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Experimental study of the deformation behaviour of compacted metal powders used in a new rapid tooling process

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AN EXPERIMENTAL STUDY OF THE DEFORMATION BEHAVIOR OF COMPACTED METAL POWDERS USED IN A NEW RAPID TOOLING PROCESS

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ABSTRACT

To examine the feasibility of a recently proposed rapid tooling process based on the backing of a metal shell with metal powders, the compressive deformation behavior of selected metal powders and metal shells was investigated. It was found that the mechanical properties of the powder material and the mixing ratio of powders of different sizes had a significant effect on the compressive deformation behavior of the compacted powders. Softer metal powders with the same compressive stress tended to produce greater plastic deformation and form a block under a stress of 138 MPa. Mixing two or more powders of different sizes could significantly increase the deformation resistance of the compacted powders. Minimum plastic deformation was achieved when the fraction of the coarse powder in a binary powder mixture reached 0.77. Initial loading at a higher stress could minimize or eliminate the plastic deformation in subsequent loading cycles. This feature could be used advantageously in powder packing for the proposed rapid tooling process. Some elastic properties of the compacted metal powders were also determined from the compression experimental data.

1. INTRODUCTION

Due to the globalization of the world economy and the consequent increase in competition, it is more important than ever for manufacturers to shorten their product development and manufacturing cycles. The current competitive market not only requires faster product development and reduced production time, but also demands higher quality, greater efficiencies, lower cost, and the ability to meet environmental and recycling objectives.

The rapid prototyping (RP) and rapid tooling (RT) technologies emerged in recent years offer alternative routes for rapid manufacturing and are attracting increased interest from the manufacturers [1]. With the RP technologies, three-dimensional models can be fabricated rapidly using a layered, additive manufacturing approach, normally in a fraction of the time needed by the conventional fabrication methods. Tooling is a critical step in the product development and manufacturing processes, and is usually expensive and time consuming. Therefore, shortening the tooling lead-time plays a key role in the reduction of the overall product development time and meets a strong demand by the manufacturing industry. The emergence of the RP technologies and the continuous improvements in the accuracy and capacity of the RP processes have led to the development of various RT technologies [2-5] aimed at reducing the cost and the lead time. Therefore, the cost and lead-time of tooling can be reduced significantly.

A recently proposed RT process is illustrated schematically in Fig. 1. The process begins with a three-dimensional computer model of the mould design. Based on the computer model, a plastic pattern complementary in shape to the mould is fabricated using a RP process. A metal shell is then generated by depositing a thin layer of the metal onto the cavity side of the plastic pattern by using an electrochemical process. Reinforcing ribs are added to the back of the metal

shell to improve its strength and rigidity. Metal powders are then packed into the back of the metal shell to provide mechanical support. Finally, the backside of the mould is sealed and the process is completed.

In this study, the effects of various parameters on the deformation behavior of metal powders under compressive loading are investigated experimentally to examine the feasibility of the recently proposed rapid tooling process based on backing of a metal shell with metal powders. The experimental results are used to obtain some elastic properties of the compacted metal powders under various loading conditions. These are important parameters for the deformation analysis of the metal shell and powder assembly used in the new RT process, which will be conducted in subsequent work.

2. EXPERIMENTAL PROCEDURES

The metal powders used for the compression experiments are given in Table 1. The T-15 tool steel powder was provided by UltraFine Powder Technology. It contains high concentration of carbon and other alloy elements and is spherical in shape. ATOMET 1001 powder is made of pure iron and provided by Quebec Metal Powders. DISTALOY 4600A is a low alloy steel powder provided by Hoeganaes. Both ATOMET 1001 and DISTALOY powders have irregular shapes. The tool steel powder has a hardness of HRB 220 as compared with a hardness of HRB 48 and 79 for the pure iron and low alloy steel powders, respectively. Two particle sizes of powders are used in the compression tests: coarse powder with particle size ranging from 45 μm to 350 μm and fine powder with grain size ranging from 6 μm to 22 μm . Coarse powders were used for “single” sized powder compression tests, and mixtures of coarse and fine powders were used for “binary” packing compression tests.

The compression tests were carried out using an Instron Mechanical Testing System according to ASTM standard B331-95 [6] in an axial compression die shown schematically in Fig. 2. The powder is dried in an oven at 105 °C for 30 minutes before the compression test to remove any absorbed moisture. The dried powder is vibrated for 15 minutes in the single component powder compression test after being loaded into the compression die. The coarse and fine powders are carefully mixed in the die and are then vibrated for 15 minutes before the compression test of the mixed powders. The powder mixtures were loaded at a rate of 10 kN/min to a maximum stress of 138 MPa, and then unloaded at a rate of 10 kN/min.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Powder Material Properties on the Compressive Properties of the Powder

Table 2 shows the results of the single loading-unloading compression experiments for the three coarse powders listed in Table 1. The powder compact density is defined as the ratio of the volume occupied by the powder to the total volume after compression, i.e.

$$f = \frac{V_{POWDER}}{V_{TOTAL}} = \frac{W / \rho}{V_{TOTAL}} \quad (1)$$

where V_{TOTAL} is the total volume of the powder, W is the weight of the powder, and ρ is the material density of the powder.

It can be seen that the powder properties have a significant effect on the compressive characteristics of the powder. The total strain under the given loading condition was 0.157 for the T-15 tool steel powder. In contrast, the total strain for the iron powder ATOMET 1001 was 0.462, which is three times of that for the T-15 tool steel powder. The packing density of loose

powders obtained from previous work [7] is also given in Table 2. Clearly, the low packing density in the loose powder for ATOMET1001 and DISTALLOY 4600, primarily resulting from the irregular shapes of the particles, contributed significantly to the large strain in the compression test. In addition, the relatively low hardness of the ATOMET1001 and DISTALLOY 4600 powders makes them easy to deform plastically, contributing further to the total strain. This is evidenced by the facts that, although the T-15 tool steel powder has the highest packing density before compression, its compact density after compression is the lowest; and the soft powders tend to form blocks after compression while the T-15 steel powder remained loose after compression test at a stress up to 138 MPa. These results suggest that powders with high initial packing density and high hardness are more suitable for the backing application in the proposed RT process. Such characteristics not only provide better load support and transfer, but also better serve the purpose of reuse of the powders. Based on these results, only T-15 tool steel powder was used in further experiments.

3.2 Effect of the Mixing Ratio on the Compressive Properties of Binary Powder Mixtures

In powder mixtures, the addition of smaller particles into a packing structure consisting of large particles can greatly improve the packing density. The effect of mixture ratio, which is defined as the ratio of the weight of the coarse powder to the total weight of the powder mixture, on the compression behavior was investigated using binary powder mixtures of the coarse and fine T-15 powders. Table 3 shows the total compressive strain and corresponding powder compact density of the binary powder mixture at different mixing ratios. It can be seen from the results that at the mixing ratio of 0.77, the total strain is minimal. This represents an optimal mixing ratio at which the small particles fill all of the voids formed by large particles without forcing the large particles apart, and the packing density of the binary powder mixture is at its

maximum [7]. It is clear that the optimal mixing ratio corresponding to the maximum powder packing density produces the least compressive deformation. .

3.3 Compressive Behavior of Powders in Multiple Loading-Unloading Cycles

To investigate the effect of loading history on the deformation behavior of the compacted metal powder, multiple loading-unloading experiments for the T-15 binary powder mixture with a mixing ratio of 0.77 are carried out using a five-cycle loading pattern shown in Fig. 3.

3.3.1 The critical point

The loading-unloading curves for the five-cycle compression test are shown in Fig. 4. The first loading curve is significantly different from the succeeding unloading and reloading curves. This is because the first loading process involves a significant portion of non-elastic and irreversible deformation mechanisms that include relative particle movement, plastic deformation, and perhaps particle fracture [8]. In contrast, unloading of the compacted powder is largely an elastic process. Upon reloading, it was observed that the reloading curve crossed over with the previous unloading curve at a certain stress level, as shown in Fig. 4. The cross point is referred to as the critical point. In addition, the unloading and reloading curves become parallel and closer to each other as the reloading cycles proceed. The tangent of the unloading or the reloading curve approaches a constant value.

The critical point has two features. First, when the load is below the critical point, the reloading curve lies on the left side of the previous unloading curve, indicating no strain increase for the same stress as compared with the previous unloading process, and the strain should be elastic in nature. On the other hand, when the reloading load goes beyond the critical point, the

strain of reloading exceeds that in the previous unloading process. Secondly, the stress corresponding to the critical point moves higher with the loading-reloading cycles, as shown in Fig. 4. These features indicate that the elastic properties of compacted powders can be controlled with properly designed loading-unloading cycles.

3.3.2 Effect of the mixing ratio on the critical point

Figure 5 shows the effect of the binary mixing ratio on the position of the critical point. The compressive stresses corresponding to the first and the fourth critical points are shown in Table 4. It can be seen from Table 4 that the binary powder mixture with a mixing ratio of 0.77 has higher critical points as compared to the powder mixtures with mixing ratios of 0.74 and 0.80, respectively. The mixing ratio of 0.77 corresponds to the highest powder packing density in the binary packing system. A higher critical point means a higher deformation resistance in the subsequent reloading, which is beneficial for maintaining the integrity of tooling under working conditions for the intended application.

3.3.3 Effect of Loading History on Deformation Behavior of Binary Powder Mixtures

For the proposed RT application, excessive deformation of the backing powders is undesirable and plastic deformation of the powder must be avoided. The results obtained in the foregoing section indicate that plastic strain can be minimized by properly controlling the loading history. The effect of preloading on the subsequent deformation behavior of a mixture of coarse and fine powders of T-15 tool steel was examined using the two loading patterns shown in Figs. 6 and 7. In these test, two and five compression cycles with a maximum stress of 138 MPa were followed by three more cycles with a maximum load set at 60% of the previous maximum.

Figure 8 shows the loading-unloading curves of the compression test using the loading pattern shown in Fig. 6 and powder mixtures with mixing ratios of 0.74, 0.77, and 0.80, respectively. For all mixing ratios examined, there was no further strain increase observed in the three loading-unloading cycles with reduced maximum load. Details of the stress-strain curves for the mixing ratio of 0.77 are given in Fig. 9. Figure 10 shows the experimental results for the second loading pattern shown in Fig. 7. Again, there is no further increase in the total strain observed in the three loading-unloading cycles with reduced maximum load. These results indicate that by properly pre-compressing the metal powders, plastic deformation of the backing metal powders can be eliminated in the proposed RT process.

It is also observed that the increase in the total strain in the first five loading-unloading cycles is smallest for the mixing ratio of 0.77 among all powder mixtures examined. This is consistent with the results from the compression test using a single loading-unloading cycle.

Table 5 shows the change in total strain and powder compact density between the second loading and the last loading for the loading pattern shown in Fig. 7. It can be observed that the powder mixture with a mixing ratio of 0.77 has the least increase in both the total strain and powder compact density between the second loading and the last loading. The increase in the total strain is less than 5% for the powder mixture with a mixing ratio of 0.77, indicating that the plastic deformation after the second loading cycle is very small.

3.3.4 Elastic Properties of Compacted Powders

Elastic properties, such as the Young's modulus and Poisson's ratio of compacted powders are important parameters for the deformation analysis of the metal shell and powder assembly

used in the new RT process. Linear elasticity (Young's modulus and Poisson's ratio) is often sufficient to describe the behavior of packed powders [9]. However, few studies report the elastic properties of unsintered compacted powders [8]. Hehenberger et al. [10] interpret the unloading curves of uniaxial compression of compacted powders in terms of the Young's modulus and Poisson's ratio.

The Young's modulus and Poisson's ratios for the compacted binary T-15 powder mixture are obtained experimentally in this study using the data from the uniaxial compression test. The compaction of powders involves a number of different mechanisms. These mechanisms are interrelated through particle interactions that in turn depend on the distribution of particles and the properties of individual particles. In contrast, unloading of the compacted powder is largely a linear elastic process. Therefore, the elastic properties of compacted powders can be more accurately determined from the elastic unloading process.

Typical unloading and reloading curves used for the calculation of the elastic properties of the compacted powder are shown in Fig. 11. Although the entire curves are not linear, both the unloading and reloading curves have an apparently linear portion that is consistent with elastic deformation. In this linear portion, the reloading compressive strain does not exceed the previous unloading strain and the curve lies on the left of the previous unloading curve in the stress-strain diagram. In the current study, the elastic properties of compacted powders are calculated from the linear portion of the unloading curves. The linear portion is taken from the point with 20% of the maximum loading stress to the critical point. The elastic parameters of compacted powders are calculated using linear elastic theory. Figure 12 shows the unloading curve obtained from the

compression test in the fifth unloading phase for the T- 15 powder mixture with a mixing ratio of 0.77.

The Young's modulus of a compacted powder is calculated as follows:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_B - \sigma_A}{\varepsilon_B - \varepsilon_A} \quad (2)$$

where σ is compressive stress [MPa] and ε is compressive strain. 'A' and 'B' could be any two points on the straight line as shown in Fig. 12. A linear regression analysis shows that the R-squared value for the curve shown in Fig. 12 is 0.9982. It indicates that the trend line of the selected segment matches well with the actual experimental data. The Young's modulus calculated for the compacted T-15 powder mixture at a mixing ratio of 0.77 is 1680 MPa.

For the calculation of the Poisson's ratio, it is assumed that the compression die is rigid, and the deformation of the inner surface of the die in the radial and circumferential directions is zero. From Hooke's Law, the triaxial stress can be written in cylindrical coordinates as:

$$\sigma_z = \frac{E}{(1+\nu)(1-2\nu)} [(1-\nu)\varepsilon_z + \nu(\varepsilon_r + \varepsilon_\theta)] \quad (3)$$

where E is Young's modulus and ν is Poisson's ratio. When ε_r and ε_θ are equal to zero, Eq. (3) can be rewritten as:

$$\sigma_z = \frac{E}{(1+\nu)(1-2\nu)} (1-\nu)\varepsilon_z \quad (4)$$

If the Young's modulus E is assumed to be a constant in Eq. (4), the compressive stress and strain have a linear relationship. Letting $\Omega = \frac{E\varepsilon_z}{\sigma_z}$, Eq. (4) can be rewritten as:

$$2\nu^2 - (\Omega - 1)\nu + (\Omega - 1) = 0 \quad (5)$$

The values of the Poisson's ratio for the T-15 powder mixture at a mixing ratio of 0.77 are calculated based on the experimental data using Eq. (5). They are tabulated in Table 6 and shown in Fig. 13. The results show that the Poisson's ratio decreases with an increase in compressive stress. This agrees with the results from Hehenberger's study [10].

4. CONCLUSIONS

The deformation behavior of compacted powders under uniaxial compression depends heavily on the properties of the powder materials, the mixing ratio of powders of different sizes, as well as the loading history. Powders with higher hardness and initial packing density showed a smaller compressive deformation under the same loading conditions. Higher hardness also helps to prevent compacted powders from forming blocks after compression, which is necessary for powder reuse. For the given particle size of the coarse and fine powders, the mixing ratio of 0.77 is found to give the highest deformation resistance.

The critical point is an interesting and important phenomenon for powder compression. It defines the stress limit that produces no plastic strain condition in compacted powder. The loading history is important for the deformation behavior of compacted powders. A higher initial compacting stress generally leads to higher operating loads without further plastic deformation in subsequent loading. The load level that corresponds to the critical point increases with the number of loading cycles. The unloading curves have a linear portion, which can be used for the calculation of Young's modulus, and Poisson's ratio of the powder compacts.

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Table 1. Characteristics of selected powders

Powder	Particle Size		Material Properties				Shape
	Coarse (μm)	Fine (μm)	ρ (g/ml)	E (GPa)	HRB	ν	
T-15 Tool Steel	150-350	6- 22	8.19	190~210	220	0.27~0.3	Spherical
ATOMET 1001	45-150	-	7.85	190~210	48	0.27~0.3	Irregular
DISTALOY 4600A	45-150	-	7.85	190~210	79	0.27~0.3	Irregular

ρ – Density; E - Young's modulus; HRB – Hardness; ν -Poisson's ratio.

Table 2. Effect of material properties on powder compressive deformation behavior

Powder (coarse)	Total Strain	Compact Density	Packing Density	Powder Condition after Compression
T-15 Tool Steel	0.157	0.627	0.63	Loose
DISTALOY 4600A	0.375	0.692	0.49	Block
ATOMET 1001	0.462	0.766	0.49	Block

Table 3. Effect of the mixing ratio on binary powder compressive deformation behavior

Powder Mixture	Mixing Ratio	Total Strain	Compact Density
T-15 Tool Steel	0.80	0.183	0.783
T-15 Tool Steel	0.77	0.162	0.822
T-15 Tool Steel	0.74	0.179	0.810

Table 4. Compressive stress at the first and fourth critical points

Powder Mixture	Mixing Ratio	At the First Critical Point (MPa)	At the Fourth Critical Point (MPa)
T-15 tool steel	0.80	52	75
T-15 tool steel	0.77	110	127
T-15 tool steel	0.74	58	98

**Table 5. Changes of the total strain and compact density
between the second loading and last loading**

Powder/ Mixing Ratio	Total Strain			Compact Density Increase (%)
	Second Loading (ϵ_s)	Last Loading (ϵ_L)	$\Delta\epsilon=$ ($\epsilon_L - \epsilon_s$)	Between the second loading and the last loading
T-15/0.80	0.157	0.183	0.026	8.1
T-15/0.77	0.155	0.162	0.007	0.6
T-15/0.74	0.162	0.179	0.017	1.8

Table 6. Poisson's ratios for T-15 tool steel powder mixture at the mixing ratio of 0.77

Compressive Stress, σ_z (MPa)	Ω	Poisson's Ratio, ν
110	0.8454	0.242
95	0.8210	0.258
80	0.7875	0.277
70	0.7570	0.293
55	0.6909	0.323
40	0.5750	0.367
25	0.3200	0.437

A CAD model of a mould half is designed on a computer.

A plastic pattern with a complementary shape to the mould half is fabricated using a RP process

A metal shell is deposited inside the pattern, and then separated from the RP pattern

Reinforcing ribs are added to the back of the metal shell

The shell is backfilled with packed metal powders

The backside of the shell is sealed

The tool is finished

Figure 1. Schematic illustration of a newly proposed rapid tooling process.

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Figure 4. Typical loading-unloading curves of the five-cycle compression test

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Figure 6. First loading pattern

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Figure 8 Loading-unloading curves of the compression test using the first loading pattern

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