0.67 to 0.86. It can be seen from the results that there is an optimal mixing ratio for each binary mixture at which the packing density of the binary mixture is maximal. When small particles are added to fill the voids between the large particles, the porosity of the binary powder mixture decreases. Therefore, the packing density of the binary mixture increases. When the small particles fill all of the voids without forcing the large particles apart, the packing density of the binary mixture is at its maximum value. Further addition of small particles will force the large particles apart and the packing density will decrease. The optimal mixing ratio falls in the range of 0.71 ~ 0.77.

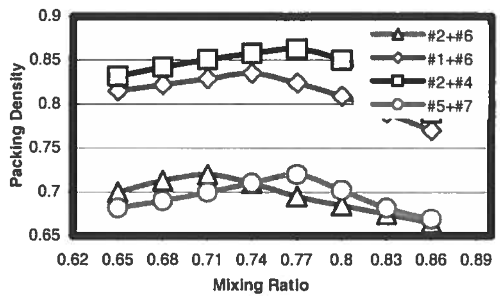


Figure 4: *Variation of the binary packing density with the mixing ratio*

5. CONCLUSIONS

In the single component packing, the particle shape has the most significant effect on the powder packing density. The spherical and round particles produce higher packing density, and therefore, are desirable for the intended RT application. The size ratio of the container and the particle (*D/d*) has little effect on the packing density when $D/d \geq 7.66$, but packing density started to drop significantly when the ratio *D/d* is less than 5. The particle size has no significant effect on the packing density.

Mixing particles of different sizes can greatly increase the packing density because the voids among large particles can be filled by small particles. In the current study, the packing density of three-component packing can reach 0.91 and binary packing density can reach 0.86. The particle size ratio is a very important parameter for multiple component packing. For best packing results, the size ratio of the large particle to the small particle should be higher than 7 so that small particles can easily enter the interstices between the large particles. On the other hand, particle size should not be too small to avoid low fluidity. The mixing ratio is another important parameter affecting multiple component packing density. There exists an optimal mixing ratio for a binary mixture at which the packing density is maximal. The optimal mixing ratio is in the range of 0.71 ~ 0.77.

Table 4. Binary and tertiary packing density
Table 5 *Binary packing density at different mixing ratios*

Case	Sample mixture	Particle size ratio	Packing density			Packing density increase (%)
			Large particle	Small particle	Mixture	
1	#1+#3+#7	144: 20.5: 1	0.63	0.63	0.91	44
2	#1+#4	(59.9~144): 1	0.63	0.63	0.84	33
3	#2+#4	(16.0~38.6): 1	0.65	0.63	0.86	32
4	#5+#7	6.82: 1	0.63	0.63	0.71	13
5	#2+#6	(5.67~10.6): 1	0.65	0.60	0.71	9
6	#1+#2	3.74:1	0.63	0.63	0.72	14

Table 5 Binary packing density at different mixing ratios

Mixture	#2+#6	#1+#4	#2+#4	#5+#7
Particle size ratio	5.67~ 10.6	59.9~ 144	16.0~ 38.6	6.82
Mixing ratio	Binary Packing Density			
0.65	0.70	0.82	0.83	0.68
0.68	0.71	0.82	0.84	0.69
0.71	0.72	0.83	0.85	0.70
0.74	0.71	0.84	0.86	0.71
0.77	0.70	0.82	0.86	0.72
0.80	0.69	0.81	0.85	0.70
0.83	0.68	0.80	0.83	0.68
0.86	0.67	0.77	0.80	0.67

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